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Abstract

Between 2000 and 2015, annual electric peak demand in Kuwait has doubled to 15000 MW and the Ministry of Energy and Water expects this number to double once more by 2030 attributing 70% of this growth to new housing projects. Within this context, this manuscript evaluates the effect of incorporating PCM-wallboards in low-rise air-conditioned residential heavyweight buildings in Kuwait. Using an EnergyPlus single-zone model, a parametric study is performed considering several window-to-wall ratios (WWRs), different solar orientations and some PCM-wallboards configurations. The main study goals are to: (*i*) explore the validity of a single PCM-wallboard solution that can be universally applied throughout residential buildings in Kuwait; (*ii*) evaluate the impact of PCM-wallboard on the reduction of both cooling demand and peak-loads; (*iii*) provide some guidelines for incorporating PCM-wallboards in Kuwait. Following an extensive parametric study, a 4 cm thick PCM-wallboard with a melting-peak temperature of 24 ºC yielded the lowest annual cooling demand across a variety of room orientations and WWRs assuming cooling-set point of 24 ºC. Its implementation lead to annual cooling energy savings of 4-5% across all the case-studies. Regarding the impact throughout the year, cooling demand and peak-loads can be reduced by 5-7% during summer months. The average daily cooling loads can be reduced by 5-8%.

Keywords

PCM-wallboards, residential buildings, hot arid climate, cooling energy demand, dynamic simulation.

1. Introduction

In recent decades, Kuwait has experienced substantial building construction activities which cause significant strain on the country's electricity grid. Between 2000 and 2015, annual electric peak demand has doubled to 15000 MW and the Ministry of Energy and Water expects this number to double once more by 2030 attributing 70% of this growth to new housing projects (Al Tayyar 2015). Moreover, previous work has shown that in established residential neighborhoods in Kuwait about half of the electricity use and 70% of peak demand in buildings stem from cooling energy demand (Reinhart *et al.* 2015). The above described, ever-growing peak demands have led to recurring summer blackouts in some residential areas. Given that Kuwait is an oil-exporting country, a possible reaction to the development in the residential sector could be to increase electricity generation. However, oil is the country's only natural resource and its main source of revenue (Ministry of Electricity and Water 2010) and while as late as 1980, only 10% of the produced energy was consumed locally, this percentage was close to 40% in 2015.

What are alternative options for the country? At 13000 kWh per person, annual energy use per capita in Kuwait is among the highest in the world (Alotaibi 2011). While this use can be partly attributed to the harsh summer climate, other contributing factors are inefficient construction practices and installed equipment, as well as energy-intensive lifestyle choices (Al-Mumin *et al.* 2003). It should therefore become a government priority to manage and reduce building energy use in Kuwait to ensure the country's long-term prosperity. To further this goal, the energy conservation code of the Ministry of Electricity and Water (Ministry of Electricity and Water 2010) establishes several recommendations to enhance the energy efficiency of buildings (including insulation, glazing, lighting and ventilation requirements) and to reduce power ratings of air-conditioning systems. (Al-ajmi and Hanby 2008) carried out a parametric study on the simulation of the energy consumption of residential buildings in Kuwait using TRNSYS-IISIBAT environment. The authors proposed several features that should be adopted to achieve more energy efficient buildings in Kuwait, including: the reduction of the amount of uncontrolled air infiltration rates; the control of the window area and the orientation and placement of the main window facades (windows in the Kuwaiti environment should face toward the north-south direction), and the use of certain treatments to the glazing to reduce heat gains. However, only traditional sensible construction materials are considered in both documents. To complement these works, this manuscript explores the incorporation of PCM-wallboards in low-rise air-conditioned residential heavyweight buildings in Kuwait.

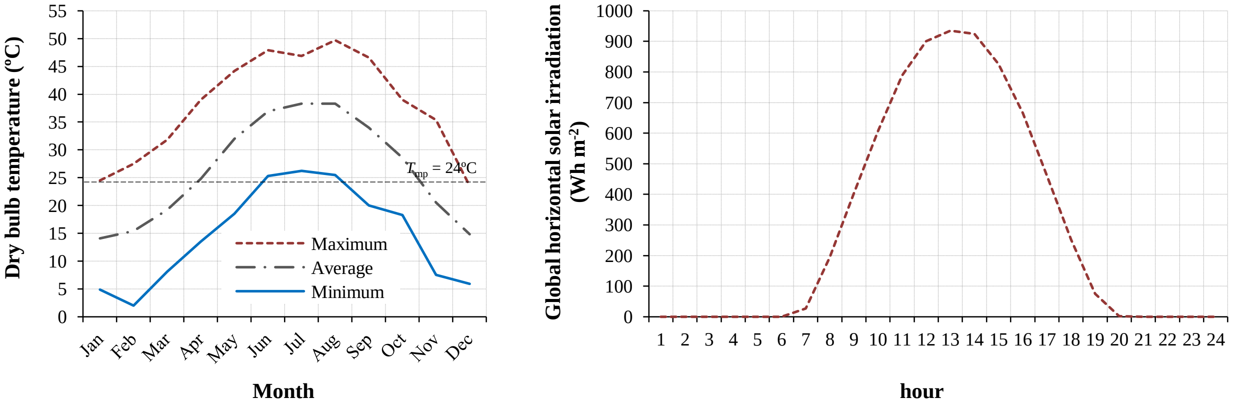
PCMs are materials that undergo melting/solidification at a nearly constant temperature, storing/releasing great amounts of energy due to the latent heat involved in the solid-liquid phase change processes. Therefore, PCMs are very suitable for thermal management and thermal energy storage (TES) applications. Ideally, PCMs to be used in TES systems should have a melting/solidification temperature in the practical range of application and they must have a high latent heat of fusion and a elevated thermal conductivity (paraffins used in buildings applications typically have low thermal conductivity, which can compromise some applications). Moreover, to be used in the design of TES systems, PCMs should have desirable thermophysical, kinetic, chemical and economic properties as suggested by (Soares *et al.* 2013) and (Cabeza *et al.* 2011). PCMs are mainly classified as organic, inorganic and eutectic. Organic PCMs are further described as paraffins and non-paraffins. Inorganic PCMs are further described as hydrated salts and metallics. Several applications of PCMs can be found in literature, including: PCM enhanced wallboards and other PCM walls; shape stabilized PCM (SSPCM) enhanced elements; PCM bricks; PCM enhanced concrete systems and mortars; PCM Trombe walls; PCM shutters, window blinds and translucent PCM walls; PCM enhanced ventilated façades; PCM enhanced photovoltaics; PCM enhanced HVAC systems, etc..

The advantages of incorporating PCMs in buildings were recently pointed out and reviewed by many authors (Soares *et al.* 2013; Cabeza *et al.* 2011; de Gracia and Cabeza 2015; Sharma *et al.* 2009; Tyagi and Buddhi 2007; Kuznik *et al.* 2011; Zhou *et al.* 2012; Zhang *et al.* 2007; Pomianowski *et al.* 2013; Baetens *et al.* 2010; Khudhair and Farid 2004; Osterman *et al.* 2012; Zhu *et al.* 2009), and several numerical and experimental studies have been carried out to assess the thermal performance of different PCM-based wallboards. The studies carried out by (Kuznik *et al.* 2008), (Kuznik and Virgone 2009) and (David *et al.* 2011) provided important information about the optimization of a paraffin-based wallboard for building use. These studies also list the importance of several aspects to be considered in the assessment of the heat transfer with solid-liquid phase change through PCM-based wallboards. (Soares *et al.* 2014) numerically evaluated the impact of incorporating PCM-wallboards in the heating and cooling energy demand of an air-conditioned lightweight steel-framed (LSF) residential room when implemented under several European climates. A multi-dimensional optimization study was carried out by combining EnergyPlus and GenOpt tools. The authors evaluated different thermophysical properties of the PCM (enthalpy-temperature and thermal conductivity-temperature functions) and design parameters, such as the solar absortance of the inner surfaces, the thickness and location of the PCM-drywalls in the room, air-infiltration rates, solar gains, internal gains, and set-points to conclude that PCM-wallboards can contribute for the annual cooling and heating energy savings in a passive way. The authors provided some guidelines for the incorporation of PCM-drywalls in LSF residential buildings in Europe. As stated by (de Gracia *et al.* 2015), this attempt to develop specific solutions for different locations based on their climate can be a good approach to foster the implementation of a specific technology. (Saffari *et al.* 2016) developed an EnergyPlus based methodology to evaluate the energy performance of a PCM-enhanced building model in Madrid. The authors used the Fanger thermal comfort model to control the HVAC operation and to evaluate the economic impact of integrating PCMs in buildings. The results showed that PCMs improve the cooling and heating energy performances of the most evaluated cases. In order to evaluate the potential of a PCM-wallboard constituted of 60 wt.% of microencapsulated paraffin within a copolymer, a renovated office building in Lyon was monitored during one year by (Kuznik *et al.* 2011). A room was equipped with PCM-wallboards in the lateral walls and in the ceiling, and another room, identical to the first one, was not equipped but also monitored. The results showed that PCM-wallboards can enhance the thermal comfort of occupants. (Mandilaras *et al*. 2013) experimentally evaluated the impact on PCM-wallboards in the thermal performance of a Mediterranean residential building. The authors concluded that the thermal mass of the walls can be enhanced during late spring, early summer and autumn (when PCMs are activated). The study was conducted for unoccupied house conditions, which can be problematic since internal loads may significantly affect the dynamics of the phase change processes of the PCM. It can be seen that, several studies concerning the application of PCM-wallboards in real buildings have been carried out in order to evaluate the influence of PCM-wallboards in more real-life conditions. However, no guidelines about the incorporation of PCM-wallboards in heavyweight construction in the dry desert climate conditions of Kuwait are found in the literature. Low-rise heavyweight construction is very widespread in Kuwait and, regarding the residential sector, low-rise buildings are the most representative Kuwaiti buildings. Therefore, this category of buildings will be used as case study in this paper.

The main goals of this work are therefore to: (*i*) explore the validity of a single PCM-wallboard solution (thickness and the melting-peak temperature) that can be universally applied throughout low-rise residential heavyweight buildings in Kuwait; (*ii*) evaluate the impact of PCM-wallboards on the reduction of both cooling demand and peak-loads; (*iii*) provide some guidelines for incorporating PCM-wallboards in Kuwait. This study forms part of an MIT-Kuwait Signature Project called Sustainability of Kuwait's Built Environment which aims at promoting an energy and carbon-efficient built environment in Kuwait.

2. Methodology

A parametric study is carried out by using a single-zone, air-conditioned residential building model in EnergyPlus (EnergyPlus 8.0.0 2014) built according to the 2010 building energy code of Kuwait (Ministry of Electricity and Water 2010). The KISR Kuwait Intl Airport - KWT weather data file is used to simulate Kuwaiti climate (Fig. 1) (EnergyPlus 8.0.0 2014). In agreement with this data file, the climate of Kuwait is classified as BWh – Subtropical hot desert (lat. 15-25 ºN) according to the Köppen climate classification. The climate of Kuwait shows unbearably hot dry periods in summer. The warmest week, on average, is in August with an average temperature of 37.85 °C. The maximum temperature during summer can reach 49.7 ºC. The coolest month on average is January, with an average temperature of about 14.76°C during the coldest week. The minimum temperature during winter can reach 2 ºC. Fig. 1a shows the monthly statistics for the evolution of the dry bulb temperatures in Kuwait, and Fig. 1b shows the average hourly statistics for global horizontal solar irradiation during August, where the extreme summer weak is verified. More statistics information about the climate of Kuwait can be found in the KISR Kuwait Intl Airport - KWT weather data file (EnergyPlus 8.0.0 2014).



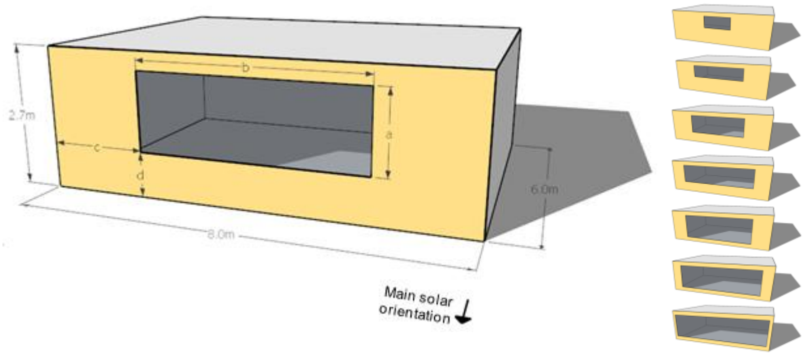
(a) (b)

Fig. 1. (a) Monthly statistics for the evolution of the dry bulb temperatures in Kuwait and (b) average hourly statistics for global horizontal solar irradiation during August (KISR Kuwait Intl Airport - KWT weather data (EnergyPlus 8.0.0 2014)).

Some internal loads and six window-to-wall ratios (WWR) of the main solar oriented window facade are considered in the study. The energy impact of incorporating seven different PCM-wallboards in the model is then evaluated in order to understand whether a single, fully-customized PCM-wallboard solution exists that could be universally used in residential construction in Kuwait. The motivation for searching for a single solution is to benefit from economy of scale effects and to facilitate smooth implementation. A set of discrete variables is considered in the parametric study, namely those related with the thermophysical properties of the PCM (enthalpy-temperature and thermal conductivity-temperature functions) and thickness of the PCM-wallboard. In order to evaluate the influence of the cooling setpoint temperature (T_{th}) of the air-conditioning system in the selection of the fully-customized PCM-wallboard solution, five values of T_{th} are considered in the study.

2.1. Reference model

As shown in Fig. 2, 28 fully air-conditioned single-zone models with seven WWRs facing the four cardinal directions were considered. The interior air volume remains as specified in ASHRAE 140 standard (ANSI/ASHRAE 2004) - interior dimensions of 8 m × 6 m × 2.7 m = 129.6 m^3. The models were assumed to have their windows concentrated on one side to reflect current, relatively dense, deep floor plan residential construction practices in Kuwait in which most spaces only have windows with one orientation. The total floor area of the room is 48 m^2 with a slab-on-grade foundation. All vertical surfaces are considered as external walls. The model is not obstructed by neighboring buildings and the ground reflectance is equal to 0.2. Table 1 shows the specific glazing types for different WWR values in accordance with the requisites of the building energy code of Kuwait (Ministry of Electricity and Water 2010). The different WWRs are obtained by changing the fenestration area as shown in Fig. 2. Table 1 shows that the higher the value of the WWR, the more selective the requirements of the glazing type, with lower *U* and *SHGC* values. This is a way to prevent the boost of cooling energy demand when increasing the fenestration area.



Room - WWR	Window			
	a (m)	b (m)	c (m)	d (m)
R1 - 10%	1.00	2.16	2.92	1.35
R2 - 20%	1.00	4.32	1.84	1.35
R3 - 30%	1.50	4.32	1.84	0.85
R4 - 40%	1.50	5.76	1.12	0.85
R5 - 50%	2.00	5.4	1.3	0.35
R6 - 60%	2.00	6.48	0.76	0.35
R7 - 70%	2.00	7.56	0.22	0.35

Fig. 2. Perspective view of the reference room and window-to-wall ratio layouts of the main solar oriented facade.

Table 1. Different types of glazing for different WWR in accordance with the building energy code of Kuwait (Ministry of Electricity and Water 2010).

WWR (%)	**Glazing type required**	***U*** **(W m^{-2} °C^{-1})**	***SHGC***
10	6-mm double-tinted	3.42	0.360
20	6-mm double-reflective	3.38	0.245
30	6-mm double-reflective	3.38	0.245
40	6-mm double-reflective	3.38	0.245
50	6-mm double-spectrally selective	1.71	0.230
60	6-mm double-spectrally selective	1.71	0.230
70	6-mm double-spectrally selective	1.71	0.230

In their work, (Al-ajmi and Hanby 2008) describe the typical Kuwaiti residential building. According to them, the traditional flat roof is almost universal in Kuwait and the exterior walls are mainly built of two types: autoclaved aerated concrete (AAC) walls and concrete block walls (the so called "classical wall"). The latter type is cheaper (if no insulation is added), widely available, locally produced and structurally stronger than AAC. It is also widely accepted by the buildings industry, and the appropriate-skilled manpower for its construction is available (Al-ajmi and Hanby 2008). The AAC has the advantage of also acting as thermal insulation, but there are few factories producing these blocks locally and their price is higher (Al-ajmi and Hanby 2008). Given these constraints, for the purpose of this study, the classical wall typology will be considered in the simulations. Fig. 3 shows a cross-section of the reference construction elements used and Table 2 lists the thermophysical properties of the underlying materials. The reference U-value for each element is considered equal to the corresponding maximum U-value specified in the regulation (for heavy construction and medium-light external color) (Ministry of Electricity and Water 2010), *i.e.*, 0.568 W m^{-2} $^{o}C^{-1}$ for the walls and 0.397 W m^{-2} $^{o}C^{-1}$ for the roof. Changes in the U-value of the construction elements can be achieved by varying the thickness of the insulation layers $tck_{\mathrm{ins,wall}}$ and $tck_{\mathrm{ins,roof}}$. For the reference rooms, the thickness of the insulation layer is equal to 4.5 cm and 6.0 cm for the wall and roof, respectively. The solar absorption coefficient was about 0.6 for the horizontal outer opaque surfaces, and 0.4 for the vertical surfaces.

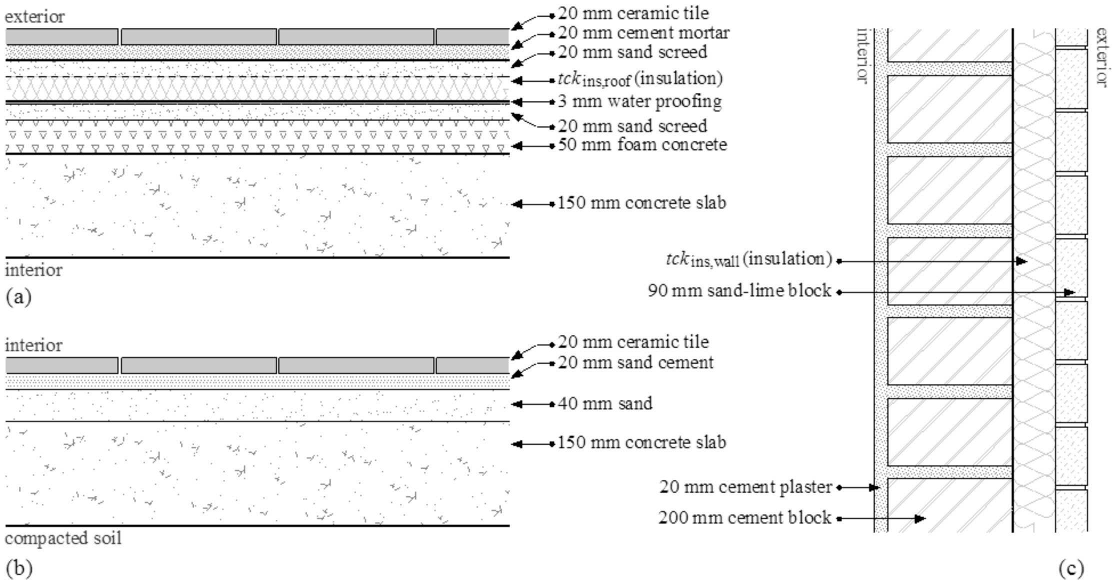


Fig. 3. Cross-section of the construction elements used in the model: (a) roof; (b) floor, and (c) exterior wall (adapted from (Al-ajmi and Hanby 2008)).

Table 2. Thermophysical properties of the construction materials (Al-ajmi and Hanby 2008).

Material	k (W m^{-1} $^{o}C^{-1}$)	c_p (J kg^{-1} K^{-1})	ρ (kg m^{-3})
Sand-lime block	1.310	795	1918
Cement block	1.640	910	2011
Cement plaster	0.944	840	2085
Cement mortar	0.944	840	2085
Concrete slab	1.214	921	2297
Foam concrete	0.210	879	351
Sand cement	0.944	840	2080
Sand screed	0.944	840	2080
Sand	0.337	920	1800
Ceramic tile	1.104	800	2284
Insulation	0.032	1120	30
Water proofing	0.140	1507	934

Regarding internal heat gains, the building model is occupied by a maximum of 4 people in sedentary activity with a constant metabolic rate of about 1.2 met (126 W $person^{-1}$). During the Sunday-Thursday 8am – 4pm weekdays hours, only 1 of the assumed 4 persons occupies the space. During the weekdays and weekends, from 1am to 6am, only 1 person is assumed to occupy the space. The remaining periods are considered at 100% occupancy. A maximum design lighting level of 10 W m^{-2} is considered in the model (Ministry of Electricity and Water 2010). The maximum load of 8 W m^{-2} is considered for equipment. Fig. 4 shows the occupancy, lighting and equipment schedules during the week. The room is air-conditioned considering an *ideal loads air system model* in the *EnergyPlus* simulations. Regarding air temperature control, the thermostat is set with a cooling setpoint temperature of 24 ºC. A ventilation rate of 0.5 air changes per hour is considered in the model (Ministry of Electricity and Water 2010).

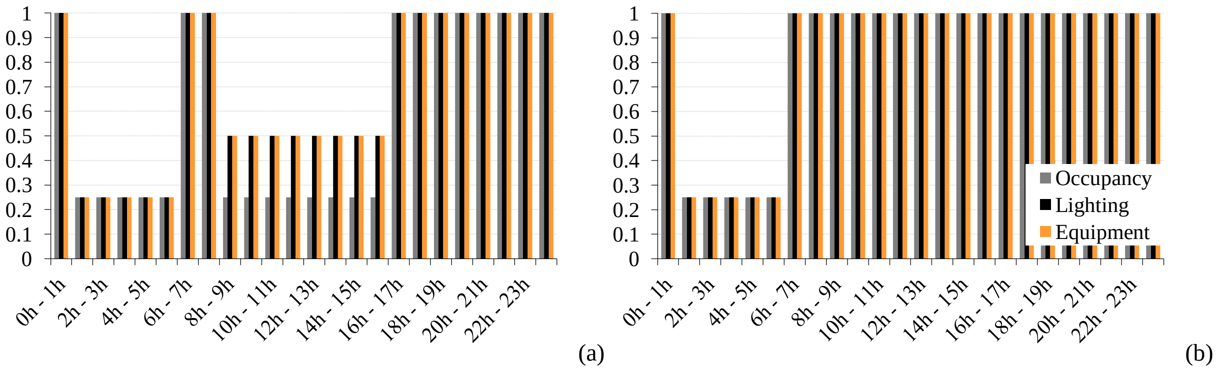


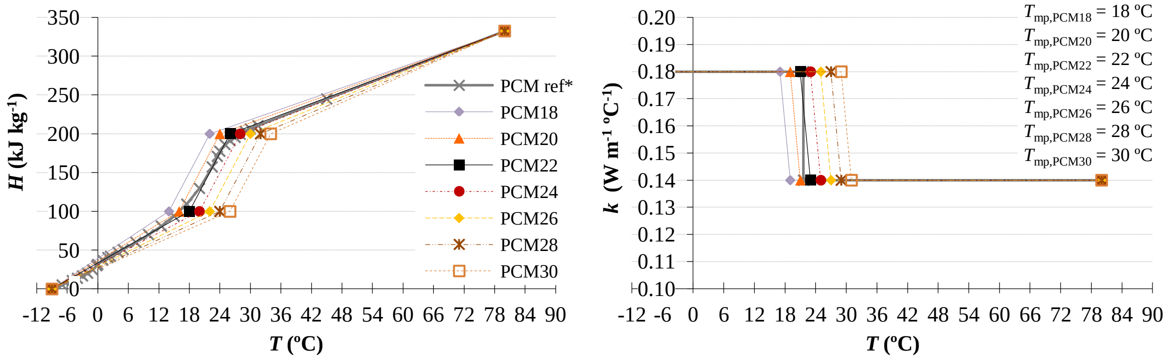
Fig. 4. Occupancy, lighting and equipment schedules during (a) Sunday-Thursday weekdays and (b) Friday-Saturday weekends.

2.2. Problem description and design variables

The monthly and annual cooling energy demands are determined for each reference model without PCM-wallboards and then compared through simulation with the monthly and annual cooling energy demands of the correspondent PCM-enhanced model. The one-dimensional conduction finite-difference (CondFD) solution algorithm, which was validated against multiple test suites (analytical verification, comparative testing, and empirical validation) by (Tabares-Velasco *et al.* 2012) was used in *EnergyPlus* 8.3 to simulate phase-change processes. It is an implicit finite difference scheme coupled with an enthalpy-temperature function to account for phase-change energy accurately. These authors stated that the default CondFD model (Fourier number Fo = 1/3 and space discretization constant c = 3) can be used with acceptable monthly and annual results, but a smaller node space should be used if accurate hourly analysis is required. In this study, the default CondFD model with 20 time steps per hour is used for assessing the monthly and annual cooling energy demand, for both the reference and the PCM-enhanced models. For the hourly analysis, the CondFD model is used with the node space equal to 1/3 of the default value as suggested by (Tabares-Velasco *et al.* 2012). The CondFD model neither simulates hysteresis of the PCM nor does it simulate subcooling during discharging, and only the enthalpy-temperature information for the heating mode is given by the user. Therefore, accuracy issues can arise when modeling PCMs with strong hysteresis or subcooling. For the purpose of this study, the hysteresis and the subcooling phenomena are not considered in the simplified model.

The PCM-enhanced model is attained by including a PCM-wallboard on the inner surface of the walls and ceiling of the reference model. Afterwards, a parametric analysis is carried out by varying the thickness of the PCM-wallboard and the melting-peak temperature of the PCM. In the parametric analysis, all the design solutions are specified as discrete independent variables that can only take predefined discrete values. The DuPontTM Energain® PCM product was considered as the reference PCM-wallboard. This material has a melting temperature range centered around 21.7 ºC, latent heat of 70 kJ kg^{-1}, density of 855 kg m^{-3}, specific heat of 2500 J kg^{-1} K^{-1} and a variable thermal conductivity (Tabares-Velasco *et al.* 2012). As proposed by (Soares *et al.* 2014) and (Tabares-Velasco 2012), based on the nonlinear enthalpy-temperature function of a reference material, a new linear function can be plotted for an hypothetical PCM-wallboard to facilitate the parametric analysis. The new material will have a melting range between 18 and 26 ºC centered around 22 ºC. (Tabares-Velasco 2012) concluded that the annual energy demand is not particularly sensitive to the linearization of the enthalpy-temperature curve. However, for hourly analysis, the simpler linear profiles should be specified in a way that the melting range covers roughly 80% of the latent heat, otherwise, results can differ by up to 20% (Tabares-Velasco 2012).

In this study, further six hypothetical PCM-wallboards with the same latent heat characteristics but with different melting ranges centered at different melting-peak temperatures are defined. Therefore, seven PCM-wallboards with melting-peak temperatures (T_{mp}) of about 18, 20, 22, 24, 26, 28 and 30 ºC are considered in the parametric study. Figs. 5a and 5b show, respectively, the enthalpy-temperature and the thermal conductivity-temperature functions for the reference PCM-wallboard and for the other seven hypothetical materials defined. In the developed model, the thermal conductivity is considered different for the solid and liquid phases but it varies linearly with temperature during phase change (Fig. 5b). The variable thermal conductivity of the reference material was plotted using the information provided by (Tabares-Velasco *et al.* 2012). Afterwards, new 7 evolutions of the thermal conductivity with the variation of temperature were defined as shown in Fig. 5b (one curve for each one of the hypothetical material defined). The thickness of the PCM-wallboard (tck_{PCM}) can be equal to 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 cm. Regarding the combination of all the referred values, a set of 49 predefined discrete solutions can be considered for comparison with the reference model for each orientation of the window and for each WWR considered.



(a) (b)

Fig. 5. (a) Enthalpy-temperature and (b) thermal conductivity-temperature functions for the reference PCM-wallboard and other seven hypothetical materials.*Data for DuPont^{TM} Energain$^{®}$ PCM product obtained from differential scanning calorimeter (DSC) measurements with a heating rate of 0.05 ºC min^{-1} (Cao *et al.* 2010).

3. Results and discussion

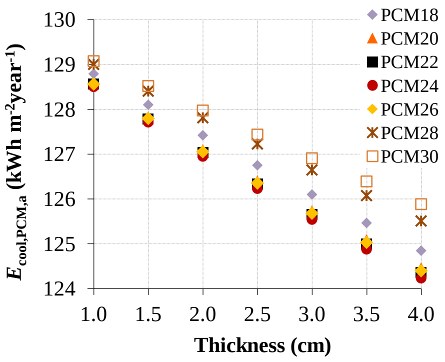
3.1. Annual assessment basis – reference rooms and fully-customized PCM-wallboard solution

The index of annual energy savings for cooling ($IESC_a$) is used for quantifying the reduction of the energy demand for cooling and to evaluate the energy performance of the PCM-enhanced room. It is defined by:

$$IESC_i = 1 - E_{\mathrm{cool,PCM},i} / E_{\mathrm{cool,ref},i} \times 100\% . \tag{1}$$

Subscript i refers to the assessment time period. Subscripts a and m correspond to the annual and monthly assessment basis, respectively. Fig. 6 shows the annual energy demand for cooling for the PCM-enhanced room facing West with WWR = 10% for different melting-peak temperatures and PCM thicknesses. The figure reveals that the best PCM-wallboard for this configuration is the one with T_{mp} = 24 ºC and the highest possible thickness considered, namely 4 cm. For the same PCM-wallboard – PCM24, annual cooling energy savings of about 3.3% can be achieved by changing the thickness of the wallboard from 1 cm to 4 cm. The results obtained in the parametric study by combining different WWR-values and solar orientations were similar to those presented in Fig. 6, *i.e.* the best solution for all the case-studies is the 4 cm thick PCM-wallboard with T_{mp} = 24 ºC. An interesting feature is that the best value of the melting-peak temperature of the PCM is equal to the air-conditioning thermostat setpoint temperature for cooling. For T_{mp} values close to 24 ºC, *i.e.*, 22 ºC and 26 ºC, the results achieved are very similar. For melting-peak temperatures of 28 ºC and 30 º C, and for the same mass of material, the energy required for cooling is higher. The same trend is verified for T_{mp} = 18 ºC.

The EnergyPlus-based simulations show that 4 cm is the optimal thickness for the PCM-wallboard regarding energy savings (Fig. 6). However, in practical applications, it may be a good compromise to adopt 2 cm instead of 4 cm thick as the energy savings achieved with 2 cm are very close to those obtained with 4 cm. This could be particular important if we take into account the cost of the PCM-wallboards, where the thickness of the wallboards may have a strong impact. Moreover, the majority of PCM-wallboards available on the marked have typically small thicknesses because of the low thermal conductivity of PCMs. In practical applications, thinner PCM-wallboards may work better as more PCM material would be involved in the phase change. However, for the purpose of this study, the best 4 cm thick solution regarding energy savings (Fig. 6) will be considered in the next sections.



$T_{mp,PCM18}$ = 18 °C
$T_{mp,PCM20}$ = 20 °C
$T_{mp,PCM22}$ = 22 °C
$T_{mp,PCM24}$ = 24 °C
$T_{mp,PCM26}$ = 26 °C
$T_{mp,PCM28}$ = 28 °C
$T_{mp,PCM30}$ = 30 °C

Fig. 6. Annual cooling energy demand for the PCM-enhanced room with WWR = 10% facing West and T_{th} = 24 °C considering different melting-peak temperatures and PCM-wallboards thicknesses.

Fig. 7 shows the annual energy demand for cooling for all the reference scenarios. As one would expect, the results show that the higher the WWR, the higher the annual energy demand for cooling. When the WWR increases from 10% to 70%, considering the West-oriented room, the annual cooling energy demand increases by 20%. This value is about 16%, 17% and 9%, respectively, for the remaining East, South and North orientations. Windows facing West lead to the highest solar heat gains, while windows facing North receive the least amount of solar radiation, becoming preferable for the climate of Kuwait. It should be noted that the increasingly stringent glazing type specifications required by the Kuwaiti building code (Table 1) (Ministry of Electricity and Water 2010) with growing WWR effectively mitigate the boost in cooling energy demand. If the same 6-mm double-tinted glazing type was used for West-oriented room with a 70% WWR, annual cooling demand would increase by 36% instead of 20% (considering the 6-mm double-spectrally selective glazing type). Fig. 7 shows that the reduction of the annual energy demand for cooling (by incorporating the fully-customized 4 cm thick PCM24-wallboard solution in the reference models) can reach 4% to 5% in all the scenarios (5.5 to 6.6 kWh m^{-2} year^{-1}).

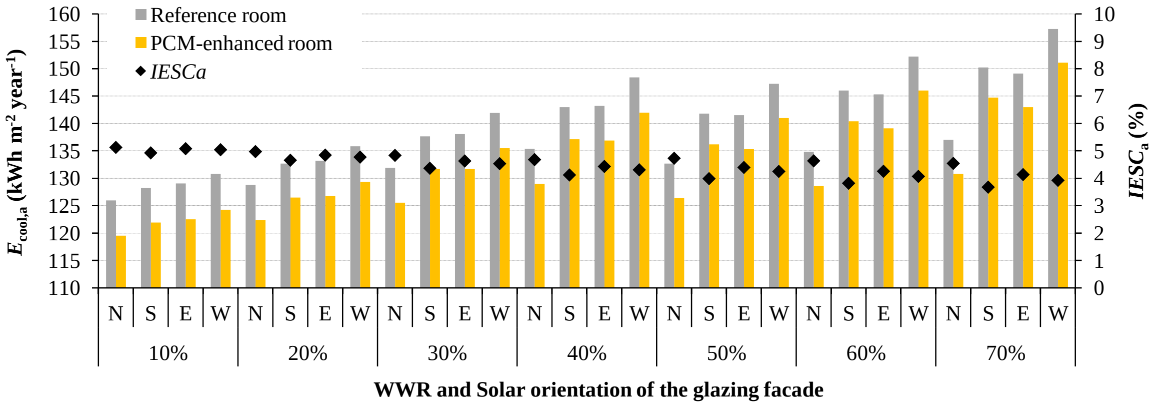


Fig. 7. Annual cooling energy demand for all the reference and PCM-enhanced models considering T_{th} = 24 ºC. Index of annual energy savings for cooling by considering the incorporation of the fully-customized PCM-wallboard solution in the reference rooms.

3.2. Annual assessment basis – impact of the cooling setpoint temperature

The results shown in the previous section may suggest that the best melting-peak temperature of the PCM incorporated in the PCM-wallboard is equal to the imposed cooling setpoint temperature of the air-conditioning system. In order to evaluate the impact of the T_{th}-value on the results, the same analysis carried out in section 3.1 is repeated by considering T_{th} equal to 18, 20, 22 and 26 ºC.

The bullets on the graph of Fig. 8 show the best value of T_{mp} for different values of T_{th} and for all the case-studies evaluated in the parametric study (read the value of $T_{mp,opt}$ on the right axis). Additionally, Fig. 8 shows the absolute annual energy savings for cooling (read on the left axis) by incorporating the best PCM-wallboard solution for each scenario (with T_{mp} = $T_{mp,opt}$) in the simulations. Therefore, the absolute annual energy savings for cooling are presented as a function of the orientation of the window and the values of WWR and T_{th}. Results show that for T_{th} = 26 ºC, the best melting-peak temperature of the PCM is also equal to T_{th}. However, for T_{th} = 18 ºC and 20 ºC, the best values of T_{mp} are 20 ºC and 22 ºC, respectively. Generally speaking, for T_{th} = 22 ºC, the best T_{mp} is 22 ºC for lower values of WWR and 24 ºC for higher values of the same parameter. These results can be used as guidelines for the incorporation of PCM-wallboards in Kuwait.

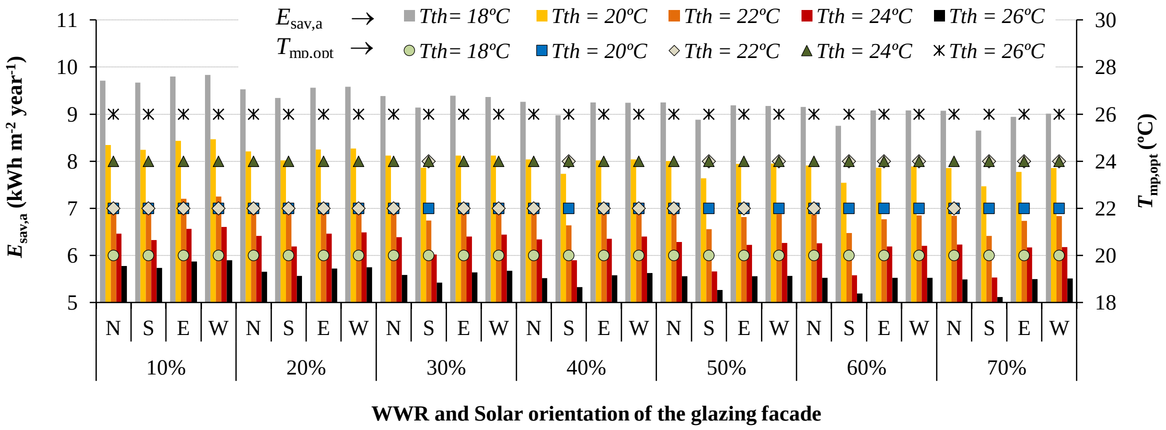


Fig. 8. Best value of T_{mp} for different values of T_{th} and for all the case-studies investigated in the parametric analysis (read the value of $T_{mp,opt}$ on the right axis). Annual absolute cooling energy savings (read on the left axis) by incorporating the best PCM-wallboard solution for each scenario (with $T_{mp} = T_{mp,opt}$) in the simulations.

Regarding the annual cooling savings by incorporating PCM-wallboards in the model, Fig. 8 shows that, in absolute terms, the lower the value of T_{th}, the higher the energy savings. However, in relative terms, *i.e.*, by evaluating the *IESC*a values, the lower the value of T_{th}, the lower the relative cooling energy savings as shown in Fig. 9. This is caused by the fact that the reference energy demand for cooling is higher for lower values of T_{th}. Therefore, a setpoint temperature of the air-conditioning system close to 22–24 ºC can be a good compromise for reducing the energy consumption for cooling in Kuwait. In the next sections, the cooling setpoint temperature will be considered fixed at 24 ºC as described in section 2.1.

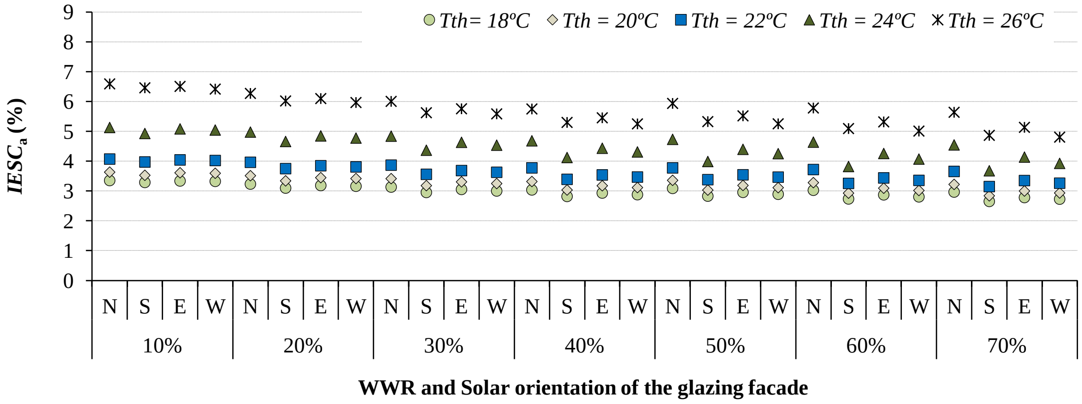


Fig. 9. Index of annual energy savings for cooling for all the case-studies investigated in the parametric study by considering the incorporation of the best PCM-wallboard solution for each scenario (with $T_{mp} = T_{mp,opt}$) in the simulations.

3.3. Annual assessment basis – Economic assessment

In this section, the economic viability of the incorporation of PCM-wallboards in Kuwait is discussed. The nominal annual savings of useful energy for cooling after the incorporation of the best PCM-wallboard solution in each simulated scenario will be used to estimate the payback period of the PCM-enhanced solution. In the economic assessment, only the initial cost of the PCM-wallboard technology is considered. The costs related to the application and maintenance of the PCM-enhanced boards are not considered in the study.

The cost of a specific PCM-wallboard solution, with certain thermophysical properties and thickness, is difficult to estimate, as the solution may not be available on the market. However, the effort to predict the payback period of a specific PCM-wallboard solution for the climate of Kuwait can be seen as a good approach to foster the implementation of the technology in the country. Table 3 shows the price of some ordinary and PCM-enhanced wallboards available on the market. It can be seen that the price of the wallboards depends on their thickness and the proportion of incorporated PCMs. It can also be estimated that, PCM-wallboards can be 5-16 times more expensive than ordinary wallboards, which is in accordance with literature (Fraser 2009).

Table 3. Price of some ordinary and PCM-enhanced wallboards available on the market.

	Product	**Thickness (mm)**	**Price (€/m^2)**	**Source**
PCM-wallboards	Dupont^{TM} Energain$^{®}$	6	69.00	(Fraser 2009)
	Datum phase change F.E.S-Board$^{®}$	25	35 - 104 *Depending on the proportion of PCM in the board*	(Rae 2014; Pullen 2012)
Ordinary drywalls	Gyptec Ibérica BA 6 A	6	5.03	(Gyptec Ibérica 2016)
	Gyptec Ibérica BA 10 A	10	3.51	(Gyptec Ibérica 2016)
	Gyptec Ibérica BA 13 A	12.5	3.25	(Gyptec Ibérica 2016)

For the purpose of this study, a hypothetical price of 140 €/m^2 will be considered for the fully-customized 4 cm thick PCM24-wallboard solution. Regarding utility charges in Kuwait, the cost of electricity is about ≈0.11 €/kWh (Ministry of Electricity and Water). However, it should be pointed out that this cost is highly subsidized and the building owners only pay ≈0.01 €/kWh (flat fixed rate). Considering the cost of electricity of about 0.11 €/kWh and the energy savings for cooling due to the incorporation of PCM-wallboards in the model, for an Energy Efficiency Ratio (EER) of the cooling system of 2, the estimated payback period for the incorporation of the 4 cm thick PCM24-wallboard solution in all the scenarios is higher than the lifespan period of the building (>50 years). These results suggest that under current economic conditions in Kuwait, PCM-wallboards are not economically viable for heavyweight construction. The reasons for this finding are the remarkably low subsidized price of electricity along with an already high thermal mass construction standard that benefits less from adding PCMs.

3.4. Monthly assessment basis

In this section, the impact of the fully-customized 4 cm thick PCM24-wallboard solution on the energy demand throughout the year is investigated. Figs. 10a and 10b show the monthly cooling energy demand for both the reference and the PCM-enhanced models with WWR = 10% and 70%, respectively. The same trends were verified for the remaining five scenarios investigated in the parametric study. Fig. 10 shows that the cooling demand is naturally higher during the summer months. During this period, the relative monthly energy savings for cooling due to PCMs can reach 5% to 7% (read the value of $IESC_m$ on the right axis). Therefore, it can be seen that PCMs may be relevant as a means to the summer cooling peaks. Another interesting feature is that the energy demand for cooling during the winter months increases by incorporating PCM-wallboards in the model ($IESC_m$ presents negative values). However, the absolute amount of energy required for cooling during the cold months is practically negligible when compared with the summer period. Fig. 11 summarizes the reduction of the monthly cooling load during the month with the highest average cooling load for each case-study evaluated. The results show that the monthly cooling loads can be reduced by 5% to 6% in all the scenarios.

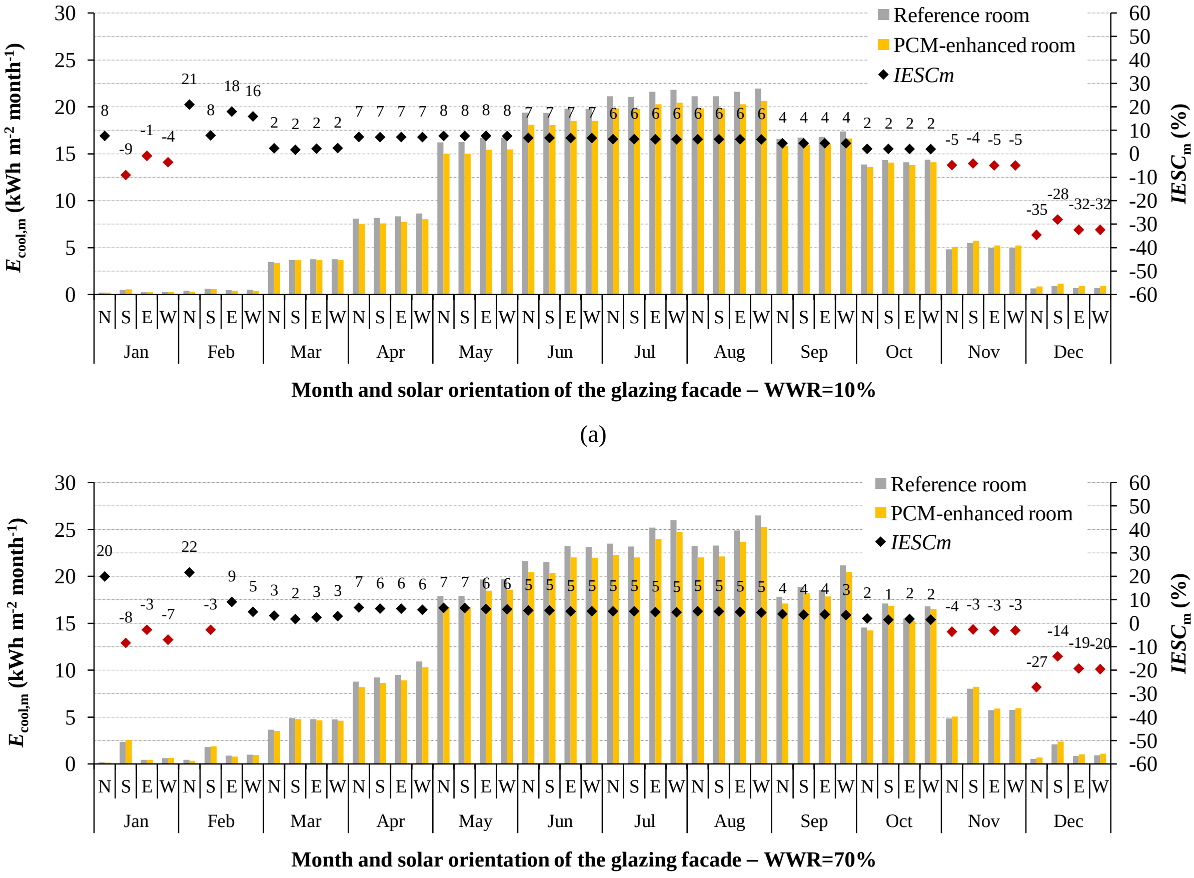


Fig. 10. Monthly cooling energy demand for both the reference and the PCM-enhanced rooms with (a) WWR = 10%, and (b) WWR = 70%. Index of monthly energy savings for cooling considering the incorporation of the 4 cm thick PCM24-wallboard solution in the model and T_{th} = 24 ºC.

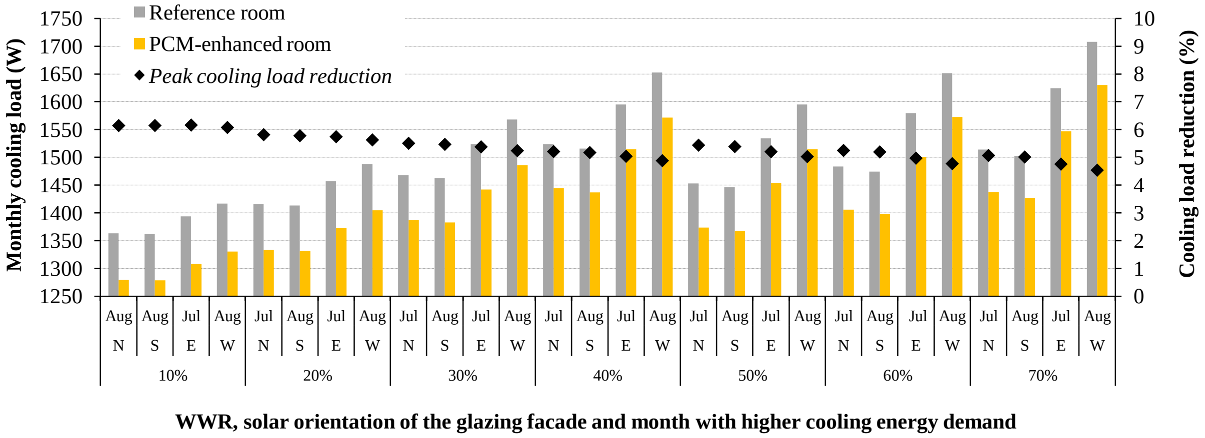


Fig. 11. Reduction of the monthly cooling load during the month with the highest average cooling load for all the case-studies considering T_{th} = 24 ºC.

3.5. Daily assessment basis

As it was remarked in the introduction section, the summer cooling peak hours are problematic in Kuwait, with the danger of recurring electricity blackouts during this period. In this section, the impact of incorporating the fully-customized 4 cm thick PCM24-wallboard solution in the model is investigated in a daily assessment basis. The final idea is to evaluate how the incorporation of PCM-wallboards influences the thermal performance of the model if the air-conditioning system was turned off during the summer peak hours. The hourly evolution of the indoor air temperature (T_a), mean radiant temperature (T_{mr}) and operative temperature (T_o) will also be evaluated for the day with the highest average daily cooling load - the 5th of August. Fig. 12 summarizes the reduction of the average daily cooling load for all the case-studies (5% to 8%) for this day. The results show that the average daily cooling load can be reduced by 107 to 131 W.

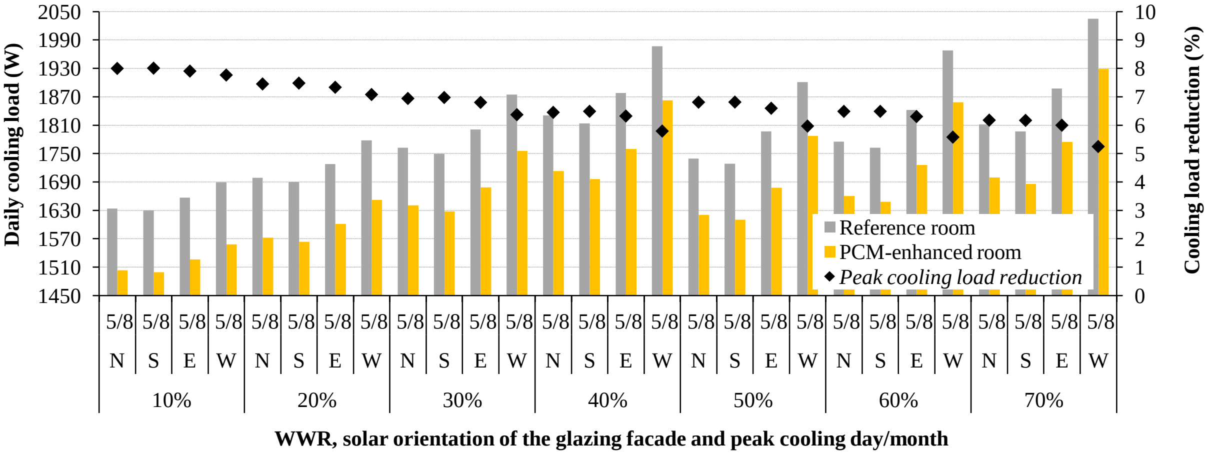


Fig. 12. Reduction of the average daily cooling load for the 5th of August, for all the case-studies evaluated and by considering T_{th} = 24 ºC.

Fig. 13 shows the cooling profiles in an hourly assessment basis for the cooling peak day, for both the reference and the PCM-enhanced models with WWR = 10% and 70%, respectively. The evolutions of T_a, T_{mr} and T_o are also shown. The results show that the maximum cooling load of ≈3300 W is estimated for the West-oriented model with WWR = 70%, between 6pm and 7pm. The incorporation of the fully-customized 4 cm thick PCM24-wallboard solution reduces the cooling load profiles for all the scenarios. An exception is the West-oriented room with WWR = 70%, where PCMs can increase the cooling loads during the peak hours.

Many times, the daily cooling profiles are simulated considering the PCMs completely discharged at the beginning of the day. In these cases, the reduction of the cooling loads is higher (with a significant delay of the peak hour) because more volume of PCM will be melted during the day and more latent heat will be stored. However, in real applications, mainly during the severe summer conditions of Kuwait, the PCM can be completely melted at the beginning of the summer peak day-cycle, which reduces the PCM capacity for latent heat storage. Moreover, large West-oriented windows are a major source of solar heat gains during the last sun-hours of the day, a period when the internal heat gains from occupancy, lighting and equipments also increase. Consequently, there is a boost in the energy demand for cooling, with no help from the latent heat loads from PCMs' phase-change processes, as they are completely melted at this time. In the East oriented rooms, a cooling peak is observed during the morning, which is caused by the morning solar heat gains and by the internal heat gains during these hours. Generally speaking, the cooling peak-loads are observed during the summer electricity demand peak hours, from 2pm to 4pm, which is problematic for the management of the energy supply in Kuwait.

Regarding the evolution of the temperature profiles during the cooling peak day, it is interesting to observe that T_{mr} is reduced by almost 1 ºC in most cases due to the incorporation of PCMs. Consequently, T_o is also reduced. As this temperature can be used for the thermal comfort analysis, it is expected that the incorporation of PCM-wallboards contributes to increase indoor thermal comfort.

Fig. 14 shows the cooling loads and temperatures profiles for the same scenarios presented in Fig. 13 considering that the cooling system is turned off from 2pm to 4pm. For these *EnergyPlus* simulations, a maximum total cooling capacity of 3500 W was imposed in the *ideal loads air system model*. The results show that T_a rises above 30 ºC in all the rooms when the cooling system is turned off. For larger glazing areas, the indoor air temperature will be higher in the PCM-enhanced rooms. Moreover, when the system is turned on again at 4pm, the cooling loads are higher for the rooms with PCM-wallboards. When the indoor temperature is lowered by the air-conditioning, the PCMs will start discharging some sensible heat indoors and more energy will be required for cooling. Another important feature is that, during the cooling cut period, both T_{mr} and T_o will be higher in the models with PCM-wallboards.

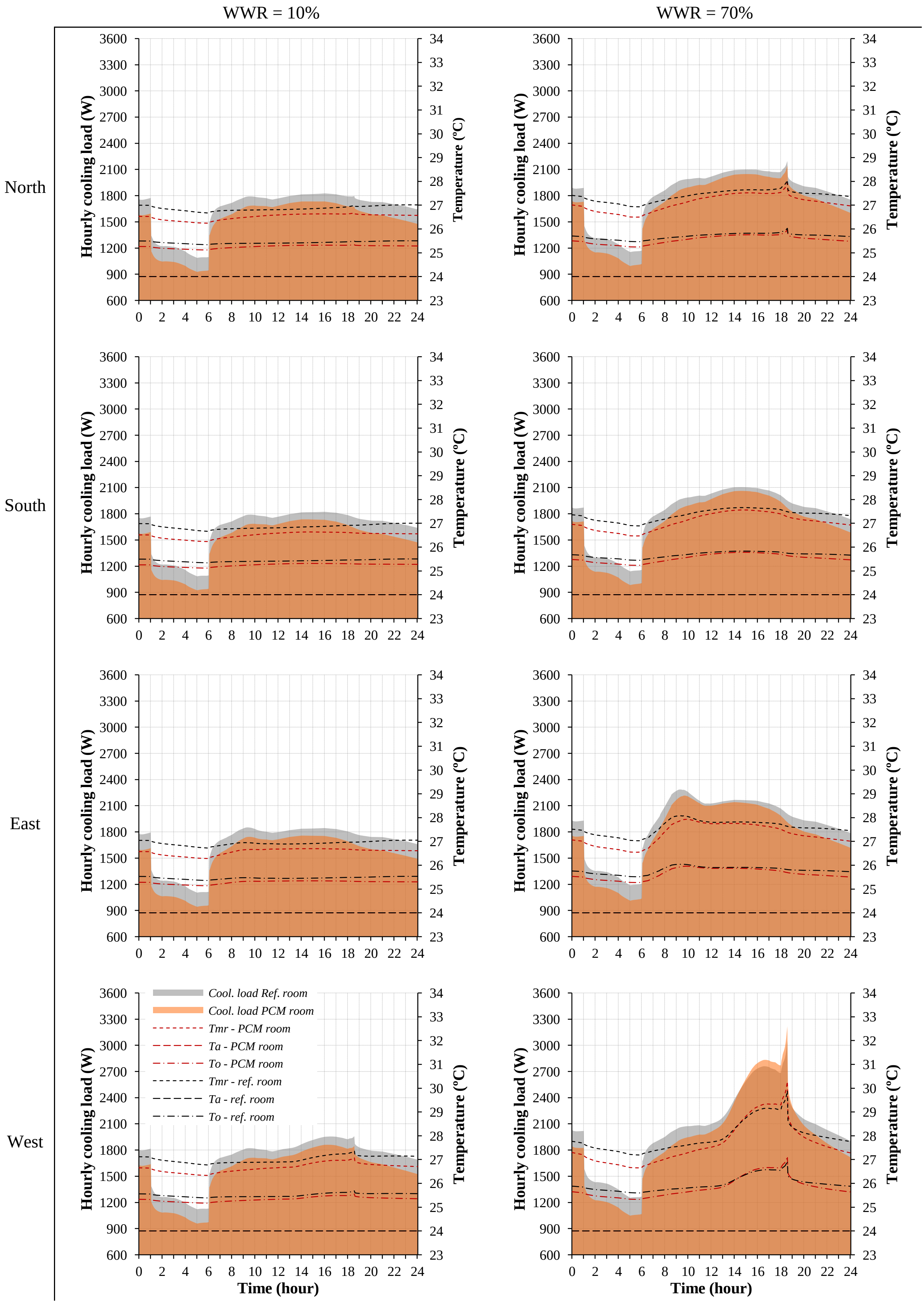


Fig. 13. Hourly cooling load profiles and evolution of the estimated temperatures for the cooling peak day (5th of August) for both the reference and the PCM-enhanced models with WWR = 10% and 70%. T_{th} = 24 ºC.

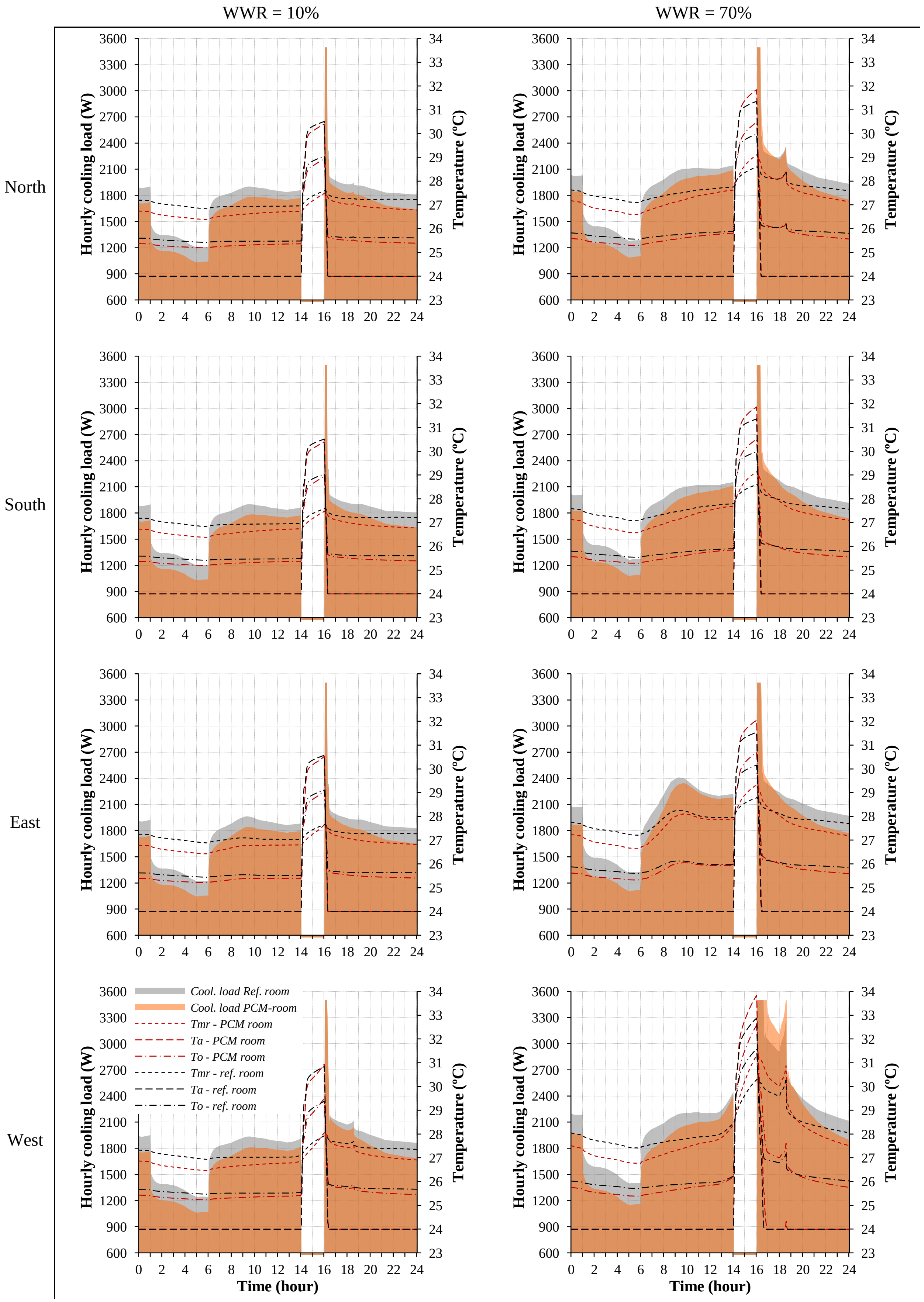


Fig. 14. Hourly cooling load profiles and evolution of the estimated temperatures for the cooling peak day (5th of August) for both the reference and the PCM-enhanced models with WWR = 10% and 70%. Cooling system turned off from 2pm to 4pm and T_{th} = 24 ºC.

The results depicted in Figs. 14 and 14 also show that the incorporation of PCM-wallboards in Kuwait can be used to reduce the hourly cooling loads when the cooling system is operating continuously. On the other hands, if the cooling system stops working during the problematic summer peak hours, the inclusion of PCM-wallboards can have a negative impact, as it may increase the indoor air temperature. As explained before, the PCM volume is already melted at this point, and no extra latent heat storage capacity exists to contribute for reducing the rise of the indoor temperature.

4. Conclusion

This extensive EnergyPlus based parametric simulation study found that introducing PCM-wallboards in low-rise residential heavyweight construction in Kuwait generally helps to create nominal annual savings of useful energy for cooling and peak-loads reductions in the order of 5%. Assuming that the majority of residential households in Kuwait will select setpoint temperatures between 22–26 ºC, a custom universal PCM-wallboard system with a thickness of 4 cm and a melting peak temperature of the PCM of 24 ºC is recommend for new construction in Kuwait. PCM-wallboards in Kuwait only reduce the hourly cooling loads if the cooling system operates continuously. However, if the cooling system stops working during the summer peak hours due to a blackout, the incorporation of PCM-wallboards may have a negative impact. Given current retail costs of electricity in Kuwait, PCM-wallboards are not economically attractive for use in air-conditioned heavyweight residential buildings.

The overall methodology proposed herein was focused on a single-zone room model. Hence, the results cannot be directly extrapolated and generalized to more complex models. Further work should be done to apply the presented methodology to more complex buildings and other sorts of construction (*e.g.* lightweight construction). Moreover, the output of this paper cannot be generalized to high-rise residential buildings nor to low/high-rise commercial buildings in Kuwait, because the internal loads, solar gains, occupation schedules, construction type, etc., would be significantly different from those considered to low-rise heavyweight residential buildings.

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
E	energy (kWh m^{-2})
E_{cool}	energy demand for cooling (kWh m^{-2})
E_{sav}	cooling energy savings (kWh m^{-2})
H	enthalpy (kJ kg^{-1})
$IESC$	index of energy savings for cooling (%)
k	thermal conductivity (W m^{-1} ºC^{-1})
PCM	phase change material
$SHGC$	solar heat gain coefficient
T	temperature (ºC)
T_{a}	indoor air temperature (ºC)
T_{mp}	melting-peak temperature of the PCM (ºC)
T_{mr}	mean radiant temperature (ºC)
T_{o}	operative temperature (ºC)
T_{th}	cooling thermostat setpoint temperature of the air-conditioning system (ºC)
$tck_{\mathrm{ins,roof}}$	thickness of the insulation layer of the roof (cm)
$tck_{\mathrm{ins,wall}}$	thickness of the insulation layer of the wall (cm)
tck_{PCM}	thickness of the PCM-wallboard (cm)
U	coefficient of heat transfer (W m^{-2} ºC^{-1})
WWR	window-to-wall ratio
ρ	density (kg m^{-3})

Subscripts

a, m	annual and monthly assessment basis
m	monthly assessment basis
opt	optimum value
PCM	PCM-enhanced room
ref	reference room

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