PROCENA POTENCIJALA ZA UŠTEDU ENERGIJE U FPM INTEGRISANOM OSUNČANOM PROSTORU

ASSESSMENT OF ENERGY-SAVING POTENTIAL OF A PCM INTEGRATED SUNSPACE

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Sunčevi prostori su jednostavne, ali efikasne pasivne solarne tehnike za poboljšanje energetske efikasnosti zgrada. Njihovi potencijali za uštedu energije zavise od različitih faktora kao što su klimatski uslovi lokacije, tip zastakljivanja, dimenzije, senčenje i kapacitet skladištenja toplote. U ovom kontekstu, istražuje se uticaj korišćenja materijala za promenu faze (PCM) kao sistema za skladištenje toplotne energije unutar pregradnog zida između sunčanog prostora i samostojeće kuće u Istanbulu na opterećenje kao i na opterećenje hlađenja. Tokom analize razmatraju se različite konfiguracije sunčevog prostora, koje uključuju tri različite dubine sunčevog prostora, šest različitih tipova zastakljivanja, uključivanje/isključivanje aktivnih uređaja za senčenje i implementaciju PCM-a unutar pregradnog zida. Dobijeni rezultati su upoređeni sa referentnim slučajem da bi se otkrio energetski najefikasniji dizajn Sunčevog prostora-PCM sistema. Pošto su optimalne konfiguracije različite u zavisnosti od sezone grejanja i hlađenja, takođe se sprovodi godišnja tranziciona optimizacija. Prema rezultatima, implementacija PCM-a u pregradni zid dovodi do veće energetske efikasnosti u poređenju sa referentnom kućom, osim u nekim posebnim slučajevima, koji izazivaju nedostatke. Osim toga, iako se razmatraju različite temperature promene faza za grejne i rashladne sezone, utvrđeno je da su njihovi uticaji na potencijal uštede energije skoro isti za klimatske uslove u Istanbulu.

Ključne reči: *sunčevi prostori; fazno promenljivi materijal; toplotno i rashladno opterećenje; energetska efikasnost; ušteda energije*

Sunspaces are simple yet effective passive solar techniques to improve the energy efficiency of buildings. Their energy-saving potentials are dependent on various factors such as climatic conditions of the site, glazing type, dimensions, shading, and thermal storage capacity. In this context, the impact of phase change material (PCM) utilization as a thermal energy storage system within the partition wall between the sunspace and the detached house in Istanbul on the heating as well as cooling loads is investigated. Throughout the analysis, various sunspace configurations are considered, which include three different sunspace depths, six different glazing types, inclusion/exclusion of active shading devices, and implementation of the PCM inside the partition wall. The obtained results are compared with the reference case to reveal the most energy-efficient design of the sunspace-PCM system. Since the optimum configurations are different depending upon heating and cooling seasons, an annual transient optimization is also conducted. According to the outcomes, implementation of the PCM in the partition wall results in higher energy efficiency compared to the reference house except in some particular cases, which cause disadvantages. Besides, although different phase change temperatures for heating and cooling seasons are considered, it is found that their influences on the energy-saving potential are nearly the same for the climate conditions in Istanbul.

Key words: *sunspace; phase change material; heating and cooling load; energy efficiency; energy saving*

1 Introduction

With the increase in energy prices and global warming, researchers around the globe put a significant effort to find solutions for reducing energy usage and greenhouse gas emissions. To solidify

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this effort, member countries of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in December 2015. According to the Paris Agreement, the increase in the global average temperature should be kept under 2°C and limited to 1.5°C since this would significantly reduce the risks and impacts of climate change [1]. To reach this goal, different solutions are proposed such as converting current energy plants to renewable energy plants, reducing heat transfer from building fabrics, utilizing environment-friendly sources for energy production, and storing excess heat for later use [2,3]. For the energy concerns, reducing building energy consumption plays a significant role as it is responsible for around 40% of end-user energy consumption [4]. For this purpose, sunspaces are considered one of the feasible alternatives that take advantage of solar energy in building heating [5]. During the day, the air inside the sunspace is heated due to solar energy and stored in building fabrics. Later, the stored heat can be used to provide passive or active heating/cooling depending on the design of the sunspace. To further improve the heating/cooling effectiveness of the sunspace, phase change materials (PCM) can be used because of their high latent heat capacities, which allows effective energy storage, particularly in cases of using intermittent energy sources such as solar energy [6].

In recent years, a lot of efforts have been put into sunspace utilization in buildings, and many studies are conducted to reveal their effects on the indoor thermal environment. For instance, López et al. [7] studied an attached sunspace utilization with a floor layer of sand in the intermediate. The floor sand layer was used to create thermal inertia in the sunspace. It was found that the temperature of the sand is usually higher than the interior air and has a higher heat transfer during spring, autumn, and winter whereas lower heat transfer in summer. Also, they stated that most of the heat storage and heat release, i.e. heat transfer, occurs at the top 10 cm of the sand layer. Another study carried out by López et al. [8] investigated the thermal inertia utilization of sunspace considering two different cases: energy storage during the day or the night. It was found that thermal inertia has a significant effect on energy collection and it enabled the collection of energy during the night. Besides, energy storage during the night was limited, and this issue can be solved by storing energy during the day also. Dušan et al. [9] investigated the application of the sunspace as a method of improving living conditions as well as energy performance with various design options and technical characteristics. They found that even though sunspace affected only 2 - 3% of the overall energy requirement of the whole building, it reduced the energy usage of the room that was attached by 8 - 11%. Monge-Barrio and Sánchez-Ostiz [10] studied the impact of sunspace utilization on energy usage in Pamplona, Spain. It was found that sunspace has a favorable impact on energy efficiency in both summer and winter seasons and their design must take into account all-year-round climate conditions. In another study, Kırmızı [11] found that temperatures in/around the sunspaces have achieved the highest temperatures compared to the other locations in the room and they are significantly affected by the outside air temperature fluctuations. Vukadinović et al. [12] analyzed a detached residential building with a sunspace integrated with a thermal storage wall which consisted of a concrete layer. This wall was also supported with a PCM layer, and three different positions were tested, i.e. near the exterior, near the interior, and middle. The building energy consumption was tracked for five cities located in regions with various climate conditions. The study revealed that the PCM provided advantages as thermal inertia, and it was suggested to use the PCM at the mid-wall position since it showed the best thermal performance compared to other cases. Ma et al. [13] showed that the integration of sunspace with a single pane window into a rural building has a significant effect on reducing energy consumption in cold climates. They also found that with the use of a double-pane window, the energy-saving rate can be incremented by nearly two folds. A sunspace louver with or without PCM was studied by Li et al. [14], and it was revealed that the PCM integration into sunspace louver can be both beneficial or harmful in the heating season depending on the internal design temperature. It was stated that 18°C internal design temperature was advantageous while 16°C or lower design temperatures have drawbacks. Moreover, the sunspace louver without PCM resulted in a nearly 23% reduction in energy-saving whereas this saving can be enhanced by 5.3% with the addition of PCM. In this study, the building modeled and analyzed to find out the sunspace effectiveness in the previous work of the authors [15] is considered to further improve the useful impact of the sunspace with PCM utilization in the present work. The partition wall adjacent to the sunspace is integrated with an additional PCM layer to investigate the effect of the PCM inclusion on the cooling and heating loads.

2 Methodology

A detached family house located in Istanbul was taken as a reference house and analyses for both heating and cooling energy usage were conducted. The data for outdoor weather conditions were taken from the Istanbul Ataturk Airport Weather Tower (WMO 170600), and the indoor air conditions were chosen based on the UK NCM Standards. The annual heating and cooling loads for the sunspace without PCM and the reference house, which has no sunspace, are taken from the previous study [15]. To analyze the effect of the PCM integration, a 75 mm PCM block with 23°C phase change temperature was added to the partition wall between the sunspace and the living room. The properties of the partition wall considered with PCM and without PCM are shown in Table 1 and Table 3, respectively. Since the PCM has different properties for solid and liquid phases, these properties are shown in Table 2. The U-values and thermophysical properties of windows are shown in Table 4 and Table 5, respectively.

Table 1: Properties of the Partition Wall with PCM

	Layer 1 (Outermost)	*Layer 2*	*Layer 3*	*Layer 4*	*Layer 5 (Inner-most)*
Construction Material	Gypsum Plastering	Dense Concrete	BioPCM M182/Q23	Dense Concrete	Gypsum Plastering
Thickness	5 mm	12.5 mm	75 mm	12.5 mm	5 mm
Thermal conductivity	1.2 W/m·K	1.4 W/m·K	See Table 2	1.4 W/m·K	1.2 W/m·K
Density	2100 kg/m³	2100 kg/m³	See Table 2	2100 kg/m³	2100 kg/m³
Specific heat	1000 J/kg·K	840 J/kg·K	See Table 2	840 J/kg·K	1000 J/kg·K

Table 2: Properties of the PCM Layer

	Solid State	*Liquid State*
Melting temperature	20°C	-
Freezing temperature	-	23°C
Thermal conductivity	1.8 W/m·K	1.5 W/m·K
Density	2300 kg/m³	2200 kg/m³
Specific heat	2000 J/kg.K	2000 J/kg.K

Table 3: Properties of the Partition Wall without PCM

	Layer 1 (Outermost)	*Layer 2*	*Layer 3 (Inner-most)*
Construction Material	Gypsum Plastering	Dense Concrete	Gypsum Plastering
Thickness	5 mm	100 mm	5 mm
Thermal conductivity	1.2 W/m·K	1.4 W/m·K	1.2 W/m·K
Density	2100 kg/m	2100 kg/m³	2100 kg/m
Specific Heat	1000 J/kg·K	840 J/kg·K	1000 J/kg·K

Table 4: U Values of Construction Materials

Construction Type	*U Value (W/m².K)*
Outer Wall	0.543
Internal Partition	1.923
Sunspace Partition (Without PCM)	2.943
Sunspace Partition (With PCM)	Variable
Flat Roof	0.25
Ground Floor	0.253
External Door	5.429

Table 5: Window Types

Window Type	*Glass Thickness*	*Air Gap Thickness*	*SHGC Value*	*U Value (W/m²·K)*
Single Clear Glass	6 mm	-	0.81	6.121
Double Clear Glass	6 mm	13 mm	0.697	2.708
Triple Clear Glass	3 mm	13 mm	0.678	1.778
Custom Glass 1	Custom		0.95	6.121
Custom Glass 2	Custom		0.35	6.121
Custom Glass 3	Custom		0.81	2

To use the previously obtained results for the reference cases, all of the properties, design conditions, building materials, and equipment were taken as the same as those of the previous study. The sunspace depths are 0.75m, 1m, and 1.25m. Since the effectiveness of the PCM cannot be determined with steady-state analysis, only transient analysis was conducted. Besides, to find the effectiveness of the PCM, an economic analysis was performed. The Seasonal Energy Efficiency Rating (SEER) and the Seasonal Coefficient of Performance (SCOP) of the heat pump are taken as 4.4 and 3.8, respectively. The considered floor plans and internal design conditions can be seen in Figure 1 along with the 3D representation of the house depicted in Figure 2.

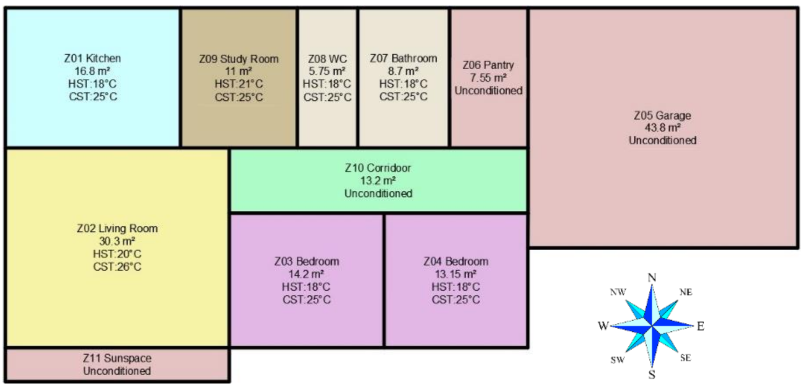

Figure 1: Floor plans and Design Temperatures

Figure 2: 3D Presentation of the House with Sunspace

3 Results and Discussions

It should be noted before presenting the analysis results that a noticeable variety of sunspace structures have been analyzed for energy-saving characteristics. Hence, a systematic abbreviation is developed to express the features of the sunspace structures for the potential readers. Here, for instance, 1.25SS-C2-WS indicates the sunspace with 1.25 m width (1.25SS) having Custom-2 type glazing (C2) with a shading device (WS).

Annual heating and cooling energy requirements for different sunspace widths are shown in Figures 3, 4, 5, and Figures 6, 7, 8, respectively. As seen from the figures, with the addition of the PCM layer, almost all cases showed improvements in heating and cooling energy requirements, i.e., the PCM utilization reduced the required heating and cooling loads. However, only the case 1.25SS-C2-WS resulted in a marginally negative impact on annual cooling when integrated with PCM, compared to the case without PCM utilization.

It is seen from the figures that the addition of the PCM remarkably enhanced the thermal performance of the sunspace along with the same thermal behavior trend, yet with the improved quantitative results. Furthermore, the order of this improvement depends on the structure of the sunspace. The highest augmentation was achieved by 1.25SS-C3-WOS with a 9.91% improvement whereas the lowest one was exhibited by the case of 1SS-C2-WS with a 2.63% improvement, each compared to their equivalent case without using PCM. It can be noticed that the addition of the PCM was most beneficial when there was no active shading system which means that the addition of the PCM was a useful technique to prevent overheating.

To compare the annual economic improvements achieved by PCM utilization, the heat pump was considered. For the electricity price, 0.3797 ₺/kWh was considered, and energy prices required for annual heating and cooling were calculated where the outcomes are presented in Figure 8. As it is seen from the figure, all of the cases gave better annual results with the PCM addition. However, even though all of the cases showed improvements compared to the sunspaces without PCM, 1SS-C3-WOS with PCM showed worse results than the reference case. Considering the economic impacts of the proposed sunspace structure with PCM, it can be noted that the overall energy price was reduced by 16.52% by the integration of PCM for the best-case scenario, while increased by 0.75% for the worst-case scenario, compared to the reference house. These scenarios were observed for cases 1SS-C2-WS and 1SS-C3-WOS, respectively.

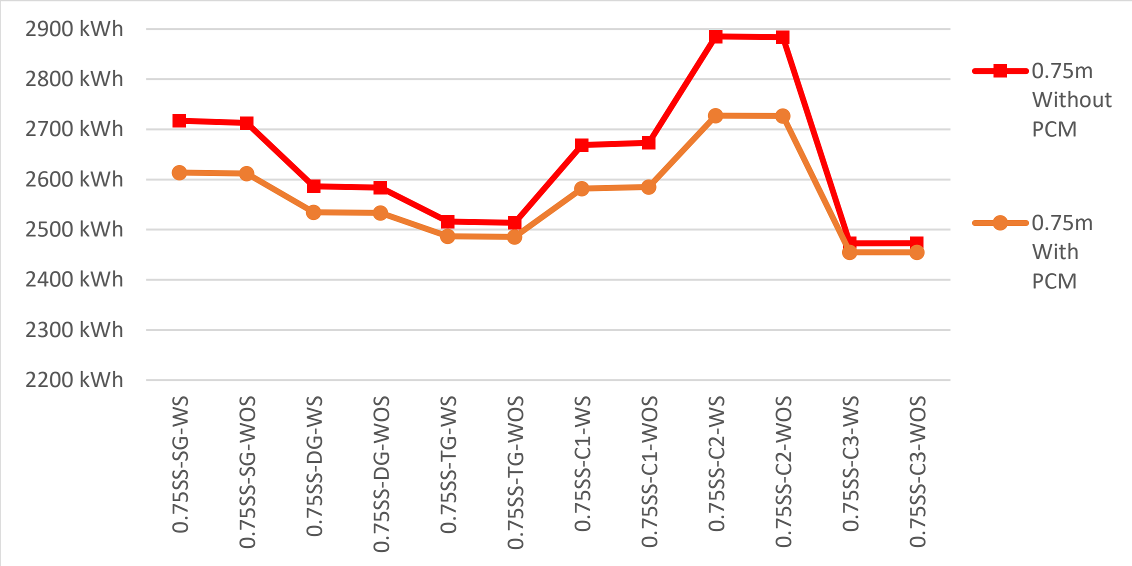

Figure 3: Annual Heating Requirements for 0.75m Sunspaces

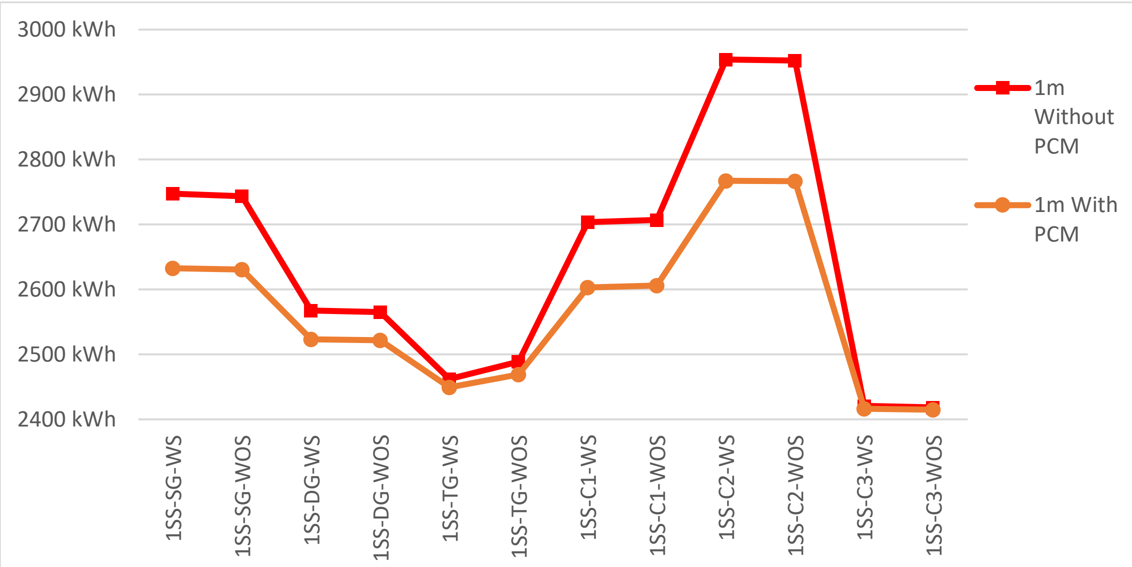

Figure 4: Annual Heating Requirements for 1m Sunspaces

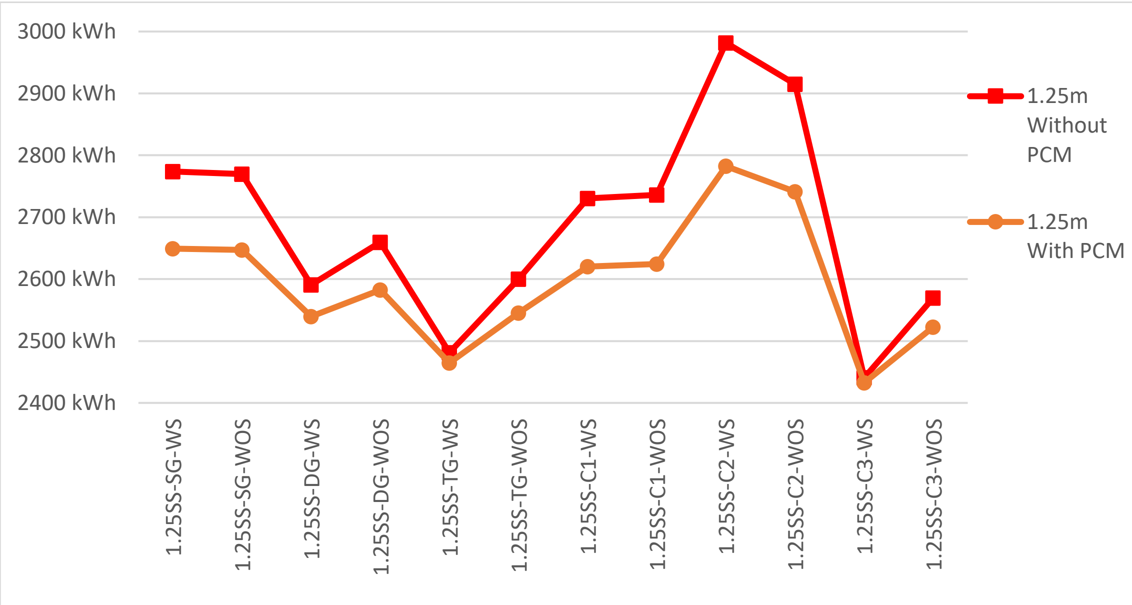

Figure 5: Annual Heating Requirements for 1.25m Sunspaces

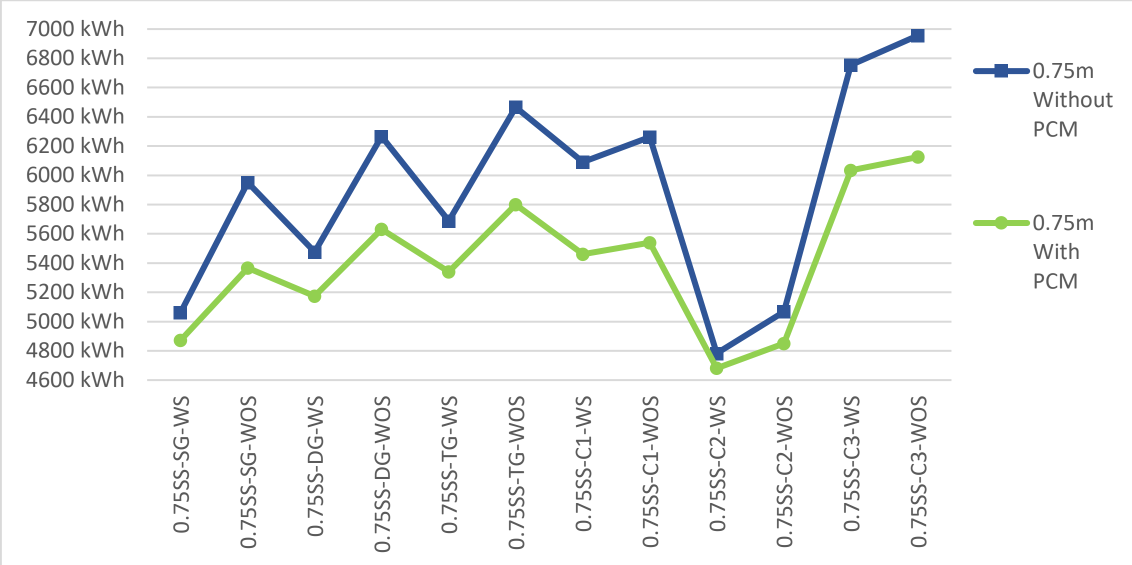

Figure 6: Annual Cooling Requirements for 1.25m Sunspaces

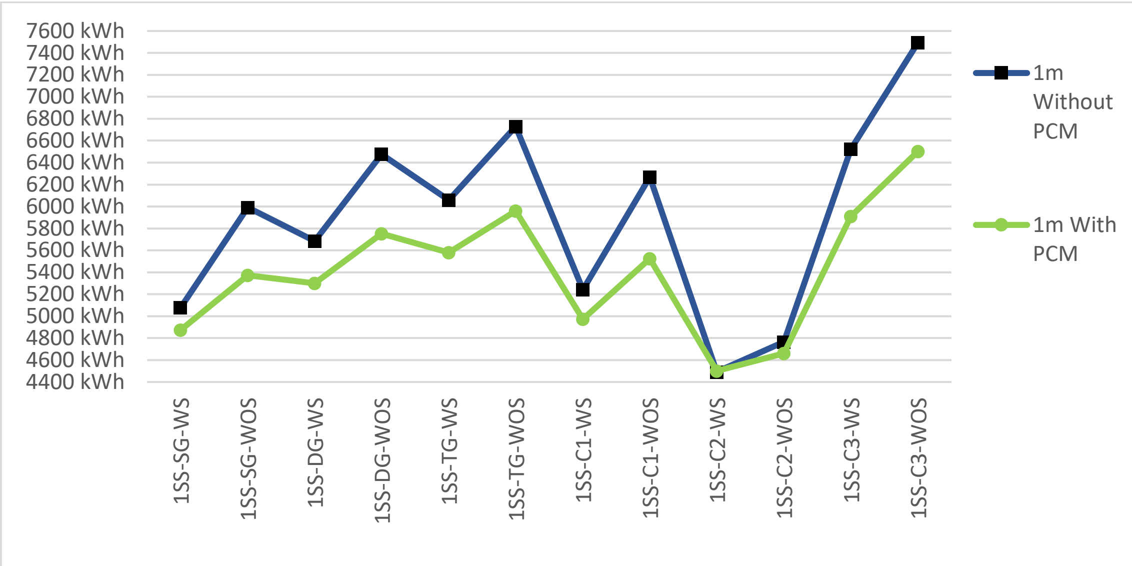

Figure 7: Annual Cooling Requirements for 1.25m Sunspaces

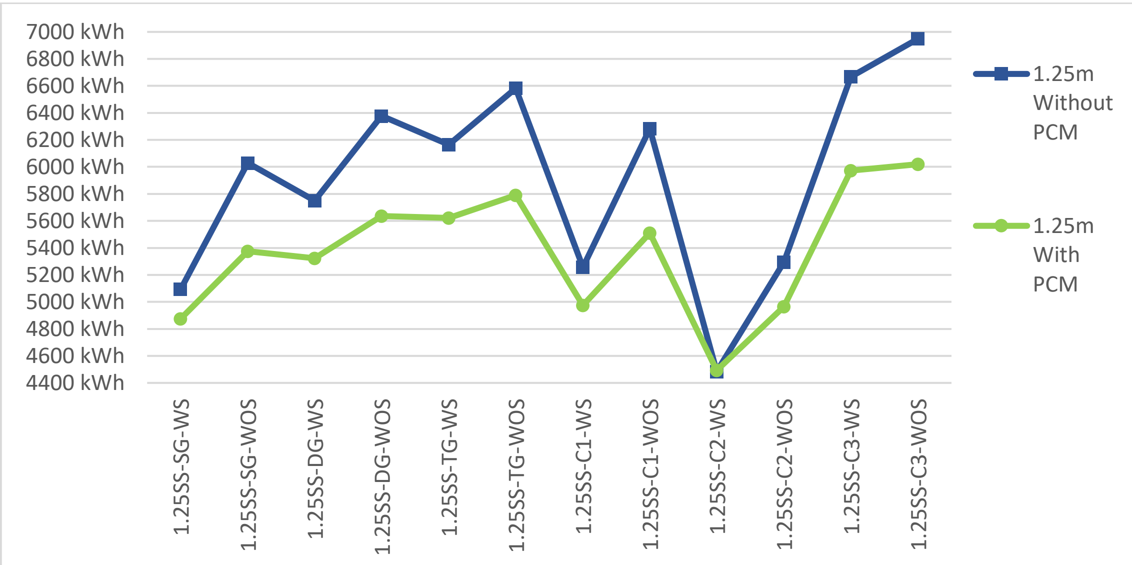

Figure 8: Annual Cooling Requirements for 1.25m Sunspaces

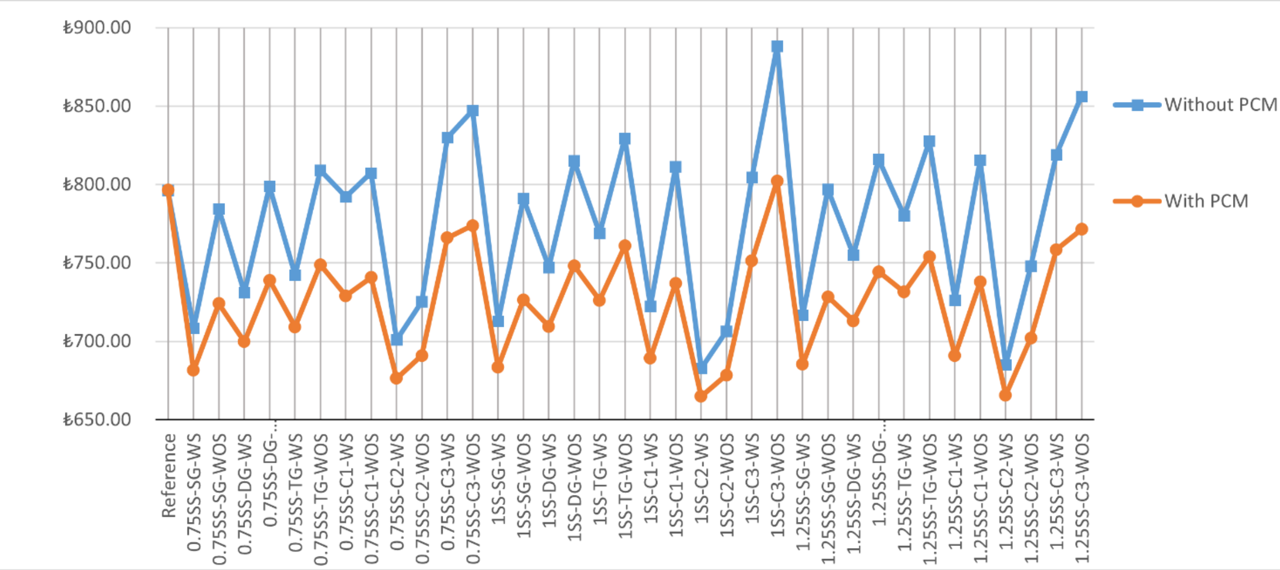

Figure 9: Annual Energy Prices Required for Different Cases

4 Conclusions

The effect of the addition of the PCM in the partition wall between sunspace and the living room of a detached house under Istanbul climate conditions were numerically investigated within the present work, and the following results were found:

- The addition of the PCM in the partition wall contributes to the heating and cooling energy saving in the considered house.
- It was found from the previous study, for the best-case scenario, the energy cost can be reduced by 14.26%, while energy cost increased by 11.53% for the worst-case scenario.
- However, with the addition of the PCM alongside the sunspace, annual energy cost can be reduced by 16.52% for the best-case scenario, while it was seen that the energy costs increased by 0.75% for the worst-case scenario. This finding revealed that the addition of an extra PCM layer, i.e. creating additional thermal inertia, has improved both the best-case and worst-case scenarios. Besides, the overheating phenomenon seen in the previous study was almost completely diminished with the PCM utilization in the sunspace partition wall adjacent to the living room.
- When comparing the effect of the PCM addition to the partition, it was found that the maximum improvements were observed for 1.25SS-C3-WOS by 9.91% energy cost reduction, while the minimum improvements were found for 1SS-C2-WS by 2.63% energy cost reduction.
- It was found that, with the addition of the PCM, required heating energy was always reduced, while the cases 1SS-C2-WS and 1.25SS-C2-WS showed increased cooling energy requirements.
- Considering the remarkable advantageous sides of the PCM utilization revealed in this study, in future studies, different PCMs with different phase-change temperatures, different locations of the PCM inside the wall, and different climate conditions can be investigated.

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