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Energetic and economic analyses of integrating enhanced macro-encapsulated PCM's with active underfloor hydronic heating system

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Abstract

Phase change materials proved their capability of enhancing buildings' thermal inertia and improving occupants' thermal comfort. More attention was triggered by the scientific community as the use of thermal energy storage systems kept evolving in the building sector. Previous experimental investigations examined the effectiveness of enhanced macro-encapsulated coconut oil bio-based PCM integrated with underfloor water radiant heating system in two similar small-scale test facilities that are modular. The current study focuses on performing comparative energetic and economic analyses of the system performance in regards to: weather conditions, PCM application, PCM type and properties, and PCM plates position at the underfloor. Results highlighted the effectiveness of utilizing coconut oil PCM in active floor, and passive wall and roof as load shifting and energy savings were obtained. It was shown that with the combination of active and passive systems, annual savings of 227 USD can be achieved; and by placing the PCM underneath the heating system, energy saving of 393.5 kWh was achieved corresponding to 169 USD annual savings. However, 32 USD annual saving was achieved by the system integrated with paraffin wax compared to that integrated with cocoa-nut oil PCM. Finally, the PCM capability in cost savings was reflected with the payback periods being evaluated as follows: 6.82 years for experiment 2, 6.75 years for experiment 3 (both encountering load shifting), and 3.94 years for experiment 4 (encountering energy saving).

Keywords: Thermal Energy Storage; Phase Change Material; Economic Analysis; Advanced Modular Prototypes; Coconut-oil; Paraffin Wax.

1. Introduction

As time flows, new research arises focusing on emerging energy consumption reduction methods. All fields are being affected by the increase in energy demand and thus require the adaptation of energy utilization techniques. The concepts behind the usage of renewable and sustainable energy sources attracted the attention of the scientific community worldwide. Also, researchers focused their attention on energy storage [1], energy saving [2] and energy recovery systems [3]. And, with the remarkable increase in buildings energy demand, efforts have been made towards

Nomenclature

TES	Thermal energy storage	SAH	Solar air heater
PCM	Phase change material	CO	Coconut oil
HVAC	Heating ventilating and air conditioning	PW	Paraffin wax
NZEB	Net zero energy building	EPS	Expanded polystyrene Foam
SWH	Solar water heater	XPS	Extruded polystyrene Foam
HRFHS	Hydronic radiant floor heating system	PEX	Polyethylene pipes
TABS	Thermally activated building structure	TW	Trombe wall
SPP	Simple payback period (years)	Pb	Boiler power consumption (kW)
C	Capital cost (USD)	Pp	Pump power consumption (kW)
C ₀	Reference capital cost (USD)	Δt	Heating time duration (hr)
CF	Cash flow (USD/year)	S	Governmental electricity generation shift (hr)
CF ₀	Reference cash flow (USD/year)	Sr	Governmental electricity rate (USD/kWh)
E	Consumed energy (kWh)	U	Personal electricity generation shift (hr)
Er	Electricity rate (USD/kWh)	Ur	Personal electricity rate (USD/kWh)
Q _{conv}	Convection heat transfer (W)	Q _{loss}	Loss Heat transfer rate by conduction (W)
Q _{cond}	Conduction heat transfer (W)	m	Y-distance from origin to pipe center (m)
Q _{rad}	Radiation heat transfer (W)		

enhancing the use of heating and cooling energy so that the efficiency is improved. The building sector nowadays accounts for 30–40%* [4–7] of the global energy demand and is continuously increasing to reach an expectation of 50% by 2050 [8]. For that, research has been conducted towards minimizing the consumption of energy in buildings. One of the major evolving methods is introducing thermal energy storage (TES). Phase change materials (PCM), being one of the major TES technologies, proved its merit to have high energy storage capacity over a narrow temperature range (near constant) during charging and discharging processes [1,9,10]. Thus, it became a dynamic subject in material science studies and energy utilization research [11]. PCM's ability of enhancing the building thermal inertia, shifting the load from high to low-peak intervals, and improving residential thermal comfort and building energy efficiency, is quite promising and emphasize on its role and contribution towards adaptation into net zero energy buildings (NZEB), which, in turns, became the international trend. The application of PCM in buildings takes various forms. PCM can be integrated passively in buildings, such as: integration into building envelope: walls [12,13], floors, ceilings and roofs, windows [14], Trombe walls (TW) [15] and solar façades [16]; or it can be integrated actively such as: incorporation in active components like solar air heaters (SAH), solar water heaters (SWH), thermally activated building structures (TABS), heating ventilating and air conditioning systems (HVAC) [17], activated solar façades and TWs, radiative cooling [18], geo-cooling [4] and floor heating systems [19]. Active PCM systems require a driving force for the charging/discharging of latent heat, however, the only driving force in passive PCM systems is the temperature difference between PCM and surroundings. Previous studies stated that the use of PCM in buildings within passive and active systems is promising, and that any combination between passive and active PCM applications yields a novel combined application that is capable of producing outstanding results regarding transformation into NZEB [20,21].

One of the major active heating systems integrated with PCM is the hydronic radiant floor heating system (HRFHS) [22–27]. Most of the recent studies within the field of radiant heating lack economic and environmental effects. The previous study by Faraj et al.[26] focused on the analysis of the thermal performance of coconut oil and paraffin wax PCMs integrated in the floor of an advanced, insulated modular prototype. The present work is a complimentary continuation of the work in [26] and the novelty resides in the addition of energetic, economic and environmental aspects to the study thus enriching the work with wide perspectives. On the energetic level, the study focuses on computing the amount of energy saved or shifted by the systems. Economically speaking, a case study for the Lebanese residency is investigated where the ability of the used PCM plates in saving money is explored. And finally, environmental impacts triggered by the PCMs used are investigated.

* The percentages differs in regions and countries: 40% in Europe [41][42], 33% in China [43], 40% in U.S. [44] and 28% in Tunisia [45].

2. Materials and Methods

As stated before, the current research is a complementary study to a previous work performed by the authors [26] in order to cover a second stage important aspect of the project: Energetic, economic and environmental concerns regarding the integration of coconut oil PCM as an active and/or passive building heating application.

2.1 Prototype design

The study was performed following experimental aspect. The design phase of the study aimed to yield an advanced, small-scale, flexible, economic and modular prototype that allows the investigation of several PCM building applications as well as judging the effect of variable parameters concerning the PCM. The prototype is assembled throughout 3 stages: (1) skeletal aluminum structure forming the base at which boundary layers are mantled; (2) different construction and insulation layers that are fitted in the cavities formed by the skeletal structure, and are firmly adjoined by hold-down toggle clamps; and (3) decorative and thermal barrier composite layer (formed of aluminum and fiberglass materials) being mounted on the top of the six faces of the prototype by means of screws. The output was a modular prototype named: ThermoGreen®, and a schematic diagram showing the different parts of the assembly is drawn using SolidWorks software as shown in figure Fig. 1. The prototype contains a window and a door that are double glazing. More design details are explained in previous research [28].

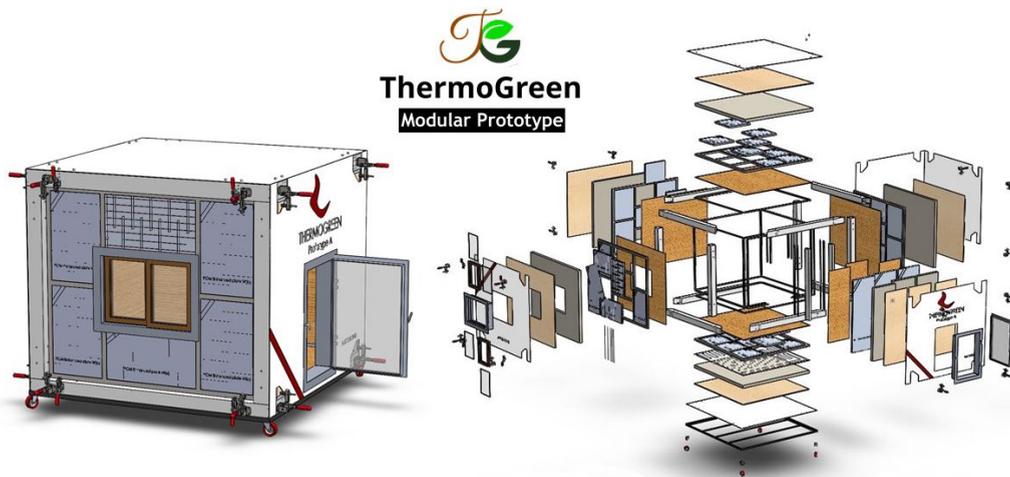


Fig. 1. The designed modular prototype "ThermoGreen" with an exploded view showing all layers and parts.



Fig. 2. (a) experimental setup of the two identical prototypes; (b) enhanced macro-container up on manufacturing; (c) underfloor heating system shown in the floor; (d) different layers being attached to the wall via hold-down toggle clamps.

To offer a direct comparison between tested parameters and control, two identical prototypes are implemented following the aforementioned stages (figure Fig. 2-a), and both are equipped with a hydronic radiant floor heating system (HRFHS) as shown in figure Fig. 2-c. The underfloor heating system comprises a circulating pump, with 100 W rated power, that is utilized to allow circulation of hot water within the spiral PEX tubes installed in the floor. The system is connected into a boiler comprising a tank of 50 L capacity and an electrical resistance heater of 1500 W rated power.

The two prototypes contain the layers prescribed in Fig. 3, where the roof and walls are made up from 6 layers placed from indoor to outdoor as follows: 8 mm wood, 30 mm XPS insulation, 15 mm glass wool insulation, 30 mm XPS insulation, 12 mm wood, and finally a 3 mm thick ALUCOBOND® layer. The floor layer is a little bit different in composition as it contains 7 layers concerning the prototype equipped with PCM. These layers are assembled from floor top to floor bottom as follows: 8 mm wood layer, 30 mm PCM plates, 16 mm hydronic heating PEX tubes, 4 mm EPS insulation holding the tubes, 30 mm XPS insulation, and a 12 mm wood.

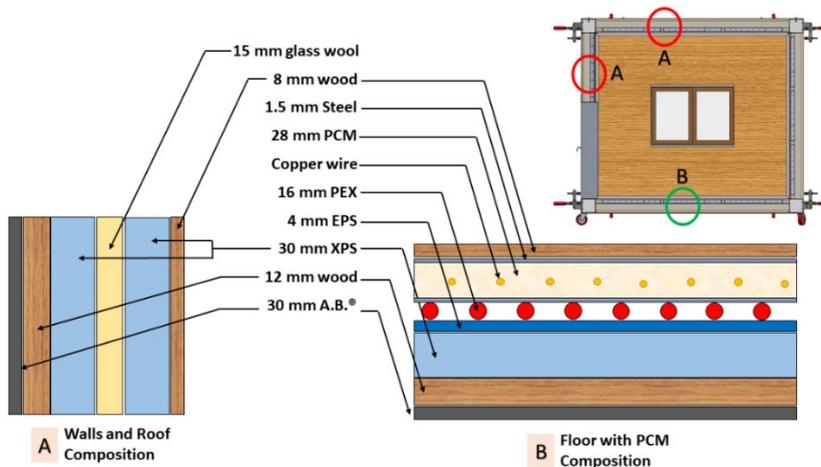


Fig. 3. Schematic diagrams showing different layers and their respective dimensions for the walls, roof and floor [26].

Two types of PCMs are used in the study: coconut oil (CO) and paraffin wax (PW). The thermophysical properties of these materials as well as of the construction materials used in building the prototypes are listed in table 2. The encapsulation method used in this study is macro-encapsulation. The PCM is filled in macro-containers formed of steel hollow rectangular prisms. These plates are equipped with buffers through which copper wires traverses them along the length of the plate for enhancing thermal conductivity (refer to figure Fig. 2-b). The containers are refillable being designed to have a vent with a screw allowing filling and eliminating liquid PCM into and from the container.

Table 1. Characteristics of possible wall layers used in the initial assembly of the prototype [26].

#	Material	Melting Temperature, T (°C)	Density, ρ (kg/m ³)	Specific Heat, C_p (kJ/kg.K)	Conductivity, λ (W/m.K)	Latent heat, L_{H} (kJ/kg)	Flammability	Ref.
1	Aluminum frames, studs and channels	<i>N.A.</i>	2698	0.921	205	-	Fire resistant	[29,30]
2	XPS insulation	<i>N.A.</i>	20.8 – 43.1	<i>N.A.</i>	0.029	-	Fire resistant	[31]
3	Glass Wool insulation	<i>N.A.</i>	16-40	<i>N.A.</i>	0.035-0.05	-	Fire resistant	[32]
4	Wood layers	<i>N.A.</i>	<i>N.A.</i>	1.3-2.4	0.41-0.19	-	Flammable	[29,33,34]
5	Al composite (Alucobond®)	<i>N.A.</i>	0.222	<i>N.A.</i>	($U = 5.54$ W/m ² .K)	-	Fire resistant	[35]
6	PW-PCM	25	919	2.174	0.5 [36]	102.97	Fire resistant	<i>by experiment</i>
7	CO-PCM	58-60	<i>N.A.</i>	<i>N.A.</i>	0.21	189	Fire resistant	[37]

2.2 Experimental methodology

The experimental aspect followed in the study comprises the use of the two identical prototypes, where prototype A contains the variable parameters and prototype B acts as a control facility. The heating system in each prototype was equipped with a control system that manages the heating process in accordance to the indoor thermal environment. When the temperature inside the chamber falls to a specified set point (minimal acceptable indoor temperature), the pump is powered on to deliver hot water into the floor spiral pipe. Then, when the temperature reaches the upper specified set point (maximal acceptable indoor temperature), the pump is switched off.

The heat transfer within the floor layer, being the system occupying the heating source, is shown in Fig. 4. Convection heat transfer occurs from the hot water flowing in the pipes into the boundaries of the pipes. Then, conduction and natural convection heat transfer throughout different layers reaching the inner and outer surfaces at which the modes become: natural convection and radiation.

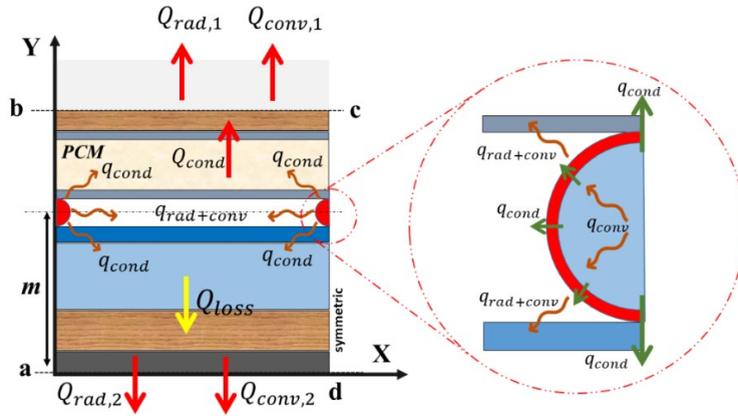


Fig. 4. Detailed cross-section of the floor showing heat transfer within the layers.

The instruments used for measurement were: K-type thermocouples to measure the temperatures at several positions, solar power meter to measure the solar irradiance, humidity sensor for humidity and air-flow anemometer to measure wind speed. The study focused on investigating the effect of: (1) weather conditions, (2) combining active and passive systems, (3) PCM type and (4) PCM position within the floor. The four main experiments and their respective configurations in rooms A and B are summarized in Table 2. Thermocouples' locations for tests 1 and 5 are demonstrated in Fig. 5.

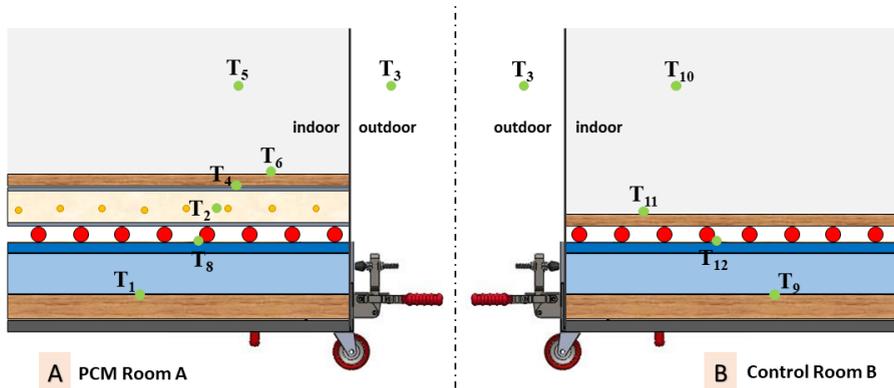


Fig. 5. Location of K-type thermocouples for temperature measurement in tests 1, 2, and 3 [26].

Table 2. Prototypes configurations for different experimental tests [26].

#	Date	Time	Experimental Objective	Prototype -A-Specifications	Prototype -B-Specifications	Heating system	Notes
1	Feb 10 th 2020 till Feb 13 th 2020	80 hr start 6:00	Effect of PCM integration with active underfloor radiant heating system at different weather* conditions and different PCM substitution layer	Underfloor active radiant with CO-PCM above Heating Pipes	Reference	Hydronic	No PCM in ref.
2	Feb 26 th 2020	24 hr start 6:00	Effect of active underfloor radiant heating – combined with passive PCM wall and roof	CO-PCM in all floor, roof and west wall	Reference	Hydronic	No PCM in ref.
3	Feb 19 th 2020	24 hr start 6:00	Effect of PCM type in active underfloor radiant application	Underfloor active radiant with CO-PCM in floor	Underfloor active radiant with PW-PCM in floor	Hydronic	

4	Dec 19 th 2020	10 h start 20:00	Effect of PCM position in the floor (below PCM plates)	Underfloor active radiant with CO-PCM below Heating Pipes	Reference	Hydronic	No PCM in ref.
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3. Experimental Results

With the large set of tests performed constituting the experimental campaign in the previous work done by the authors [26], part of the graphic results focused on temperature distribution and respective power consumption are reproduced in this article such that they comply with the objective: performing energetic, economic and environmental analyses. These curves are an important element that serves as a reference for numerical data throughout section 4.

3.1 Effect of weather conditions

Primary tests included the investigation of the effect of integrating CO-PCM above the HRFHS (Room A), and compared with a control prototype deprived from PCM (Room B) at variable weather conditions. The indoor temperature in rooms A and B as a function of time are shown in Fig. 6 with the changing outdoor weather conditions reflected by the varying ambient temperature. The figure shows that CO-PCM successfully eliminated the fluctuations of indoor temperature resulting in thermal comfort enhancement. This is reflected by the reduction of heating-cooling cycles from 12 to 5 in accordance to control room.

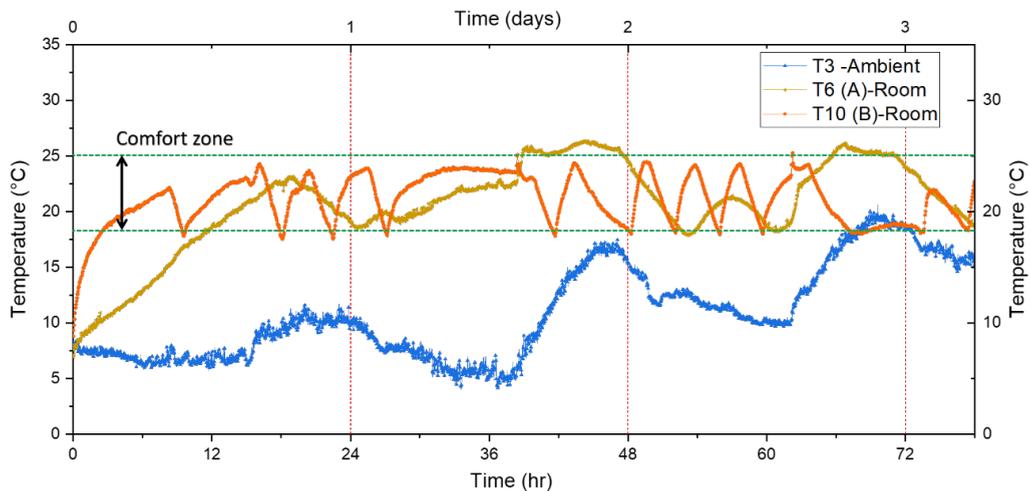


Fig. 6. Variation of room temperatures for experiment 1 as function of time within three testing days [26].

From the data obtained, power curves showing the pump power consumption as function of time for the two test prototypes are produced. These curves are layered with zone representation showing the high-peak and low-peak periods according to the Lebanese electricity tariffs at Bekaa Valley, Lebanon. Fig. 7 clarify the obtained reduction in the fluctuation of energy demand leading to a decrease of start-up and shut-down processes of the boiler and pump, which in turns, reduces the maintenance requirements.

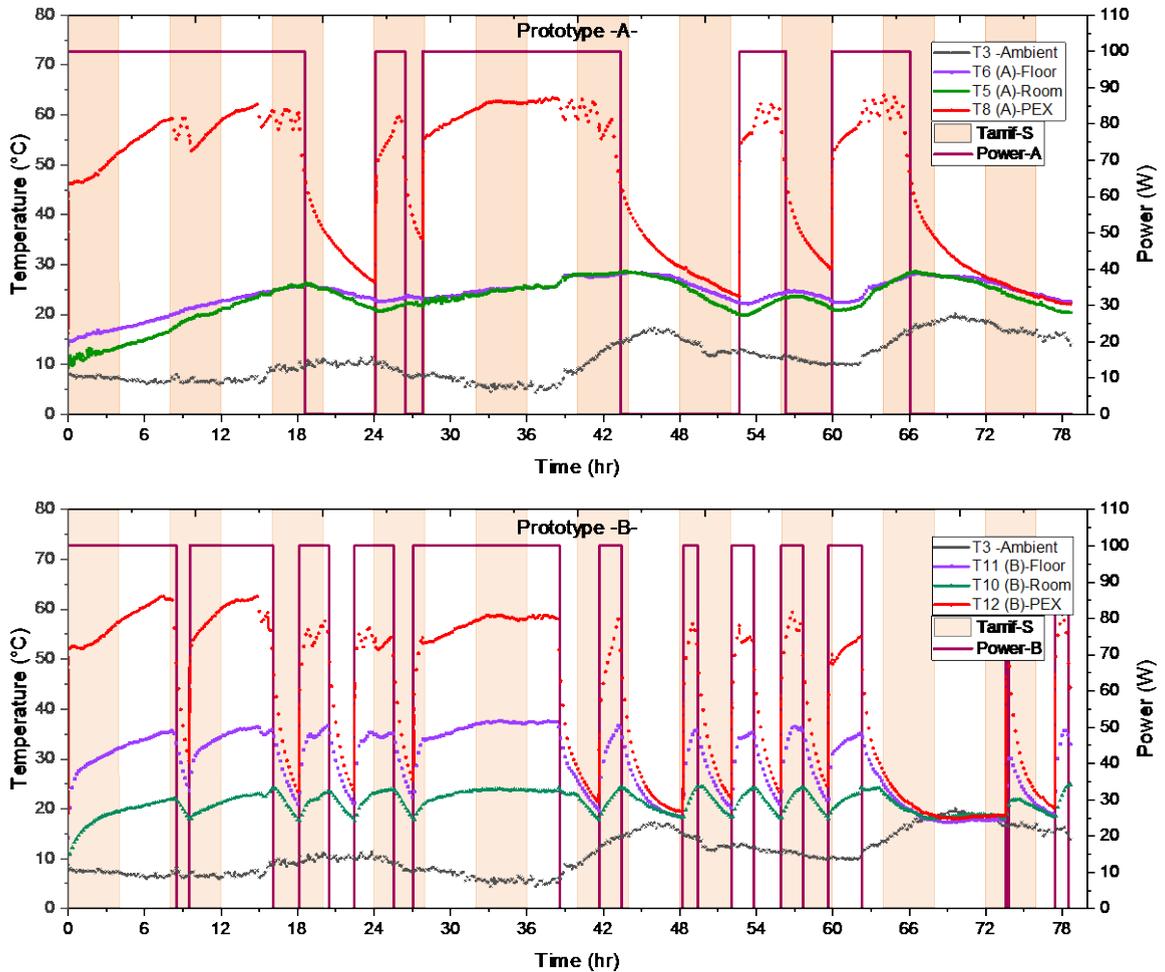


Fig. 7. Temperature distribution and pump power consumption for rooms A and B during test 1 [26].

3.2 Effect of application combinations

The second experiment compares the thermal performance of a prototype incorporating active and passive PCM applications with the reference control prototype. CO-PCM plates were installed in the floor, western wall and roof of prototype A, while prototype B contained no PCM. The temperature distribution in both prototypes and the relative pump operational power consumptions are illustrated in Fig. 8. The shaded parts in each graph represent the time of the day with high-peak electricity tariff. It is clear from the graphs that the combination of active and passive PCM systems shifted the load from high-peak to low-peak stages. As an example, the HRFHS operated for 0.667 hr during low-peak shifts and 3.933 hr during high-peak shifts; however, CO-PCM proved its ability to shift the load from high to low peak stage, by which the heating system operated for 0.983 hr and 4 hr for the cases of low and high electricity tariffs, respectively. Economic savings are investigated further more in *section 4*.

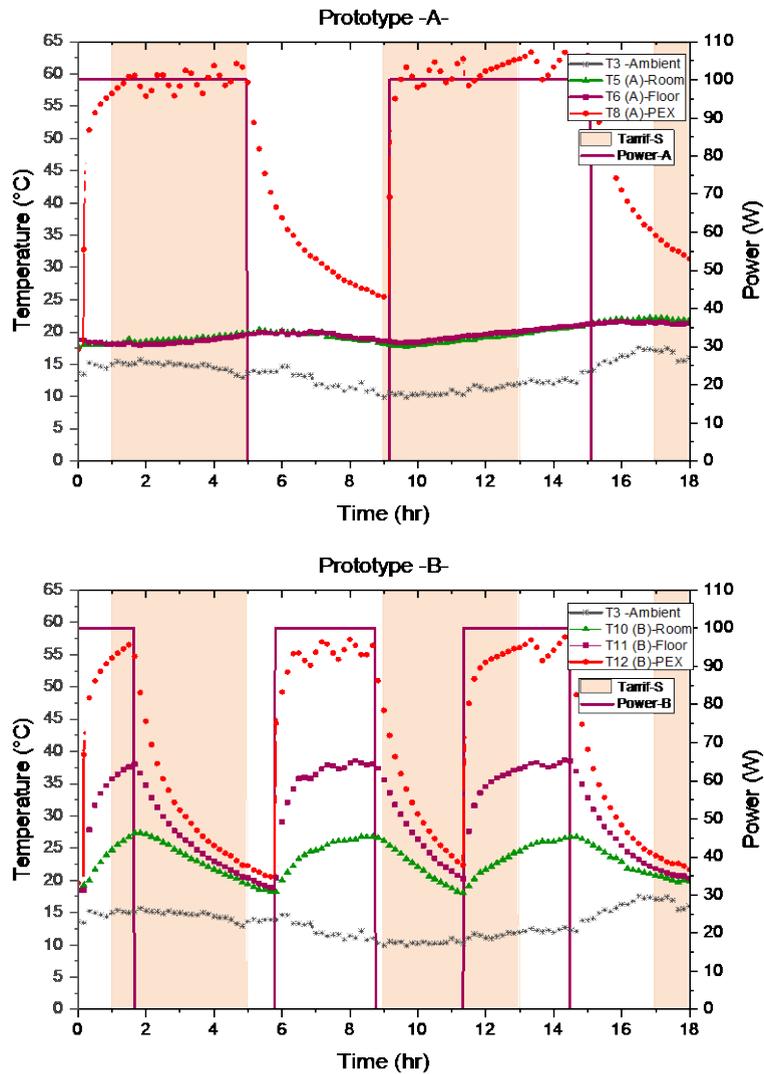


Fig. 8. Temperature distribution and pump power consumption for rooms A and B during test 2 [26].

3.3 Effect of PCM type: coconut oil vs. paraffin wax

The main important parameter that affects the functioning of the PCM application in a building is the type of the PCM as it defines the respective thermophysical properties, particularly the melting range and storage capacity. Coconut oil PCM (CO), being placed in the floor above the heating source prototype A, was compared with paraffin wax PCM (PW) in prototype B. The temperature distribution for the two prototypes with their respective pump power consumptions are presented in Fig. 9. It is depicted in the graphs that load shifting occurred by the CO-PCM, however, a large heating duration is observed which hinders the benefits in regards of load shifting. In such a case, PW has improved thermal response over CO, having less operation duration at both high-peak and low-peak zones.

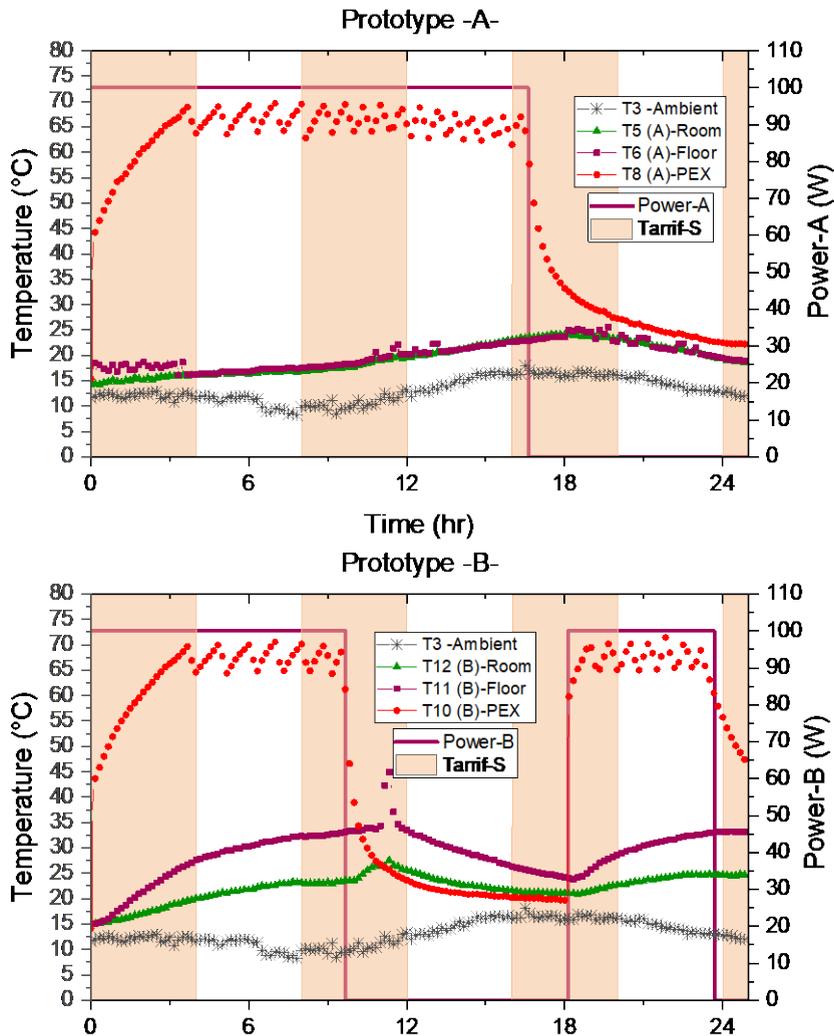


Fig. 9. Temperature variations recorded by the floor and room sensors for prototypes A (containing CO-PCM in floor) and B (containing PW-PCM in floor) with pump power consumption during test 3 [26].

3.4 Effect of the location of PCM in the floor: Active systems

The location of PCM plates is studied in two configurations: under the HRFHS and above it. For the 4th experiment, the CO-PCM macro-containers are placed underneath the HRFHS and compared with the control room with no PCM. Fig. 10-a shows the temperature distribution in the test facilities: A (CO-PCM under HRFHS) and B (control). It is shown that the temperature fluctuations durations are reduced accompanied with a slight load shifting by means of CO-PCM. The duration of heating is reduced from 4.784 hr to 3.418 hr. This reflects energy savings achieved by PCM in this case.

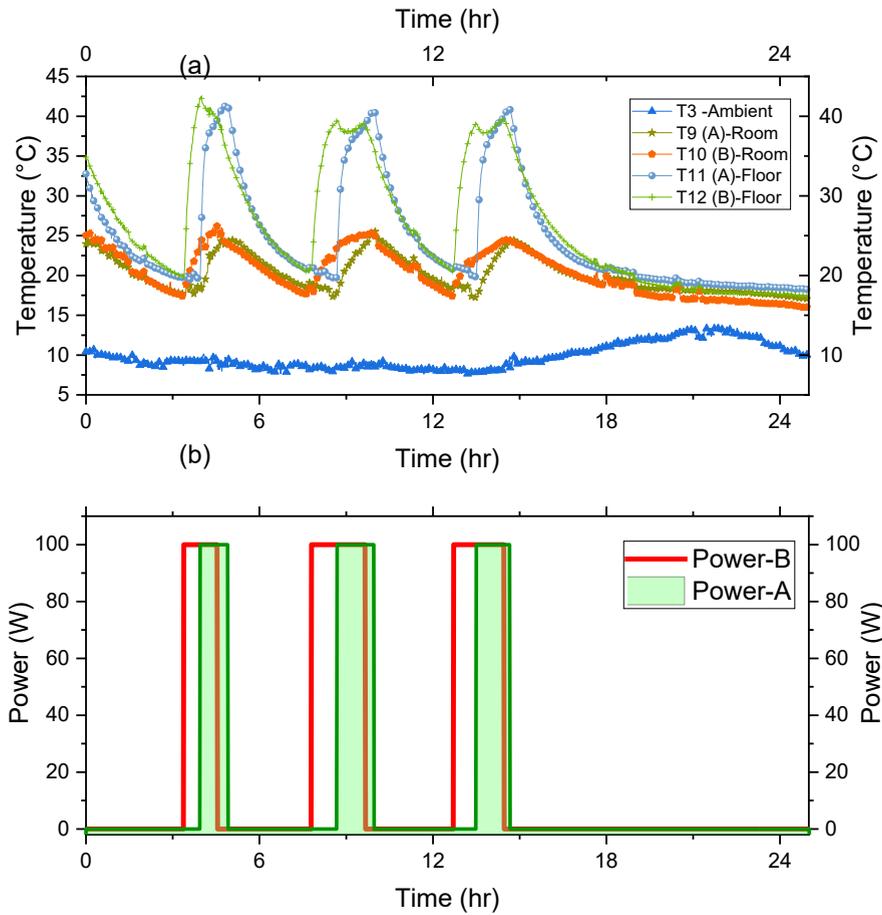


Fig. 10. (a) Variation of room temperature and floor surface temperatures for prototypes A and B of experiment 4 – stage 2 and (b) Pump power consumption for both prototype during the same test [26].

For a more consistent analysis, the plot of the pump power consumption for prototypes A and B is shown in Fig. 10-b. The duration of heating is observed to be smaller in prototype A indicating energy saving capability by the PCM. Thus, the position of the PCM being below the HRFHS yields an energy saving that yields cost savings at a stable defined electricity tariff (either full high-peak or full low-peak).

4. Energetic, Economic and Environmental Evaluations

The main approach within this study is directed toward energetic, economic and environmental aspects. For the energetic and economic aspects, the experiments involving load shifting results are treated based on *economic method 1*; and the experiments involving energy saving results are treated based on *economic method 2*, where both methods are detailed below. After that, a financial evaluation based on the simple payback period (SPP) is performed for all cases. The equation used for computing SPP is mentioned by Plytaria et al. [5]:

$$SPP = \frac{\Delta C}{\Delta CF} = \frac{C - C_0}{CF_0 - CF} \quad (1)[5]$$

Where: CF is the cash flow and C is the capital cost, both in USD. The subscript “0” stands for the reference system (control) having the conventional layout of a boiler and an underfloor radiant heating system (refer to Fig. 5). As prescribed by the equation, it takes into consideration the extra capital cost of each system used (ΔC) and the cash

flow gain (ΔCF) by the use of any system, both compared to reference. Table 3 summarizes all the unit costs, amount and total cost of the used system components in this study.

For *economic method 1*, according to the authors' previous study [19], the Lebanese Government offers local electricity for different regions in the country on the basis of consecutive 4-hour time interval followed by 4-hour cut-off. During cut-off, non-governmental companies distributed in different districts offer electricity but with higher expenses. Thus, the advantage of using PCM for load shifting from high-peak load to low-peak load time zones arises. The assumptions made for considering the value of electricity rate retrieved from the governmental website are: (1) government electricity is considered outside the night drop and evening peak periods for medium tensions, and (2) tariff policy is unique for all time shifts by the government.

Table 3 Detailed financial data of the tested systems integrated in the prototypes.

	Device/equipment	Specific unit cost	Amount	Total cost
<i>Conventional system without PCM and containers</i>	PEX tubes	0.65 USD/m	20 m	13 USD
	EPS insulation	10 USD/plate	3 plates	30 USD
	XPS insulation	68 USD/item	1 item	68 USD
	Boost Pump	50 USD/item	1 item	50 USD
	Boiler	68 USD/item	1 item	68 USD
	hydronic accessories	-	-	45 USD
	Control System	44 USD/item	1 item	44 USD
	Total			318 USD
<i>PCMs and containers</i>	PCM containers	78 USD/container	3 (or 7) containers	234 (or 546) USD
	CO-PCM	8 USD/liter	54 (or 126) liters	432 (or 1008) USD
	PW-PCM	4 USD/liter	54 liters	216 USD
	Total			882 (or 1770) USD

For *economic method 2*, the assumption that the Lebanese Government offers continuous electricity of stable cost is made. The target of such assumption is to investigate the effect of PCM energy saving on yearly cost saving without the intervention of different Electricity Tariff.

For all cases, and referring to Fig. 7, Fig. 8, Fig. 9, and Fig. 10 (taking into account the power consumption of the pump and boiler), the consumed energy can be calculated using the following equation:

$$E = (P_p + P_b) \times \Delta t \quad (2)$$

Where: E is the consumed energy in kWh, P_p and P_b are the power consumed in Watts by the pump and boiler, respectively, and Δt is the heating time duration in hrs. Δt is equal to S (time of heating operation within government electricity shift) plus U (time of heating operation within personal electricity shift). Then the operational cost or cash flow (CF) in USD or LBP is calculated as follows:

$$CF = E \times Er = (P_p + P_b) [(S \times S_r) + (U \times U_r)] \quad (3)$$

Where: Er is the electricity rate in LBP/kWh or USD/kWh; it can be either equals to S_r or U_r which are the electricity rates when electricity provider is the Lebanese Government or the personal electrical generator, respectively. Zones detailed specifications are summarized in Table 4 where S refers to the shaded part and U refers to the unshaded part in the power consumption curves presented in section 3.

Economic evaluations using the above methods are applied for the experiments done. Results for experiments 1, 2 and 3, that influence load shifting and indoor temperature fluctuations reduction, are summarized in Table 5. Results for experiment 4 that is accompanied by energy savings are summarized in Table 6. It is shown from the results of the

energetic and economic evaluations that:

- (1) For test 1 dealing with active CO-PCM above heating system in floor, the total annual operational cost of the heating system is 1002 USD for the control room which is slightly less than that for the PCM room (1026 USD). This means that no cost saving was obtained although load shifting has occurred. It is a result of the small repetitive duration in shifts of electricity cost based on tariff policy while variable weather is affecting the heating-cooling cycle duration and temporal time for the PCM-active heating system;
- (2) For test 2, using CO-PCM actively with HRFHS, combined to passive wall and roof usage, it is shown that the total annual operational cost for the control test was higher by 227 USD.
- (3) For test 3, there was load shifting between Active PW-PCM compared to Active CO-PCM resulting in a yearly saving of 32 USD only.
- (4) For test 4, and without taking into consideration electricity tariff shifts, placing CO-PCM plates below the heating system results in annual energy savings of 393.5 kWh; leading to cost savings of 29 USD if the supplier of the electricity was the Lebanese Government and 169 USD if the supplier was the personal electrical generator.

Table 4 Zones S and U specifications

Zone	Electricity generation Provider	Electricity cost (L.L./kWh)	Electricity cost (\$/kWh)
S	Lebanese Government [38]	112	0.07392
U	Personal electric generator [39]	650	0.429

Table 5 Durations of heating cycles at different Electricity rate zones and the respective operational costs for tests 1,2 and 3 encountering load shifting.

Test Number	Test Scenario	Heating duration zone S (hr)	Heating duration zone U (hr)	Total daily energy consumption (kWh)	Total daily operational cost (USD)	Total annual operational cost (USD) [†]
1	Control test	18.992	23.349	20.642	5.567	~1002
	Active CO-PCM	22.837	23.317	22.5	5.699	~1026
2	Control test	2.3	5.433	16.497	5.335	~960
	Combined active and passive	7.816	3.1	23.287	4.07	~733
3	Active CO-PCM	8.633	8	14.31	3.5	~630
	Active PW-PCM	7.55	7.7	13.12	3.322	~598

Table 6 Power consumption and operational costs for experiment 4 encountering energy saving.

Test Number	Test Scenario	Heating duration t (hr)	Total daily energy consumption (kWh)	Total daily operational cost (USD)		Total annual operational cost (USD)	
				For Sr	For Ur	For Sr	For Ur
4	Control test	4.784	7.654	0.565	3.283	~102	~591
	Active CO-PCM	3.418	5.468	0.404	2.345	~73	~422

The SPP can be calculated for experiments 2, 3 and 4 where experiment 1 do not exhibit any cost saving by the new system compared to the control test as the weather conditions play a significant role in affecting the performance of PCM with the short repetitive change in electricity tariff. The estimated values of SPP for experiments 2 and 3 are 6.82 years and 6.75 years[‡], respectively; and the estimated values of SPP for experiment 4 are 22.96 years for Sr electricity rate and 3.94 years for Ur electricity rate. A graph illustrating the variation of SPP results for experiments 2,3 and 4 as function of actual heating months per year is given in Fig. 11. It is shown that SPP decreases exponentially as the annual actual heating time decrease for all test cases, where tests 2 and 3 are approximately similar. As the

[†] The total annual operational cost is calculated by multiplying the daily cost with 180 days considering the duration of heating season each year is 6 months.

[‡] In this case, since the comparison is between CO-PCM and PW-PCM, CO-PCM system is considered the control or reference.

heating time varies from 7 to 12 months, the variation in SPP is decreased clearly for tests 2, 3 and 4 (case of Ur). Also, it is noticeable that for Sr case in test 4 the system seems to be ineffective when heating time reaches 7 months and above, as SPP values exceeds 15 years. It is clear from the figure that the effect of load shifting on economic saving (Tests 2 and 3) is less efficient compared to the effect of energy saving on economic saving (Test 4 – Sr), where, for a moderate 6 months of heating, SPP provided by the room with PCM in the floor placed below heating tubes (Test 4 – Ur) when personal generators are the electricity sources for the residencies is below 4 years which is less than that for the cases 2 and 3 related to prototypes having the PCM above the heating tubes and depending on load shifting that is in-relation with different tariff shifts (SPP between 5 and 10).

The environmental concerns are of highly importance. Coconut oil PCM is a bio-based PCM that is not flammable meaning that no threats are detected regarding exposition of environment to greenhouse gases. Savings in energy demand addressed within experiment 4 leads to decrease in power consumption of electrical supply, which in turns - on large scale - will result in governmental and local electrical generators CO₂ emission reduction. Moreover, CO-PCM is considered a functional food that is friendly to the ecosystem, and it has many health advantages stated by Srivastava et al. [40]: helps in healing foot cracks, removes skin scars and reduces levels of both cholesterol and triglyceride. These multidisciplinary benefits that CO-PCM has influence further research on the capabilities of coconut and other bio-based natural products that are key factors in the process of going green: in energy toward NZEB and in society toward healthier community.

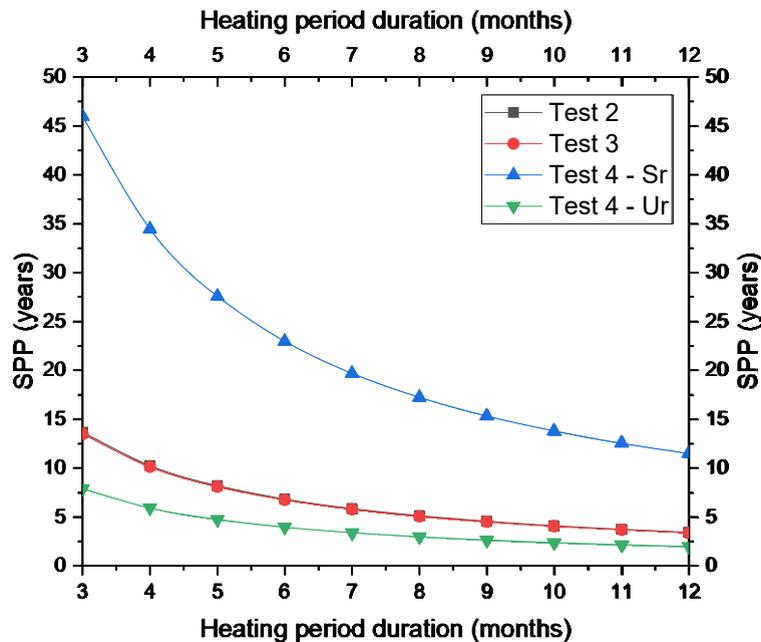


Fig. 11. SPP results for experiments 2,3 and 4 as function of actual annual heating months.

5. Conclusions and future work

The current research is a complementary study for a previous work published recently by the authors, and is focused on studying the energetic, economic and environmental aspects related to the thermal performance of a water underfloor radiant heating system integrated with enhanced macro-containers that are filled with coconut oil PCM. Experiments were performed covering four parameters: (1) effect of variable weather conditions on the active PCM application; (2) effect of passive-active PCM application combination; (3) effect of PCM type; and (4) effect of PCM position. The energetic and economic aspects relied on the difference in electricity tariff thus focusing on the load shifting capability of the specified application under test, and particularly in the case of PCM position, the study examined the capability of energy savings. Major conclusions and contributions of the current work are detailed as

follows:

1. CO-PCM integrated in active application and in combined active-passive application incorporating HRFHS, permit load shifting from high-peak to low-peak periods resulting in daily and annual cost savings.
2. Residential thermal comfort was achieved by PCM in all studied configurations as the temperature fluctuations are reduced.
3. Economic study proved that annual cost saving of 227 USD (resulted from load shifting) is achieved by combining PCM applications in comparison with control room, with a payback period reaching 6.82 years.
4. The annual saving reached 169 USD (resulted from energy saving) for the case of active CO-PCM placed below HRFHS with a payback period reaching 3.94 years, reflecting the importance of PCM position and proving that PCM placement under HRFHS is more beneficial than being at its top.
5. The comparison between PW-PCM and CO-PCM integrated with HRFHS shows a higher effectiveness for PW even with load shifting achieved by CO-PCM, where 32 USD annual cost saving was attained by PW.
6. PCM serves as a key element in the global trend towards sustainability and cleaner environment as it permits a drop in greenhouse gases on the building level. PCM is an important factor towards the transition into NZEB.

For future research, four main recommendations are set as follows:

1. The use of PCM in summer for cooling load reduction must be studied on the 4 aspects: thermal, energetic, economic and environment.
2. More combination of dual and triple systems is to be studied covering active and passive applications.
3. Energetic and economic studies are to be extended from small-scale prototype to large-scale residential compartments for direct linking to reality.
4. Optimization studies using simulation software such as COMSOL Multiphysics are needed for PCM building application conceptualization after performing experimental, numerical and analytical investigations.

References

1. Du, K.; Calautit, J.; Wang, Z.; Wu, Y.; Liu, H. A Review of the Applications of Phase Change Materials in Cooling, Heating and Power Generation in Different Temperature Ranges. *Applied Energy* **2018**, *220*, 242–273, doi:10.1016/j.apenergy.2018.03.005.
2. Xing, X.; Lu, W.; Zhang, G.; Wu, Y.; Du, Y.; Xiong, Z.; Wang, L.; Du, K.; Wang, H. Ternary Composite Phase Change Materials (PCMs) towards Low Phase Separation and Supercooling: Eutectic Behaviors and Application. *Energy Reports* **2022**, *8*, 2646–2655, doi:10.1016/j.egy.2021.12.069.
3. Farhat, O.; Faraj, J.; Hachem, F.; Castelain, C.; Khaled, M. A Recent Review on Waste Heat Recovery Methodologies and Applications: Comprehensive Review, Critical Analysis and Potential Recommendations. *Cleaner Engineering and Technology* **2022**, *6*, doi:10.1016/j.clet.2021.100387.
4. McKenna, P.; Turner, W.J.N.; Finn, D.P. Geocooling with Integrated PCM Thermal Energy Storage in a Commercial Building. *Energy* **2018**, *144*, 865–876, doi:10.1016/j.energy.2017.12.029.
5. Plytaria, M.T.; Tzivanidis, C.; Bellos, E.; Antonopoulos, K.A. Energetic Investigation of Solar Assisted Heat Pump under Floor Heating Systems with and without Phase Change Materials. *Energy Conversion and Management* **2018**, *173*, 626–639, doi:10.1016/j.enconman.2018.08.010.
6. Maccarini, A.; Hultmark, G.; Bergsøe, N.C.; Afshari, A. Free Cooling Potential of a PCM-Based Heat Exchanger Coupled with a Novel HVAC System for Simultaneous Heating and Cooling of Buildings. *Sustainable Cities and Society* **2018**, *42*, 384–395, doi:10.1016/j.scs.2018.06.016.
7. Kong, X.; Jie, P.; Yao, C.; Liu, Y. Experimental Study on Thermal Performance of Phase Change Material Passive and Active Combined Using for Building Application in Winter. *Applied Energy* **2017**, *206*, 293–302, doi:10.1016/j.apenergy.2017.08.176.
8. Lizana, J.; Chacartegui, R.; Barrios-padura, A.; Ortiz, C. Advanced Low-Carbon Energy Measures Based on Thermal Energy Storage in Buildings: A Review. *Renewable and Sustainable Energy Reviews* **2018**, *82*, 3705–3749, doi:10.1016/j.rser.2017.10.093.
9. Kasaeian, A.; Bahrami, L.; Pourfayaz, F.; Khodabandeh, E.; Yan, W.M. Experimental Studies on the

- Applications of PCMs and Nano-PCMs in Buildings: A Critical Review. *Energy and Buildings* **2017**, *154*, 96–112, doi:10.1016/j.enbuild.2017.08.037.
10. Zhang, T.; Lu, G.; Zhai, X. Design and Experimental Investigation of a Novel Thermal Energy Storage Unit with Phase Change Material. *Energy Reports* **2021**, *7*, 1818–1827, doi:10.1016/j.egy.2021.03.029.
 11. Meihan, C.; Li, J.; Shigang, M.; Xianming, S. Energy Saving Simulation of Phase Change Materials in the Enclosure Structure of Archives Warehouse in Lhasa. *Energy Reports* **2022**, *8*, 532–538, doi:10.1016/j.egy.2022.01.217.
 12. Hamidi, Y.; Malha, M.; Bah, A. Analysis of the Thermal Behavior of Hollow Bricks Walls Filled with PCM: Effect of PCM Location. *Energy Reports* **2021**, *7*, 105–115, doi:10.1016/j.egy.2021.08.108.
 13. Yang, H.; Zhang, G.; Dou, B.; Yan, X.; Liu, Z.; Qi, W. Investigations of Double Layer Phase Change Walls with Expanded Graphite on the Temperature and Energy Consumption. *Energy Reports* **2021**, *7*, 9023–9034, doi:10.1016/j.egy.2021.11.237.
 14. Vik, T.A.; Madessa, H.B.; Aslaksrud, P.; Folkedal, E.; Øvrevik, O.S. Thermal Performance of an Office Cubicle Integrated with a Bio-Based PCM: Experimental Analyses. *Energy Procedia* **2017**, *111*, 609–618, doi:10.1016/j.egypro.2017.03.223.
 15. Li, C.; Yang, X.; Peng, K. Performance Study of a Phase Change Material Trombe Wall System in Summer in Hot and Humid Area of China. *Energy Reports* **2022**, *8*, 230–236, doi:10.1016/j.egy.2021.11.032.
 16. Medved, S.; Arkar, C.; Domjan, S.; Zizak, T. *Performance of Multilayer Glass and BIPV Facade Structures*; 2021; ISBN 9780128207918.
 17. Zhu, H.; Guo, B.; Geng, W.; Chi, J.; Guo, S. Simulation of an Improved Solar Absorption Refrigeration System with Phase Change Materials. *Energy Reports* **2022**, *8*, 3671–3679, doi:10.1016/j.egy.2022.02.306.
 18. He, W.; Yu, C.; Yang, J.; Yu, B.; Hu, Z.; Shen, D.; Liu, X.; Qin, M.; Chen, H. Experimental Study on the Performance of a Novel RC-PCM-Wall. *Energy and Buildings* **2019**, *199*, 297–310, doi:10.1016/j.enbuild.2019.07.001.
 19. Faraj, K.; Faraj, J.; Hachem, F.; Bazzi, H.; Khaled, M.; Castelain, C. Analysis of Underfloor Electrical Heating System Integrated with Coconut Oil-PCM Plates. *Applied Thermal Engineering* **2019**, *158*, doi:10.1016/j.applthermaleng.2019.113778.
 20. Faraj, K.; Khaled, M.; Faraj, J.; Hachem, F.; Castelain, C. A Review on Phase Change Materials for Thermal Energy Storage in Buildings: Heating and Hybrid Applications. *Journal of Energy Storage* **2020**, doi:10.1016/j.est.2020.101913.
 21. Faraj, K.; Khaled, M.; Faraj, J.; Hachem, F.; Castelain, C. Phase Change Material Thermal Energy Storage Systems for Cooling Applications in Buildings: A Review. *Renewable and Sustainable Energy Reviews* **2019**, doi:10.1016/j.rser.2019.109579.
 22. Prieto, M.M.; Gonzalez, B. Radiant Heating Floors with PCM Bands for Thermal Energy Storage: A Numerical Analysis. *International Journal of Thermal Sciences* **2021**, *162*, doi:10.1016/j.ijthermalsci.2020.106803.
 23. Plytaria, M.T.; Tzivanidis, C.; Bellos, E.; Antonopoulos, K.A. Parametric Analysis and Optimization of an under Floor Solar Assisted Heating System with Phase Change Materials. *Thermal Science and Engineering Progress* **2019**, *10*, 59–72, doi:10.1016/j.tsep.2019.01.010.
 24. Barzin, R.; Chen, J.J.J.; Young, B.R.; Farid, M.M. Application of PCM Underfloor Heating in Combination with PCM Wallboards for Space Heating Using Price Based Control System. *Applied Energy* **2015**, *148*, 39–48, doi:10.1016/j.apenergy.2015.03.027.
 25. Devaux, P.; Farid, M.M. Benefits of PCM Underfloor Heating with PCM Wallboards for Space Heating in Winter. *Applied Energy* **2017**, *191*, 593–602, doi:10.1016/j.apenergy.2017.01.060.
 26. Faraj, K.; Khaled, M.; Faraj, J.; Hachem, F.; Castelain, C. Experimental Study on the Use of Enhanced Coconut Oil and Paraffin Wax Phase Change Material in Active Heating Using Advanced Modular Prototype. *Journal of Energy Storage* **2021**, *41*, doi:10.1016/j.est.2021.102815 Received.
 27. Larwa, B.; Cesari, S.; Bottarelli, M. Study on Thermal Performance of a PCM Enhanced Hydronic Radiant Floor Heating System. *Energy* **2021**, *225*, doi:10.1016/j.energy.2021.120245.
 28. Faraj, K.; Khaled, M.; Faraj, J.; Hachem, F.; Castelain, C. A Summary Review on Experimental Studies for PCM Building Applications: Towards Advanced Modular Prototype. *Energies* **2022**, *15*.
 29. Young, H.D. Values for Diamond and Silica Aerogel from CRC Handbook of Chemistry and Physics Available online: <http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/thren.html>.

30. Thermtest COMMON MATERIAL THERMAL PROPERTIES Available online: <https://thermtest.com/materials-database>.
31. Owens-corning Foamular Extruded Polystyrene (XPS) Insulation: SI and IP Units for Selected Properties Available online: <https://dcpd6wotaa0mb.cloudfront.net/mdms/dms/EIS/10015703/10015703-FOAMULAR-SI-and-I-P-Units-for-Selected-Properties-Tech.-Bulletin.pdf>.
32. Hammond, G.; Jones, C. *Inventory of Carbon and Energy*; 2nd ed.; Elsevier, 2011;
33. Engineering Toolbox Specific Heat of Some Common Substances Available online: https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html (accessed on 30 September 2020).
34. Maclean, J.D.; Madison, W. Thermal Conductivity of Wood. *Heatig, Piping and Air conditioning* **1941**, *13*, 380–391.
35. 3A Composites ALUCOBOND Technical Data Available online: <https://alucobond.com.sg/products/alucobond/technical-data/>.
36. Krishna, P.V.; Srikant, R.R.; Rao, D.N. Experimental Investigation on the Performance of Nanoboric Acid Suspensions in SAE-40 and Coconut Oil during Turning of AISI 1040 Steel. *International Journal of Machine Tools and Manufacture* **2010**, *50*, 911–916, doi:10.1016/j.ijmachtools.2010.06.001.
37. Ukrainczyk, N.; Kurajica, S.; Sipusic, J. Thermophysical Comparison of Five Commercial Paraffin Waxes as Latent Heat Storage Materials. *Chemical and Biochemical Engineering Quarterly* **2010**, *24*, 129–137, doi:10.15255/CABEQ.2014.240.
38. (EDL), E. du L. Electricity Tarrif - Understand My Bill Available online: <http://www.edl.gov.lb/page.php?pid=39&lang=en> (accessed on 21 December 2020).
39. Kadri, A. Al-Rafid Electricity Generators Tarrif Policy 2020.
40. Srivastava, Y.; Semwal, A.D.; Sajeekumar, V.A.; Sharma, G.K. Melting, Crystallization and Storage Stability of Virgin Coconut Oil and Its Blends by Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR). *Journal of Food Science and Technology* **2016**, *54*, 45–54, doi:10.1007/s13197-016-2427-1.
41. Shen, D.; Yu, C.; Wang, W. Investigation on the Thermal Performance of the Novel Phase Change Materials Wall with Radiative Cooling. *Applied Thermal Engineering* **2020**, *176*, doi:10.1016/j.applthermaleng.2020.115479.
42. Jelle, B.P.; Kalnæs, S.E. *Phase Change Materials for Application in Energy-Efficient Buildings*; Elsevier Ltd, 2017; ISBN 9780081011287.
43. Li, Y.; Zhou, J.; Long, E.; Meng, X. Experimental Study on Thermal Performance Improvement of Building Envelopes by Integrating with Phase Change Material in an Intermittently Heated Room. *Sustainable Cities and Society* **2018**, doi:10.1016/j.scs.2018.01.040.
44. Wijesuriya, S.; Brandt, M.; Tabares-velasco, P.C. Parametric Analysis of a Residential Building with Phase Change Material (PCM) -Enhanced Drywall , Precooling , and Variable Electric Rates in a Hot and Dry Climate Time of Use. *Applied Energy* **2018**, *222*, 497–514, doi:10.1016/j.apenergy.2018.03.119.
45. Mehdaoui, F.; Hazami, M.; Messaouda, A.; Taghouti, H.; Guizani, A. Thermal Testing and Numerical Simulation of PCM Wall Integrated inside a Test Cell on a Small Scale and Subjected to the Thermal Stresses. *Renewable Energy* **2018**, doi:10.1016/j.renene.2018.12.029.