ENERGY AND FEASIBILITY ANALYSIS OF APPLYING BIO-BASED PHASE CHANGE MATERIALS TO BUILDINGS IN EAST ASIA

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ABSTRACT
The application of phase change materials (PCMs) in building envelopes can help promote energy efficiency due to its high heat capacity. Our study aimed to provide energy and economic insights for deploying PCM to buildings in eight different regions of East Asia through a series of energy and economic analysis using computer modelling and simulations. The static payback period (SPP) and dynamic payback (DPP) methods were used to evaluate the economic feasibility of applying a PCM at different melting phase temperatures (20°C, 23°C, 25°C, 27°C and 29°C). Results show that the proper choice of a PCM melting temperature is a key factor to improve the performance of the PCM applied to buildings. A melting phase temperature of 29°C achieved the highest economic feasibility in Seoul, Tokyo; Pyongyang; Beijing; and Ulaanbaatar and a melting temperature of 23°C in Hong Kong had the highest economic feasibility. Overall, the combined economic and energy analysis presented in this study can play an important role in improving the energy and economic feasibility of PCM in buildings.

KEYWORDS
BioPCM; SPP; DPP; energy savings; office building; heating & cooling seasons; melting point temperature

1. INTRODUCTION
Reducing energy consumption in buildings has become a main issue when evaluating the global energy demand due to rising greenhouse gas emissions (mainly carbon dioxide), which are environmentally undesirable products that result from economic growth, increasing population density and the quest for improving quality of life. This is particularly true in East Asia (Walheer 2018), where the majority of energy consumption in buildings comes from heating and cooling (Ye et al. 2017). Globally, buildings consume around 45% of the total energy, 40% of which is consumed by heating, ventilation and air conditioning systems (HVAC) (Wu et al. 2017). For example, existing buildings in the US, UK and EU consume approximately 40% of the total energy consumption

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and 30–40% of the total energy consumption in East Asia (Leung 2018). In China, the building sector is responsible for around 40% of the total energy (Mi et al. 2016). According to the International Energy Agency (IEA), the building sectors in South Korea and Japan consume 26% and 33% of the total energy used, respectively (Evans et al. 2009; Evans et al. 2009). Based on the European reference scenario trend projection in 2016, the share of energy demand in buildings accounted for around one-third of the final energy consumption in all sectors, and it is expected to increase slightly by 2050 (EU Reference Scenario 2016). This will contribute to the urban heat island (UHI) phenomenon in urban areas, which causes higher surface and air temperatures in city centers rather than in the outskirts of the city (Akbari et al. 2016).

Data show that 20–50% of the heating and cooling energy consumption is caused by the building envelope (Yu et al. 2015). A significant increase in demand for cooling energy is expected by 2050, and the estimated increase will be roughly 150% worldwide and around 300–600% in developing countries (Saffari et al. 2017). To overcome this global concern, policy makers are seeking to find energy saving solutions because energy efficiency is the most economical and fastest way to reduce carbon emissions (Yu et al. 2015). For example, the Roadmap 2050 long-term policy is seeking to achieve a low-carbon economy with a minimum cost in the EU. Improving the building envelope is a basic step to achieve this goal, especially as 20–60% of the energy use in buildings is impacted by the design and construction of the building envelope (IEA 2013; EC 2018). Improving the building envelope can be realized through the use of passive technologies such as phase change materials (PCMs) to reduce energy demand in buildings (Solgi et al. 2018). This is because of the high latent heat capacity of PCMs, which allows them to store a large amount of energy in small temperature intervals, resulting in a significant increase in the thermal mass of the building when PCMs are incorporated into its envelope (Saffari et al. 2016; Wang et al. 2018). PCMs can be classified into three major categories: inorganic, organic and eutectic PCMs. The inorganic PCM is composed of salt hydrates and metals, the organic PCM is made of paraffins and non-paraffins, whereas the eutectic PCM is a mixture of organics and inorganics (Tatsidjodoung et al. 2013). Each of these groups has its typical range of melting point temperature and melting enthalpy.

Investment in the building envelope is a promising and environmentally-friendly solution since a good passive design could bring long-term energy efficiency and carbon dioxide reduction using sunlight, and it could provide higher thermal comfort, which leads to an increase in energy savings due to the stable indoor temperature (the balance between diurnal and nocturnal energy demand) (Moreno et al. 2014). Effectively applying a PCM in the building envelope (e.g., walls, floors, roofs, slabs, façade, shading system, and windows) requires appropriate selection of thermo-physical properties, quantity and position of the PCM to guarantee the performance of the PCM and ensure economic feasibility (Cascona et al. 2018). Therefore, before applying PCMs in the building envelope, their performance should be analyzed using validated numerical simulation tools that focus on the incorporation of PCMs to help select materials, determine thicknesses and set appropriate positions within the building envelope (Kosny et al. 2010). In this context, mathematical modelling and computer simulations have become an economical and rapid way to provide a better understanding of the practical processes that involve PCMs (Haghighat 2014). Reliable building energy simulation tools can facilitate design and analysis and can improve the PCM-enhanced building components without the need to set up expensive building field experiments or waste time (Saffari et al. 2017). Furthermore, computer-based simulation tools help engineers and designers assess potential decisions and achieve long-term targets (Kapetanakis et al. 2017).

The energy performance of building envelopes integrated with PCMs in reducing the cooling load energy in tropical Singapore was assessed using EnergyPlus (Lei et al. 2016). They reported that PCM in the exterior surfaces of walls showed better performance, while thinner PCM layers provided higher efficiency and lower cost. Mi et al. (2016) also used EnergyPlus to evaluate the economic feasibility of applying PCMs in building envelopes in different cities of China. They found that integration of a PCM layer with a phase change temperature of 27°C in a typical multi-story office building is more beneficial in cold regions (Shenyang and Zhengzhou) as well as in Changsha during its hot summer and cold winter. A multi-dimensional optimization study was conducted by Soares et al. (2014) and Saffari et al. (2017) by combining EnergyPlus and GenOpt tools to identify the effect of PCM on the energy performance in residential buildings in different climates. The researchers concluded that an optimum solution incorporating PCM can be obtained for each climatic zone, which in turn improved cooling and heating energy savings and reduced carbon dioxide emissions.

Chan (2011) also used EnergyPlus to evaluate the energy performance of a typical residential flat integrated with PCM located in Hong Kong. The application of PCM into the building envelope with a cost payback period of 91 years made the project economically infeasible. However, the environmental assessment showed that the energy payback period was 23.4 years. Baniassadi et al. (2016) utilized the building energy simulation program EnergyPlus to determine the appropriate thickness of a PCM integrated with a residential building envelope in different regions of Iran. They concluded that PCM thickness differed significantly depending on the region, current prices and current economic situation of the country. In cold regions, the optimum thickness was more than 6 cm, while in the southern parts of the country, it was approximately zero. Sun et al. (2014) used the energy savings ratio (ESR) and simple payback period (SPP) to evaluate the application of PCMBs in building enclosures during the cooling season in five cities located in different climate regions of China. They suggested that the phase transition temperatures should be at least 3°C higher than the average outdoor air temperature. Using a simple payback period, they found that the use of PCMBs in buildings with moderate temperature climates will be economically feasible. The energy savings potential of PCMs in eight main cities of Australia was also assessed by Alam et al. (2014) in EnergyPlus utilizing five different phase temperature ranges. It was found that the effectiveness of PCM is strongly based on different factors (e.g., local climate, surface area of PCM, thickness and thermostat range).

Similarly, Gassar and Yun (2017) studied the ability of PCM to reduce building energy demand in three different regions of East Asia under climate future changes for the years 2017, 2020, 2050 and 2080. They concluded that the application of PCM into the envelopes of buildings reduce indoor temperature fluctuations and increase the thermal comfort of occupants, as well, produce energy savings, but, they did not address the economic analysis in more detail. Several previous studies (Sage-Lauck and Sailor 2014; Seong and Lim 2013; Cui et al. 2015) have also been conducted on the energy performance of buildings for passive cooling and heating applications to shift toward economic and eco-friendly buildings. Most previous studies have given more attention to the energy performance and the discomfort hours observed for a fixed thermostat temperature (Saffari et al. 2016). However, the financial and economic aspects should be considered, as they represent the end user and external costs (cost of carbon dioxide emissions), respectively (Stritih et al. 2018). The key incentive of applying a PCM technology for decision makers and building owners is to obtain a deep understanding of the cost and feasibility of investment in this field over the project life cycle for different PCM implementations. An important step in implementation decisions of a PCM project is to evaluate the operational revenue of PCM integration with building envelopes, which is derived mainly from the amount of energy generated by savings achieved using PCM. Operational revenue is significantly impacted by different factors such as phase melting temperature, thickness, site of the PCM on the building envelope and weather conditions. PCM properties and building characteristics are other impact factors that should also be considered for two reasons. First, most regions of East Asia are experiencing high humidity with hot weather during the cooling season; this impacts the performance of a PCM when applied in the building envelope. Secondly, building envelopes, namely walls, roofs and floors are commonly considered suitable places for PCM application in rural and urban regions. Next, it is essential to detail the cost of a PCM project, such as PCM prices, installation cost, and energy savings for evaluating many widely-used economic indicators such as net present value and payback period.

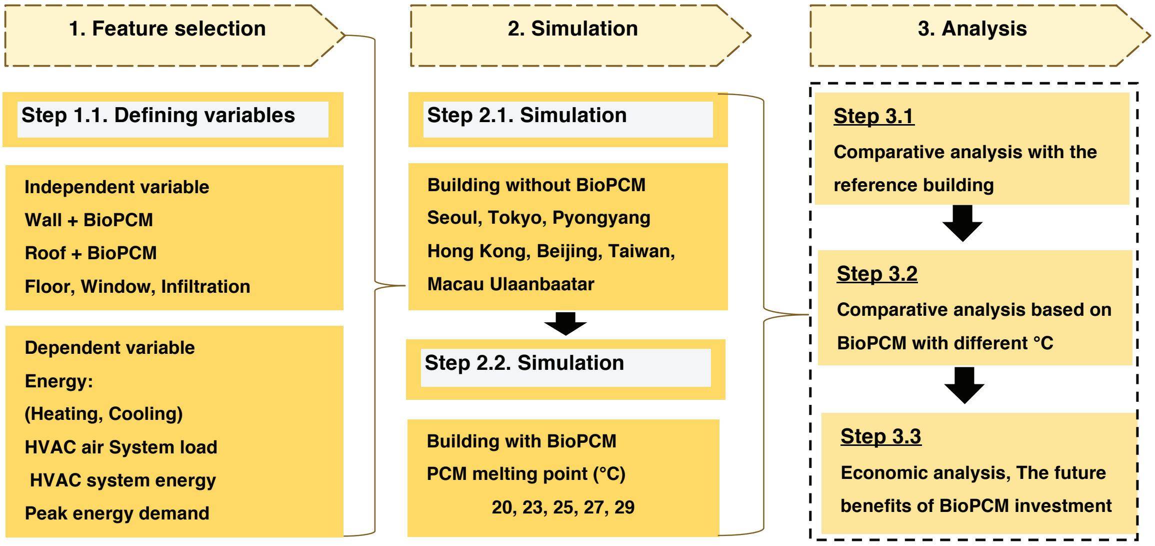
Although the literature on the techno-economic aspects of PCM has increased recently, few works addressed the feasibility of applying PCM in building envelopes. However, most of these studies on economic feasibility and energy management of buildings integrated with PCMs are not comprehensive. Sun et al. (2014) have used a simple static payback period, which does not account for the time value of money. In addition, their results were built on a range of phase change temperature between 23 and 25°C (small scale). Mi et al. (2016) have also used a simple payback period and dynamic payback period. However, their results are only based on a 27°C PCM phase change temperature. Similarly, Baniassadi et al. (2016) suggested that capital investments in energy saving strategies for residential buildings are not a good idea in Iran despite increases in energy prices and environmental costs. Therefore, an economic evaluation may not be enough and may overestimate the overall efficiency of the system. Analysis of simple payback period (SPP) or dynamic payback period (DPP) requires consideration of both phase change temperature and properties of the PCM used. The originality of this study is in analyzing the economic feasibility of applying a PCM while accounting for the time value of money over a wide phase change temperature range (i.e., 20°C, 23°C, 25°C, 27°C and 29°C) to determine the optimum PCM melting temperature that will provide economic benefits based on the outdoor boundary conditions and geographic location. In addition, we addressed the shortcomings/deficiencies in the previous studies. BioPCM was selected as an effective and well-known technology that has been proven in a number of studies when applied in building envelopes in different places of the world (Chan 2011; Gassar and Yun 2017; Pons and Stanescu 2017; Muruganantham 2010). PCMs will enhance energy efficiency in buildings in East Asia and achieve economic benefits as a result of the use this environmentally-friendly technology. Energy efficiency policy is essential in East Asia due to its acute energy dependence and the fact that most buildings in East Asia are not meeting their GHG targets established at the Paris Convention.

A typical medium office building model was selected from the U.S. Department of Energy Commercial Reference Building Models from the National Building Stock as the base case model (DOE's Commercial Reference Building Models) (DOE 2012) for this energy simulation in East Asia buildings.

2. METHODOLOGY

This work is presented in five steps: 1) selecting an office building, materials and BioPCM, 2) attaching BioPCMs with different melting phase temperatures into building envelopes, 3) analyzing and comparing energy savings in the study regions in the building model, 4) analyzing

FIGURE 1. Overall schematic form of the methodology followed.



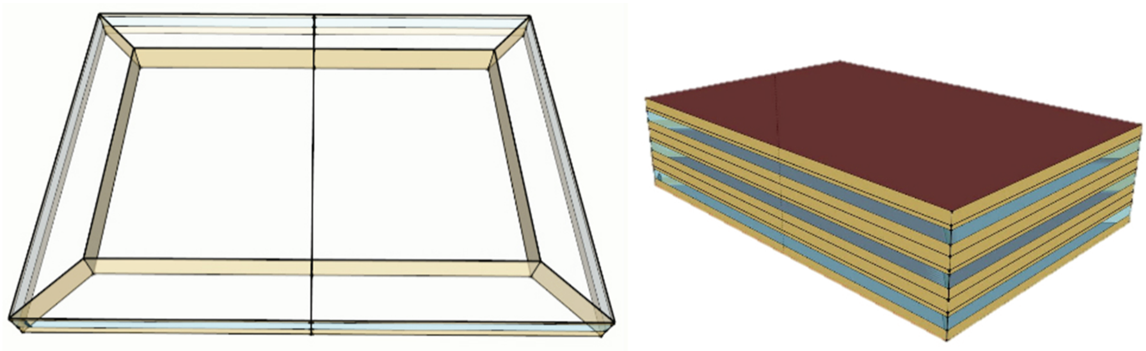
and evaluating economic feasibility, and 5) determining the future benefits of BioPCM investment in the buildings (Figure 1).

2.1 BioPCM and case study building

BioPCM is a bio-based phase change material that depends on organic compounds and changes from one state to another (e.g., from a solid to a liquid), as seen in Figure 2 (PHASECHANGE 2018). It is chemically inert and nontoxic (compared to traditional PCMs) (Muruganantham 2010). BioPCM was chosen as the phase change materials in this work due to its high heat capacity in storing amounts of heat within small ranges of temperature and its chemical and thermal stability. As seen in Figuire 2, BioPCM are encapsulated as separate blocks with air gaps between them. During the daytime with high outdoor temperature, the BioPCM melts and

FIGURE 2. BioPCM; Bio-Phase Change Material (PHASECHANGE 2018).

FIGURE 3. Reference building model in this work (DEO 2012).



stores a large amount of thermal energy and thus energy demands reduce. During the nighttime, the BioPCM dissipates heat to the building and to the outside environment. This process is useful during the winter time as the released heat helps in warming the indoor environment of a building. Also, the BioPCM works as an insulating layer to reduce thermal conductivity between the exterior and interior facade of the envelope. The energy storage capacity of a 19-mm-thick film of this product (BioPCM) is around 400–1250 kJ/m^2. The material is available with different melting points: 20°C, 23°C, 25°C, 27°C and 29°C. The value 29°C was chosen to represent the approximate peak of the heating curve. Furthermore, these materials can be manufactured such that their melting points can be varied from –22.7°C to 78.33°C, and this facilitates its use in different climatic zones within desired residential temperatures.

The building was selected from the U.S. Department of Energy Commercial Reference Buildings from the National Building Stock (DOE) as a base case (BC) model to conduct the simulation in different weather conditions that can be found in East Asia (DOE 2012). The building has a rectangular shape with an aspect ratio of 1.5, the window to wall ratio is 33% of the total of building wall area, and the floor to ceiling height is 2.7 m, as seen in Figure 3. The construction components are described and compared as in the work of the ANSI/ASHRAE Standard (ASHRAE 2011; Henninger and Witte 2010).

To investigate the effects of BioPCM on the building energy performance, a thin layer (19 mm) of the BioPCM was inserted into the interior surface between the fiberglass and plasterboard of the roof and all four sides of the interior walls of the three story office building in this study (Table 1 and Figure 4). The BioPCM enthalpy was considered constant and the change of its density from changing its phase was ignored. The enthalpy of the BioPCM was calculated from the enthalpy and temperature relation of the BioPCM.

2.2 Climates in the studied regions of East Asia

Eight cities located in different regions of East Asia were selected to study the relationship between climate parameters and the feasibility of applying BioPCM with different melting temperatures in the building envelopes. Eight cities were chosen to cover the main climate regions of East Asia and to reveal the climatic influences of the performance BioPCM. Detailed climate information for the selected cities for a period of one year is shown in Table 2 (World Climate and Temperature 2018). The weather data files for building simulations were obtained from the EnergyPlus weather database, which includes weather data provided in an EnergyPlus

FIGURE 4. The cross-sectional schematic view of walls and roof.

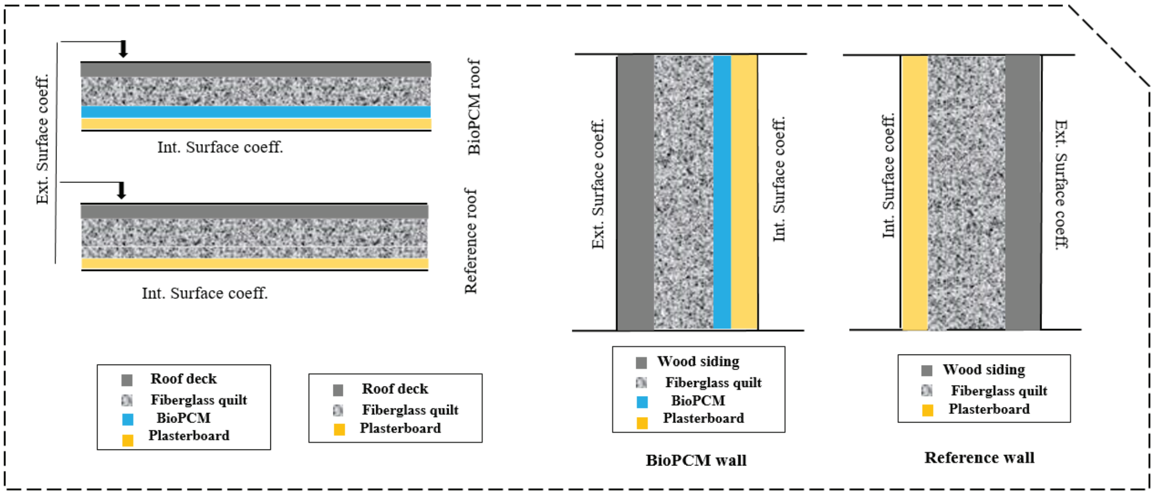


TABLE 1. Material properties of the building walls and roof with BioPCM integrated into the office building model (ASHRAE 2011; Henninger and Witte 2010).

	Material	Conductivity (W/m K)	Thickness (m)	U (W/m² K)	R (M² K/W)	Density (kg/m³)	Specific heat (J/kg K)
Wall	Int. surface coeff			8.26	0.121		
	Plasterboard	0.160	0.012	13.33	0.075	950	840
	BioPCM	0.20	0.019		0.025	860	1970
	Fiberglass quilt	0.040	0.066	0.61	1.650	12	840
	Wood siding	0.140	0.009	15.56	0.064	530	900
	Ext. Surface coeff.			29.41	0.034		
	Overall, air-to-air			0.501	1.944		
Roof	Int. surface coeff			8.26	0.121		
	Plasterboard	0.160	0.01	16.00	0.063	950	840
	BioPCM	0.20	0.019		0.025	860	1970
	Fiberglass quilt	0.040	0.1118	0.36	2.795	12	840
	Roof deck	0.140	0.019	7.37	0.136	530	900
	Ext. Surface coeff.			29.41	0.034		
	Overall, air-to-air			0.313	3.198		

TABLE 2. Climate information for the eight selected cities (World Climate and Temperature 2018).

City	Location	Elevation (m)	Region description	Average annual temperature (°C)	Temperature range (°C)
Seoul	37° 34′N 126° 57′E	38	Hot and humid summer, cold and dry winter	11.8°C	–7.3°C–29°C
Tokyo	35° 40′N 139° 46′E	37	Hot, humid and rainy summer, fairly mild and sunny winter	15.6°C	2.3°C–28.3°C
Pyongyang	39° 10′N 125° 46′E	36	Hot and humid summer, cold and dry winter	9.5°C	–11°C–28.3°C
Hong Kong	22° 18′N 114° 10′E	65	Hot, humid summer, mild with dry winter	23.2°C	14.1°C–30.9°C
Beijing	39° 55′N 116° 16′E	55	Humid and hot summer, severe, dry winter	11.8°C	–7.7°C–30.2°C
Taiwan	25° 1′N 121° 31′E	9	Hot, humid and rainy summer, mild winter	21.6°C	12.3°C–32°C
Macau	22° 11′N 113° 32′E	22	Hot, humid and rainy summer, very mild winter	22.7°C	14.5°C–28.9°C
Ulaanbaatar	47° 54′N 106° 51′E	1729	Short warm summer, long and frigid winter	–2.4°C	–25°C–17°C

Note: Temperature range represents the average range during summer and winter (the heating and cooling seasons).

format (EPW) from sources (EnergyPlus 2018). The PCM performance in buildings depends on the weather conditions and geographical location.

The effect of weather conditions and geographical location on the energy performance in East Asia's buildings are the focus of this work in buildings with a passive system (BioPCM). This is because a particular type of PCM has the potential of increasing the energy savings in a specific climatic zone and might decrease the energy saving performance in another climatic zone (Ahangari and Maerefat 2019; Solgi et al. 2019).

2.3 Simulation details

EnergyPlus 8.7.0 version software was employed to study the effect of BioPCM at different melting point temperatures on the energy performance for a multi-story office building located in different climatic regions of East Asia. EnergyPlus takes advantage of both the DoE-2 and BLAST programs. It has many featured characteristics such as heat balance load calculations, integrated loads, system and plant calculations in the same time step, a user-configurable HVAC system description, simple input and output data formats to facilitate virtualization of the results, and the ability to simulate BioPCM and materials with variable thermal conductivity. Furthermore, several advanced human thermal comfort algorithms are included in the software to model the indoor air quality and thermal comfort of the occupants (Saffari et al. 2017). The conduction finite deference (CondFD) solution algorithm was used for simulating BioPCM in EnergyPlus, which makes it capable of simulating the thermal performance of BioPCM in any location within the surface structure. The zone time step can be reduced to correspond with the one minute minimum time step used in the integrated system in EnergyPlus because of the short time steps used in the conduction finite difference solution algorithm.

Five ideal hypothetical BioPCMs were selected (20°C, 23°C, 25°C, 27°C, and 29°C main peaks) with melting ranges of 5°C. These were directly selected during the simulation period by EnergyPlus. Density change due to phase change was not considered, since it was negligible. Material properties of BioPCM in EnergyPlus models were as follows: melting point (20°C, 23°C, 25°C, 27°C and 29°C), thickness (0.019 m; the latent heat capacity of 19 mm thick of BioPCM was 400–1250 kJ/m^2), specific heat (1970 J/kg K),latent heat (219 kJ/g) and thermal conductivity (0.20 W/mk), (Table 1). The phase-change energy was considered by applying an enthalpy-temperature function. The formulation of a node of BioPCMs is given by Equation (1). In all models, the simulation time step was set to 1 minute, and a node discretization of 3 was selected, otherwise, inaccuracies may occur in the simulation results (Tabares-Velasco et al. 2012).

$$\rho Cp\Delta X \frac{T_i^{j+1} - T_i^j}{\Delta t} = K_{\text{int}} \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta X} + K_{\text{ext}} \frac{T_{i-1}^{j+1} + T_i^{j+1}}{\Delta X} \quad (1)$$

Here, ρ is the density (kg/m^3), Cp is the specific heat capacity (kJ/kg K), ΔX is the layer thickness (m), T is the node temperature (k), $j + 1$ is the new time step, j is the previous time step, i is the node being modeled, $i + 1$ is the node adjacent to the interior of construction, $i - 1$ is the node adjacent to the exterior of construction, K is the thermal conductivity (kW/m K), and Δt is the calculation time step (sec).

To find out the appropriate melting point temperature for regions of East Asia, first the comfort temperatures were determined using Mi et al. (2016) and Kwak and Huh (2019). On this basis, the thermal comfort temperature range was set to 18°C–29°C. That is, the heating system was functional when the indoor temperature was lower than 18°C, while the cooling system was operational when the indoor temperature exceeded 29°C (Table 3). The static payback period (SPP) and a dynamic payback period (DPP) were obtained to estimate the number of years required for the project's savings to equal the investment.

2.4 Validation

The BioPCM and CondFD models of EnergyPlus were verified and validated by previous studies (Cabeza et al. 2007). The PCM algorithm of EnergyPlus was validated against the experimental data by Sega-Luck and Sailor (2014) and Kuznik and Virgone (2009). The conduction finite deference (CondFD) solution and PCM algorithms of EnergyPlus were verified and validated using analytical verification, comparative testing and empirical validation by Tabares-Velasco et al. (2012). The PCM algorithm of EnergyPlus was also validated against the experimental data of Sun et al. (2014), where strong agreement was achieved between the numerical simulation results and the experimental data. Moreover, the simulation results were compared with (Kosny et al. 2013) regarding the energy performance of existing buildings and energy consumption. The percentage deviation in annual energy consumption of the PCM model (heating and cooling) simulated in EnergyPlus was quite weak.

TABLE 3 HVAC system.

Design parameter	Value
Cooling set point	29°C
Heating set point	18°C
Cooling airflow rate	Auto size
Heating airflow rate	Auto size
No load airflow rate	0
Zone heating sizing factor	1.5
Zone cooling sizing factor	1.5
Outdoor air flow rate	0.00056896 m^3/s per m^2
Cooling coil	Single speed DX
Heating coil	Single speed DX heat pump

2.5 Evaluating energy performance from reduced use of HVAC systems

The energy performance was defined as the ratio of energy savings obtained due to lower energy consumption by HVAC systems when the PCMs were installed in building envelopes compared to the reference building without PCM in the same climatic zone. Three different scenarios were considered to optimize the energy performance of the building enhanced with BioPCM. The optimization was applied in three proposed scenarios throughout the year and for both heating and cooling seasons. In the integrated passive designs, the buildings are influenced by BioPCM technology throughout the year, so optimization that takes advantage of the highest annual energy benefits by applying this passive technology should be considered. For example, the PCM achieves significant benefits in the cooling period, while in the heating period adverse effects might result with regard to the energy savings (Saffari et al. 2017). In this context, the objective of the first scenario was to find the optimum BioPCM melting point to reduce the annual cooling energy consumption (Equation 2). In the second and third scenarios, the objective was to reduce the annual heating energy consumption (Equation 3) and the overall energy consumption (heating and cooling, Equation 4). Accordingly, these three scenarios were taken to account in each climatic zone.

$$f_{cl}(x) = Q_{\text{cooling}}(x) \tag{2}$$

$$f_{ht}(x) = Q_{\text{heating}}(x) \tag{3}$$

$$f_{\text{total}}(x) = Q_{\text{cooling}}(x) + Q_{\text{heating}}(x) \tag{4}$$

We applied three scenarios using BioPCM with different melting temperatures in each climatic zone, and we found that BioPCM with a high melting point had better performance, as shown in Tables 4 and 5 and Figure 4.

TABLE 4. Energy prices for eight regions of East Asia.

No.	Region	Energy price (1/kWh)	Converted Energy price ($US/kWh)
1	Seoul	93.3 (Won)	0.084
2	Tokyo	19.52 (Yen)	0.180
3	Pyongyang	60.7 (KPW)	0.067
4	Hong Kong	1.349 (Yuan)	0.174
5	Beijing	0.906 (Yuan)	0.139
6	Taiwan	2.72 (NT$)	0.089
7	Macau	0.963 (MOP)	0.119
8	Ulaanbaatar	66 (MNT)	0.027

2.6 Economic analysis

An economic analysis was conducted to calculate the static payback period (SPP) and dynamic payback period (DPP) for the BioPCM integrated building models. BioPCM prices, the price of the insulation layer and local energy prices were considered. Finding an exact price for BioPCM in East Asia's market is challenging for two reasons. First, it is considered to be a state-of-the-art technology with a limited market. Secondly, fluctuations in the currency market of the countries have a significant effect on the prices of imported commodities such as BioPCM (Baniassadi et al. 2016). Thus, prices of the BioPCM were modified to the equivalent current US dollar price. Hence, the average prices of BioPCM of 22.53 (U.S. $/m^2) were considered for the purchase, transport and installation of BioPCM with an equivalent thickness of 2.01 cm (Baniassadi et al. 2016; PHASECHNGE 2018). It was also suggested that BioPCM prices change in proportion to the insulation layer thickness in buildings. The insulation layer used in all building surfaces are the same, i.e., 19 mm (1.9 cm). On the other hand, current prices of energy for residential use are needed to find the energy prices of the first year. Official prices are available on websites (KEPC; TEPCO; HK Electric Investments; FOCUS TAIWAN; CEM; RFA; Beijing Service) for 2017–2018. These prices were used in energy savings calculation for each region, Table 4. Later, they were modified to be equivalent with the current US dollar price.

The static payback period was calculated for the energy saving measures by dividing the total incremental cost of the measures (Equation 5) by the energy savings as in Equations 6 and 7.

$$\text{Initial cost}\left(I_C\right) = \text{BioPCM cost} + \text{Insulation cost} \tag{5}$$

$$\text{Energy Saving (ESA)} = M \times \text{Energy const of the first year} \tag{6}$$

$$\text{The static payback period (SPP)} = \frac{I_C}{ESA} \tag{7}$$

The latter term of Equation 6 (ESA) is a nonlinear series of payments through the operating years of the building. To sum this term, it must be in the present value. *M* is the present worth factor that corrects for the time value of money, and accounts for the energy inflation rate, discount rate and number of operating years. We assumed that payment is due at the end of each year; thus all the mentioned parameters must be in annual form. Equation (8) shows the formula used to obtain the present worth factor (Baniassadi et al. 2016).

$$PWF(n,i,d) = \frac{1}{d-i}\left(1-\left(\frac{1+i}{1+d}\right)^{n}\right) \tag{8}$$

Here, d is the discount rate, i is the energy inflation rate, and n is the number of operating years.

The discount rate is the general interest rate of the country, and the rate which the banks often pay interest for investments. Therefore, when assessing the current value of a certain investment via PWF, the discount rate should be considered in the formulation. A higher discount rate means a lower PWF, and thus a lower current value. In contrast, the investment attractiveness in energy efficiency measures a decrease with high discount rates. The energy inflation rate is the rate at which the price of energy increases. Since the investment in energy efficiency measures is highly dependent on the future price of energy, the energy inflation rate is also included in the PWF. In general, the higher the rate of inflation in energy, the greater the interest in investing in energy efficiency measures. Lastly, the number of operating years represents the time period for investment. The PWF increases with increasing operating years, and thus the current value of the project increases. In other words, an increase in energy prices favors interest in capital investments in energy saving strategies by increasing the cost of energy in the total cost function. In fact, East Asian governments can encourage investment in energy efficiency by lowering the discount rate in the coming years.

3. RESULTS

The results can be divided into two parts: energy performance evaluation in buildings compared to the reference building in terms of the simulations with a BioPCM temperature setting and economic analysis. In the first part, a simulation was conducted to identify energy performance changes at the different melting temperatures of BioPCM and then compare the performance with the reference building. In the second part, we applied an economic analysis to determine the feasibility of applying BioPCMs with different melting point temperatures in the building envelope to determine how much energy reduction was due to improving the indoor thermal comfort of the study regions in East Asia.

3.1 Analysis of energy performance during cooling and heating seasons

The energy consumption of a multi-story office building with and without BioPCM was obtained to identify the feasibility of applying BioPCM in the building envelope in different climatic zones of East Asia. The energy consumption data for heating and cooling seasons is tabulated in Tables 5 and 6. Here, Q_{BioPCM} and $Q_{NOBioPCM}$ represent the energy consumption of office buildings with and without BioPCM, while Q_{ESave} is the energy savings ($Q_{ESave} = Q_{NOBioPCM} - Q_{BioPCM}$). An increase in Q_{ESave} reflects an effective BioPCM application in the building envelopes. Tables 5 and 6 show the annual cooling and heating energy performance of the office buildings enhanced with BioPCM under different climatic zones of East Asia. We note that the BioPCM peak melting temperatures used to improve the cooling and heating energy performance were 20°C, 23°C, 25°C, 27°C and 29°C. This could be because a BioPCM requires a high melting temperature for charging during the night. Simulation results show that the use of BioPCM was very feasible in the climatic zones of East Asia.

In terms of Q_{ESave} in summer, the cooling energy consumption was reduced by 4.23% [20459.23 kWh], 3.18% [18811.85 kWh], 3.22% [16612.45 kWh], 3.08% [15780.14 kWh] and 2.89% [13599.65 kWh] at 29°C in Ulaanbaatar, Beijing, Pyongyang, Tokyo and Seoul, respectively. Similarly, cooling energy consumption savings were achieved in the same climatic zones with 27°C BioPCM, Table 5. Otherwise, limited cooling energy savings were achieved by 20°C, 23°C, and 25°C BioPCM in all climatic zones, except Ulaanbaatar, due to the weather conditions prevailing there (low humidity during summer). Some researchers (Lei et al. 2016; Saffari et al. 2017) have reported that higher energy savings could be achieved in hot, humid climatic conditions by altering the PCM location in the envelope of the building (wall, roof and floor) and by using a PCM with a higher melting temperature. The reason for this is as follows. When the BioPCM is installed on the interior surfaces of the building envelope, there will be reduced thermal conduction through the wall and roof in both summer and winter, where the BioPCM serves as an insulation layer regardless of the main function of the BioPCM.

High cooling energy savings of 1.21% [7512.72 kWh], 1.22% [7848.34 kWh] and 1.46% [9122.80 kWh] were observed for Hong Kong, Macau and Taiwan, respectively, at a melting

TABLE 5. Annual cooling savings in kilowatt hours during summer season compared to the reference building.

Region	BioPCM—20°C	BioPCM—23°C	BioPCM—25°C	BioPCM—27°C	BioPCM—29°C
Seoul	9077.27 (1.93%)	9077.27 (1.93%)	8841.90 (1.88%)	9759.08 (2.08%)	13599.65 (2.89%)
Tokyo	9331.93 (1.82%)	10400.74 (2.03%)	10133.27 (1.98%)	11105.54 (2.17%)	15780.14 (3.08%)
Pyongyang	9479.12 (1.84%)	10451.65 (2.03%)	10240.17 (1.99%)	11338.55 (2.20%)	16612.45 (3.22%)
Hong Kong	4161.12 (0.67%)	6989.14 (1.12%)	4425.48 (0.71%)	5250.59 (0.84%)	7512.72 (1.21%)
Beijing	10452.96 (1.76%)	11419.18 (1.93%)	11228.28 (1.90%)	12502.44 (2.11%)	18811.85 (3.18%)
Taiwan	5075.95 (0.81%)	5448.85 (0.87%)	5382.94 (0.86%)	6272.92 (1.00%)	9122.80 (1.46%)
Macau	4137.43 (0.64%)	4504.64 (0.70%)	4453.05 (0.69%)	5223.63 (0.81%)	7848.34 (1.22%)
Ulaanbaatar	11046.90 (2.29%)	12231.74 (2.53%)	11992.83 (2.48%)	13148.70 (2.72%)	20459.23 (4.23%)

Note: % of energy savings in buildings with BioPCM compared to the reference building during the cooling months.

point temperature of 29°C, while the cooling savings were limited at melting point temperatures of 20°C, 23°C, 25°C and 27°C, except Hong Kong [6989.14 kWh] at 23°C, Table 5. There is a stark contrast between these regions in terms of cooling energy savings. There are several possible explanations for these results; first, altitude influences the solar radiation, sky cover, and wind characteristics, which in turn affect charging and discharging of the BioPCM during the daytime and nighttime. Secondly, the average monthly relative humidity also varies. Taiwan has an altitude of 9 m in comparison to 55 m in Beijing. Macau's elevation is 22 m compared to 55 m in Beijing, which influences the sky cover, solar radiation and the wind characteristics. For example, the average monthly relatively humidities in Taiwan (81.6%) and Macau (80%) are higher than other study regions (Beijing 56.5%, Seoul 68.5%, Tokyo 63.7%, and Ulaanbaatar 54.3%). On the other hand, the cooling energy savings in Hong Kong was only 7512.72 kWh, which was lower than other study regions. The reason for this difference might be related to the amount of direct normal solar radiation (180 Wh/m^2) and average wind speed (3 m/s) in Hong Kong (Saffari et al. 2017). Table 6 also shows the annual heating energy performance (Q_{ESave}) of the same building enhanced with BioPCM under different climate conditions in East Asia. Clearly, the energy savings were not limited to only cooling savings. The integration of BioPCM in the building envelope has led to significant benefits in energy consumption reductions in all regions, particularly at 27°C and 29°C. Use of BioPCM with an optimized melting

TABLE 6. Annual heating savings in kilowatt hours during winter season compared to the reference building.

Region	BioPCM—20°C	BioPCM—23°C	BioPCM—25°C	BioPCM—27°C	BioPCM—29°C
Seoul	6276.51 (4.16%)	6276.51 (4.16%)	6126.85 (4.06%)	6532.47 (4.33%)	8394.11 (5.56%)
Tokyo	6810.45 (5.60%)	7545.35 (6.21%)	7366.14 (6.06%)	7798.45 (6.42%)	10043.08 (8.26%)
Pyongyang	7306.85 (4.28%)	8107.45 (4.75%)	7826.66 (4.58%)	8397.25 (4.92%)	11248.39 (6.59%)
Hong Kong	775.15 (5.97%)	978.13 (7.53%)	912.56 (7.02%)	1034.80 (7.97%)	1451.17 (11.17%)
Beijing	7473.67 (4.79%)	8250.10 (5.28%)	8064.43 (5.17%)	8665.89 (5.55%)	11725.67 (7.51%)
Taiwan	836.18 (5.26%)	1025.39 (6.45%)	1089.78 (6.86%)	1109.02 (6.98%)	1436.45 (9.04%)
Macau	732.26 (4.34%)	912.96 (5.42%)	851.59 (5.05%)	983.15 (5.83%)	1444.61 (8.57%)
Ulaanbaatar	11418.16 (3.00%)	12480.00 (3.27%)	12169.75 (3.19%)	13092.39 (3.43%)	18366.57 (4.82%)

Note: % of energy savings in buildings with BioPCM compared to the reference building during the heating months.

temperature of 29°C has resulted in heating energy savings of 11.17% [1451.17 kWh] in Hong Kong, 9.04% [1436.45 kWh] in Taiwan, 8.57% [1444.61 kWh] in Macau, 8.26% [10043.08 kWh] in Tokyo, 7.51% [11725.67 kWh] in Beijing, 6.59% [11248.39 kWh] in Pyongyang, 5.56% [8394.11 kWh] in Seoul and 4.82% [18366.57 kWh] in Ulaanbaatar.

To fully understand the energy savings, we note that integration of BioPCM into the building envelope in Hong Kong, Taiwan and Macau resulted in significant benefits in heating energy savings that were higher than other regions. A possible explanation for these results is the average monthly temperature during the heating season. The average temperature in January was 16°C in Taiwan, 16°C in Hong Kong, and 12°C in Macau, which is higher than other regions (–3°C in Seoul, 5°C in Tokyo, –8°C in Pyongyang, –4°C in Beijing, and –25°C in Ulaanbaatar). Moreover, the geographical characteristics of Taiwan and Macau may also play a role with 9 m and 22 m elevations from sea level, respectively. Hence, the use of passive BioPCM in buildings will enhance the heating energy performance in these the regions during the heating season.

3.2 Analysis of energy performance over the whole year

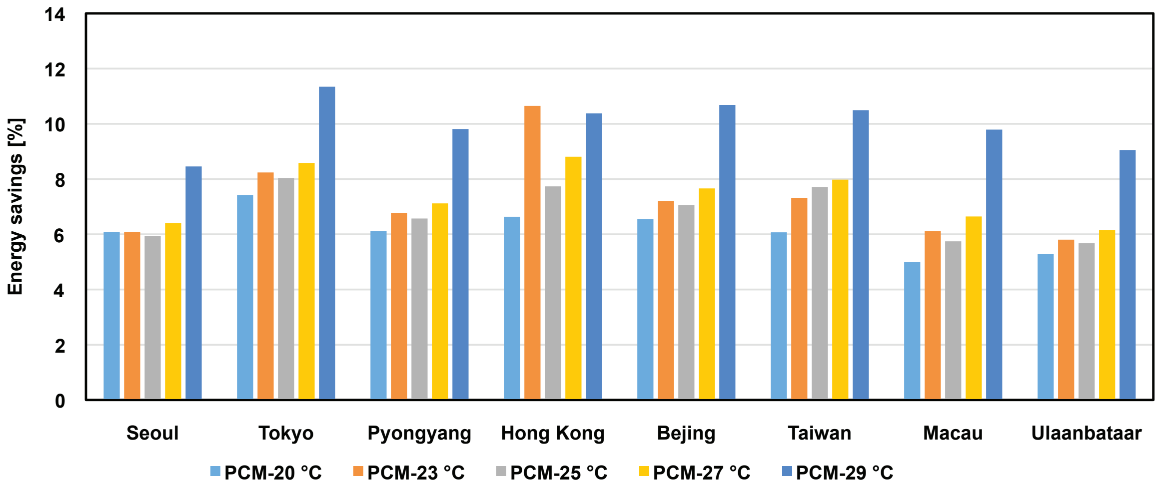
To identify the effectiveness of BioPCM applications in the building envelope, decreases in energy consumption during the heating and cooling seasons for an office building located in different regions of East Asia were assessed. For this research, the summer cooling period is from June to September, while the winter heating period is from November to March. Figure 5 presents the percentage of annual energy savings data for the eight regions of East Asia. We note that the optimum melting temperature of the BioPCM highly depends on the weather conditions of each specific region, and the altitude of the region in many cases.

In general, it can be said that the optimum BioPCM melting temperature is closer to the maximum of 29°C (melting range of 27–29°C) in cooling dominant climates. It remains closer to the maximum of 29°C (melting range of 20–29°C) in heating dominant climates, except Hong Kong, where 23°C is the optimum BioPCM melting temperature during the whole year (Mi et al. 2016; Saffari et al. 2017). Figure 5 illustrates that the best BioPCM melting temperature for the annual total cooling and heating is 29°C followed by 23°C in Hong Kong, which leads to higher energy savings. This could be justified because higher energy is required for cooling purposes due to the high humidity in the hot climate of East Asia (Sun et al. 2014; Mi et al. 2016). Thus, an ideal BioPCM could be a BioPCM with a higher melting temperature, which can be effectively melted and solidified in hot seasons by solar heat. Hence, a BioPCM melting at 29°C is the optimum solution for energy savings for the total annual cooling and heating energy consumption.

To have a clearer view of energy performance in different climatic zones, the energy consumption coefficient (Equation 9) was studied as a function of the BioPCM melting temperatures for the eight regions of East Asia. The results were utilized to analyze the energy performance of BioPCM in eight different regions. The energy consumption coefficient indicates the ratio of energy required for sustaining thermal comfort in the building to the heat gained beyond the building thermal comfort. A small value of the energy consumption coefficient means that BioPCM reduced the heat gains, thus the energy consumption to maintain building thermal comfort with air-conditioning systems became smaller, Figure. 6.

$$\mu = \frac{q}{\Delta q} \tag{9}$$

FIGURE 5. Percentage of energy savings in different regions of East Asia during the whole year for different melting temperatures of the BioPCM.



Here, μ is the energy consumption coefficient, q is the necessary energy required for building thermal comfort, and Δq is the heat gained beyond building thermal comfort.

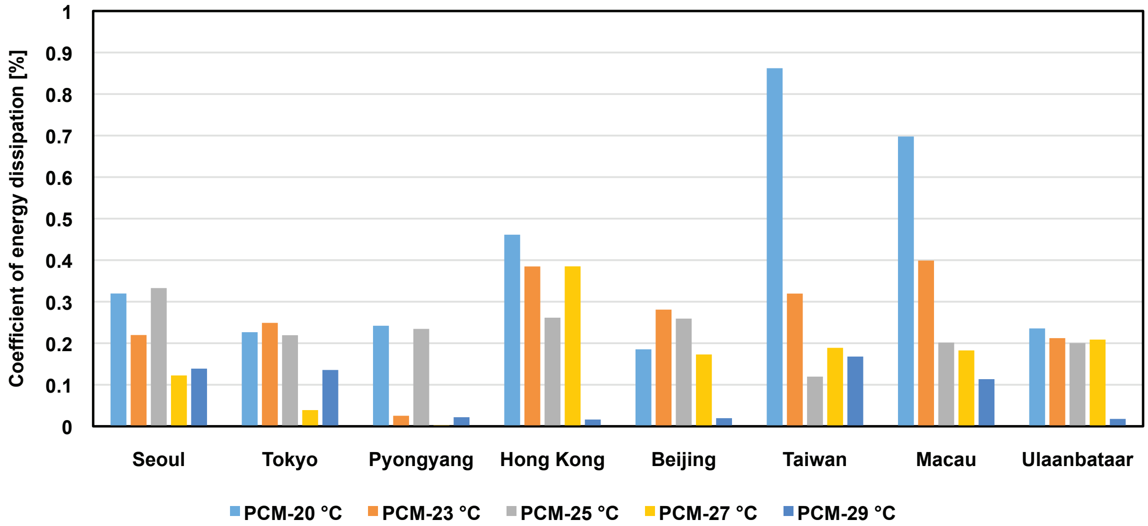
$$\Delta q = K_{ht} \times A \times \Delta t \tag{10}$$

Here, K_{ht} is the heat transfer coefficient of the envelope in W/m^2, A is the area of the building envelope, and Δt is the difference in inside and outside temperature of each building envelope when the indoor temperature is higher than that required for thermal comfort (°C).

Figure 6 shows the energy consumption coefficient (μ) as a function of the BioPCM melting temperature under different climatic zones of East Asia. Energy coefficient values are less than 1% in buildings with BioPCM compared to the reference building without BioPCM in all regions. This means that the installation of BioPCM into the building envelope maintained the indoor thermal comfort level, and thus energy consumption decreased. This is particularly true for 27°C and 29°C BioPCM. Figure 6 shows that the energy consumption coefficients of Beijing, Pyongyang and Ulaanbaatar for the 29°C BioPCM are smaller than for Seoul, Tokyo, Taiwan and Macau. Additionally, the energy consumption coefficient values of Seoul, Tokyo, Beijing, Pyongyang and Ulaanbaatar were the smallest at BioPCM melting points of 20°C, 23°C, 25°C, and 27°C. This can be justified based on the weather fluctuations during the heating and cooling seasons in these regions. In the other regions, the temperatures prevailing during the heating and cooling seasons might be closer to the human comfort zone; thus, the energy consumption decreased.

Furthermore, the peak energy demand during the annual cooling and heating seasons decreased, as shown in Figure. 6. Peak energy demand decreased by 1952.31 kWh in Seoul, 2329.34 kWh in Tokyo, 2311.19 kWh in Pyongyang, 2467.59 kWh in Beijing, 1242.47 kWh in Hong Kong, 1350.23 kWh in Taiwan, 1253.45 kWh in Macau and 2551.08 kWh in Ulaanbaatar with a 29°C BioPCM. In this context, it can be said that the energy savings for the eight regions decreased gradually with an increase in the melting temperature of BioPCM.

FIGURE 6. Annual energy performance in different regions of East Asia with BioPCM.

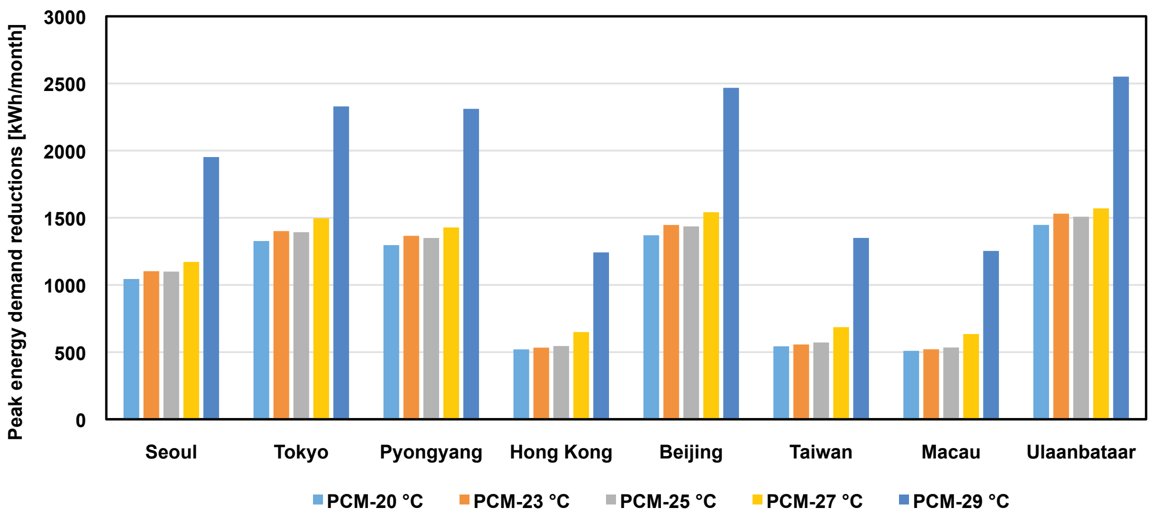


The energy savings potential of Hong Kong followed by Tokyo (Q_{ESave}) was the best, as shown in Figure 7. This is because the climate of Hong Kong does not require higher heating energy in the winter compared to the other regions.

3.3 Economic analysis

To highlight the economic aspects, an economic analysis of office buildings in summer and winter was performed for a typical building located in eight different regions of East Asia. Using Equations 5–8, the static payback period (SPP) for BioPCM applications in the building envelope during heating and cooling seasons was evaluated, and the results are shown in Table 7. The SPP in capital budgeting indicates the time period required to recover the funds spent on

FIGURE 7. Decrease in peak energy demand during cooling and heating seasons in a building with BioPCM.



the investment, starting from the date of implementation of the project and using the annual net income of the project (annual income minus annual expenditure) (Mi et al. 2016). Table 7 shows that investment returns due to energy savings in the first year of the office building with BioPCM in Ulaanbaatar, Tokyo and Beijing were the best. The SPP payback periods for Ulaanbaatar, Pyongyang, Tokyo and Beijing were the shortest at 7.94, 10.10, 11.07 and 11.94 years for a 29°C BioPCM, respectively. The payback period for Macau followed by Taiwan and Hong Kong were the longest at 33.19 years. The service life of PCM is approximately 35 years (Lei et al. 2017; Memon 2014; Ascione et al. 2014). Therefore, the BioPCM investment could not be recovered for the eight regions located in different climatic zones of East Asia if energy savings in winter or summer were considered for the investment payback period. The annual heating and cooling energy requirements for these regions were different because the eight regions are located in eight different climatic zones of East Asia. Hence, the energy savings resulting from BioPCM applications over the entire year should be considered for investment payback analysis.

On this basis, the BioPCM investment for the office building located in eight regions could be recovered within the service life of the building (35 years). Table 7 shows SPP results indicating that the BioPCM investment for the office buildings located in Seoul, Tokyo, Pyongyang, Beijing, Ulaanbaatar, Hong Kong, Taiwan, and Macau can be recovered, particularly when using a BioPCM with a 29°C melting point. In contrast, BioPCM investments with 20°C,

TABLE 7. Static payback period analysis for BioPCM applications in heating and cooling seasons by USD/yr.

Region	BioPCM—20°C ($)	BioPCM—23°C ($)	BioPCM—25°C ($)	BioPCM—27°C ($)	BioPCM—29°C ($)
Seoul	2023.67 (12.74)	2023.67 (12.74)	1874.01 (13.76)	2028.03 (12.71)	2054.51 (12.55)
Tokyo	2905.63 (19.11)	3230.30 (17.19)	3149.89 (17.63)	3402.72 (16.32)	4648.18 (11.94)
Pyongyang	1126.34 (18.38)	1245.32 (16.62)	1212.28 (17.07)	1324.27 (15.63)	1869.46 (11.07)
Hong Kong	859.40 (62.49)	3478.62 (15.44)	3032.29 (17.71)	2994.30 (19.07)	3033.02 (17.70)
Beijing	2506.14 (17.21)	2749.77 (15.68)	2697.12 (15.99)	2959.33 (14.57)	4269.15 (10.10)
Taiwan	530.32 (52.17)	580.74 (47.64)	580.60 (47.65)	662.16 (41.78)	947.16 (29.21)
Macau	579.98 (63.34)	645.24 (56.93)	631.78 (58.15)	739.23 (49.70)	1106.79 (33.19)
Ulaanbaatar	613.30 (13.73)	674.63 (12.48)	659.64 (12.77)	716.38 (11.75)	1059.94 (7.94)

Note: outside the brackets means the annual energy savings estimated by (USD/year) whereas inside the brackets () means number of the corresponding years according to static payback period (SPP).

23°C, 25°C, and 27°C melting points for office buildings located in Taiwan and Macau cannot be recovered. Therefore, the use of BioPCM in these two regions is not feasible. Based on the SPP results in Table 7, the BioPCM investment using a 23°C BioPCM for the office buildings located in Hong Kong can be recovered. Hence, the use of 23°C BioPCM in Hong Kong will be more economically feasible. Mi et al. (2016) reported that the application of PCM at high melting temperatures is not economically feasible in Hong Kong because of outdoor temperature constraints.

By considering the time value of money in keeping with other studies (Mi et al. 2016), six discount rates (r) with dynamic payback periods (DPPs) ranging from 5% to 10% with intervals of 1% were considered. The dynamic payback period is much closer to real energy management and represents a better economic analysis. DPP results with 29°C BioPCM show that office buildings located in Seoul, Tokyo, Pyongyang, Beijing and Ulaanbaatar had high economic values. Among these regions, the payback period for Ulaanbaatar was the shortest and ranged from 7.94 to 8.83 years, while the payback period for Taiwan was the longest and varied from 29.21 to 32.46 years (Table 8). This means that the BioPCM investment in Taiwan can be recovered in 32.46 years with a discount rate of 10%, while in Ulaanbaatar it can be recovered in 8.83 years. If the discount rate was set to 5%, the BioPCM investment with 29°C in Taiwan and Ulaanbaatar can be recovered in 29.21 and 7.94 years, respectively.

Furthermore, the DPP results showed that BioPCM investments with 20°C, 23°C, 25°C and 27°C BioPCMs in office buildings located in Seoul, Tokyo, Pyongyang, Beijing, Taiwan, Macau, and Ulaanbaatar cannot be economically feasible if compared to BioPCM investments at 29°C. Table 9 shows that the application of 23°C BioPCM does not have a high economic value in comparison with BioPCM at 29°C. However, the payback period of Hong Kong was short and ranged between 16.25 and 17.15 years compared to BioPCM investment at 29°C. Hence, the utilization of BioPCM at 23°C in Hong Kong was more economically feasible.

TABLE 8. Dynamic payback period evaluation for BioPCM application with 29°C melting point for the whole year including heating and cooling seasons.

Region	Energy Savings (kWh/yr) at 29°C	SPP (year)	DPP (r = 5%)	DPP (r = 6%)	DPP (r = 7%)	DPP (r = 8%)	DPP (r = 9%)	DPP (r = 10%)
Seoul	24575.49	12.55	13.21	13.35	13.50	13.64	13.79	13.95
Tokyo	25823.22	11.94	12.57	12.71	12.84	12.98	13.13	13.27
Pyongyang	27860.84	11.07	11.65	11.78	11.90	12.03	12.17	12.30
Hong Kong	17416.83	17.70	19.51	19.90	20.29	20.69	21.10	21.52
Beijing	30537.52	10.10	10.63	10.75	10.86	10.98	11.10	11.22
Taiwan	10559.25	29.21	30.75	31.08	31.41	31.75	32.10	32.46
Macau	9292.95	33.19	34.94	35.31	35.69	36.08	36.47	36.88
Ulaanbaatar	38825.8	7.94	8.36	8.45	8.54	8.64	8.73	8.83

Note: yr means year

TABLE 9. Dynamic payback period evaluation for BioPCM application with 23°C melting point for the whole year including heating and cooling seasons.

Region	Energy Savings (kWh/yr) at 23°C	SPP (year)	DPP (r = 5%)	DPP (r = 6%)	DPP (r = 7%)	DPP (r = 8%)	DPP (r = 9%)	DPP (r = 10%)
Seoul	24206.60	12.74	13.41	13.56	13.70	13.85	14.00	14.16
Tokyo	17946.1	17.19	18.09	18.28	18.48	18.68	18.89	19.10
Pyongyang	18559.10	16.62	17.49	17.68	17.87	18.06	18.26	18.47
Hong Kong	19980.59	15.44	16.25	16.42	16.60	16.78	16.96	17.15
Beijing	19669.28	15.68	16.51	16.68	16.86	17.05	17.23	17.42
Taiwan	6474.24	47.64	50.15	50.68	51.23	51.79	52.35	52.94
Macau	5417.6	56.93	59.93	60.57	61.22	61.89	62.57	63.26
Ulaanbaatar	24711.74	12.48	13.14	13.28	13.42	13.57	13.72	13.87

Note: yr means year

This means that the BioPCM investment in Hong Kong can be recovered in 17.15 years with a discount rate of 10%. Further, if the discount rate is set to 5%, the BioPCM investment can be recovered in 16.25 years.

Based on SPP and DPP analysis, we concluded that a BioPCM investment with a melting temperature of 29°C was more promising for office buildings located in Seoul, Tokyo, Pyongyang, Beijing, Taiwan and Ulaanbaatar. Therefore, the application BioPCM29 in energy savings in these regions provide high economic value, and the investment appears to be attractive. In addition, a BioPCM investment with a melting temperature 23°C for the office building located in Hong Kong will have a high economic value. According to current prices, the BioPCM investment in Macau cannot be recovered and does not offer economic benefits. However, future decreases in the price of BioPCM and increasing energy rates may provide an investment incentive in Macau.

4. DISCUSSION

This study provides a scientific vision for evaluating the feasibility of applying passive technology in the building envelopes of East Asia to reduce energy consumption and identify its influence on the building energy performance under different climate conditions. This paper's combined economic, energy and building analysis within integrated modelling provides a faster tool to evaluate the applicability of PCM in building sector. The model can forecast how economic planning policies in building sectors would affect the adoption of promising technologies and energy efficiency and how this would differ between regions.

For the strategic application of PCM in buildings of East Asia, the economic assessment of energy saved was conducted to reveal important factors and underlying mechanisms that govern the performance of building envelopes integrated with BioPCM for energy load reductions in air-conditioned buildings in East Asia climates. Our results have shown that the proper selection of phase change temperature is critical in the energy performance of PCM integrated buildings. We found that BioPCM selection with a melting temperature of 29°C leads to higher energy savings in Seoul, Ulaanbaatar, Beijing, Tokyo, Taiwan, Macau and Pyongyang, while, the best melting point is 23°C in Hong Kong over the whole year. Similarly, Saffari et al. (2017) and Mi et al. (2016) found that the application of PCM with a high melting temperature (26–28°C) in buildings of Hong Kong could not be economically feasible due to the outdoor temperature constraints.

We have also revealed that the location of PCM is a key factor influencing heat gains through building envelopes. We found that inserting a thin layer of the BioPCM in the interior surfaces between the fiberglass and plasterboard of the roof and all the four sides of the interior walls of the office building could reduce the thermal conduction between the inside and outside of the building. In other words, BioPCM works as an insulating layer to reduce the heat losses. Its distinctive organic properties and availability as discrete blocks with air gaps between them make BioPCM effective and efficient when applied in building envelopes (Muruganantham 2010).

Another finding of this study is that the BioPCM investment in Macau cannot be recovered since at current prices it does not offer economic benefits. The shortest payback period in Macao was found to be 36 years, which is beyond the normal service life of PCM. However, BioPCM integrated with building envelopes located in Macau would provide a significant reduction in greenhouse gas emissions, mainly carbon. Sage-Lauck and Sailor (2014) found that installation of the PCM in the building envelope has a positive effect on thermal comfort, reducing the estimated number of annual overheating hours from 400 to 200. This would reduce energy consumption in HVAC systems in buildings that lead to increased carbon emissions due to increased operating hours of HVAC systems.

The methodology reported in this study could also help to improve the forecasting of passive technologies, which would be promising for future applications. Our method could also be used to explore the feasibility of applying BioPCM even in small regions or individual buildings to identify the most suitable phase change materials (PCM). This may provide a clear vision for policy makers in the buildings sector regarding (i) the feasibility of PCM use, (ii) identification of melting phase temperatures, (iii) specification of the requested thickness and (iv) determining the appropriate position of the PCM in the building envelopes. Local planning authorities could then seek to achieve these characteristics or reject certain designs through their local development frameworks. This would provide an improved basis for future policy support in regions of East Asia.

6. CONCLUSIONS

In this study, the economic feasibility of BioPCM applications with different melting temperatures in building envelopes was analyzed against reference buildings of East Asia through numerical simulations. Energy savings, energy savings ratio, peak energy demand, payback period and dynamic payback period were calculated to evaluate the feasibility of this application. From the analysis of energy saving in the whole year, the energy saving potential of Ulaanbaatar located in a severely cold winter and warm summer was found to be the best. Besides, energy savings in office buildings located in Seoul, Tokyo, Pyeongyang, Beijing, Taiwan and Ulaanbaatar increased with increasing melting temperature (29°C) of the BioPCM and increasing difference of average daily temperature. In contrast, energy savings in office buildings located in Hong Kong increased with decreasing melting temperature (23°C) of the BioPCM. Based on economic analysis, the application of BioPCM with 29°C in office buildings located in Seoul, Tokyo, Pyongyang, Beijing and Ulaanbaatar showed high economic benefits. The payback period for Ulaanbaatar was the shortest and ranged from 7.94 to 8.83 years, while the payback period for Taiwan was the longest and varied from 29.21 to 32.46 years. The utilization of BioPCM at 23°C is more economically feasible in Hong Kong. This means that a BioPCM investment in Hong Kong can be recovered in 17.15 years with a discount rate of 10%, and if the discount rate is set to 5%, the BioPCM investment can be recovered in 16.25 years. According to current prices, a BioPCM investment in Macau cannot be recovered and does not offer economic benefits. However, a future BioPCM investment may provide benefits in Macau due to a possible future decrease in the BioPCM price and increasing rates of energy consumption prices.

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