ANALYSIS OF ENERGY-SAVING POTENTIAL OF SUNSPACES INCORPORATING PHASE CHANGE MATERIAL IN DIFFERENT CLIMATIC REGIONS OF TURKEY

A THESIS SUBMITTED TO
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
KOCAELİ UNIVERSITY

BY

MURAT ÇAĞRI ULUDAŞ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

KOCAELİ 2022

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May-2022 Murat Çağrı ULUDAŞ

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c_p	:Specific heat capacity, (J/kg·K)
ρ	:Density, (kg/m^3)
Δx	:Spacing between the nodes, (m)
Δt	:Temporal time step, (s)
T	:Temperature, (K)
k	:Thermal conductivity, (W/m·K)
i	:Node modeled
i+1 , i-1	:Neighboring nodes
j	:Current time step
j+1	:Next time step
F_{Relax}	:Relaxation factor
h	:Enthalpy, (J/kg)
Q_c	:Rates of Exterior Heat Transfer, (W)
h_c	:Convective Heat Transfer Coefficient, (W/m²·K)
$h_{c,glass}$	:Convective Heat Transfer Coefficient for glass, (W/m²·K)
h_n	:Natural Convective Heat Transfer Coefficient, (W/m²·K)
R_f	:Surface Roughness Multiplier
T_{surf}	:Surface Temperature, (°C or K)
T_{air}	:Air Temperature, (°C or K)
ΔT	:Temperature Differance Between Surface and Air, (C° or K)
V_z	:Local Wind Speed Calculated at the Height Above Ground of the Surface Centroid, (m/s)

Abbrevations

CED	:Cooling Energy Demand
CST	:Cooling Set Temperature
DG-1	:Double Clear Glass
DG-2	:Double Reflective Coating Tinted Glass
EPBD	:Energy Performance of Buildings Directive
HED	:Heating Energy Demand
HST	:Heating Set Temperature
PCM	:Phase Change Material
PSM	:Phase Stabilized Material
SCOP	:Seasonal Coefficient of Performance
SEER	:Seasonal Energy Efficiency Rating
SG-1	:Single Clear Glass
SG-2	:Electrochromic Colored Glass
UK-NCM	:United Kingdom National Calculation Methodology
TARP	:Thermal Analysis Research Program
TG-1	:Triple Clear Glass
TG-2	:Triple Glass with Low-E Film

ANALYSIS OF ENERGY-SAVING POTENTIAL OF SUNSPACES INCORPORATING PHASE CHANGE MATERIAL IN DIFFERENT CLIMATIC REGIONS OF TURKEY

ABSTRACT

Sunspace integration is an effective yet simple solar system application to improve the energy efficiency of buildings. However, numerous factors can affect its effectiveness. They should be evaluated regarding different design parameters and climatic conditions to achieve the most appropriate implementation. From this point of view, the impacts of sunspace integration to a detached house located in five different climate zones in Turkey were numerically investigated. The effect of the active shading and location of the phase change material (PCM) inside the partition wall were studied. Also, various PCMs introduced sunspace configurations considering six phase transition temperatures from 19 °C to 29 °C, a phase stabilized material (PSM), and six different glazing unit structures including single, double, and triple pane glass, were examined to determine the most effective designs. The analyses were performed for different climatic conditions in Turkey (namely, for the cities of Ankara, Antalya, Erzurum, Istanbul, and Sivas). By the annual analysis, it was revealed that sunspace attachment is significantly beneficial for the reduction of cooling and heating demands, which leads to lower energy consumption and CO_2 emission, for the majority of considered sunspace configurations. Results showed that, depending on the configuration, the total required energy and CO_2 emission can be reduced by up to 629 kWh and 168 kg/year, respectively. It was also seen that a PCM incorporated sunspace can attain a yearly energy saving of up to 20.86%.

Keywords: Annual Energy Analysis, CO_2 Emission, Energy Saving, Phase Change Material, Sunspace.

TÜRKİYE'NİN FARKLI İKLİM BÖLGELERİNDE BULUNAN FAZ DEĞİŞİM MALZEMESİ İÇEREN GÜNEŞ MEKANININ ENERJİ TASARRUFU POTANSİYELİNİN ANALİZİ

GENİŞLETİLMİŞ ÖZET

Güneş mekanları, basit olmasina rağmen etkin sistemlerdir. Güneş mekanına gelen güneş ışınlarındaki enerji, binayı oluşturan yapılarda (duvar, taban vs.) ve de güneş mekanının içindeki hava yardımıyla depo edilip gerektiği zaman kullanılır. Depo edilen ısıyı arttırmak için, termal depolama sistemleri kullanılabilir. Bu tez çalışmasında, güneş mekanı ile oturma odasının arasındaki duvarın içine faz değişim malzemesi (FDM) eklenerek, güneş mekanının ısıyı tutma kapasitesi arttırılmıştır. Bu etkileri incelemek amacıyla, Türkiye'nin beş farklı iklim bölgesindeki beş şehir seçilip, müstakil bir bina tasarlanmıştır. Daha sonra, bu binaya güneş mekanı eklenerek, ve bu güneş mekanının parametreleri değiştirilerek, EnergyPlus™ programı yardımıyla aylık ve yıllık enerji ihtiyaçları bulunmuştur. Aktif gölgeleme sistemi, bölme duvarının içinde üç farklı faz değişim malzemesi konumu, altı farklı faz değişim sıcaklığı, ve altı farklı cam tipi incelenen parametreleri oluşturmaktadır. Ayrıca, analizler, faz değiştiren malzemenin gizli ısısının etkisini görmek amacıyla ayrıca FDM özelliklerine sahip ancak faz değişiminin olmadığı (faz stabil malzeme, PSM) bir malzeme için de gerçekleştirilmiştir.

Aktif gölgeleme sistemi, 31 Mart-30 Eylül tarihleri arasında çalıştırılıp, saat 6:00'dan 18:00'e kadar rulo perde açılarak, içeri giren güneş ışığı miktarının azaltılması sağlanmıştır. Diğer günlerde ise aktif gölgeleme sistemi, pasif duruma geçirilerek gölgeleme yapması engellenmiştir. Faz değişim malzemesinin, bölme duvarının ön, orta ve arka konumlarına yerleştirildiği durumlar için analizler yapılmıştır. Aktif gölgeleme ve faz değişim malzemesi konumu İstanbul iklim koşullarında araştırılmış olup, aktif gölgelemenin tüm konfigürasyonlarda yararlı olduğunun görülmesi ve konumunun ciddi bir etki yapmadığı göz önüne alınarak diğer konfigürasyonlarda aktif gölgeleme sistemi açık ve faz değişim malzemesinin de duvarın orta konumuna yerleştirildiği durumlar dikkate alınarak analizlere devam edilmiştir. Faz değişim sıcaklığı olarak, 19 °C'den 29 °C'ye kadar 2 °C aralıklarla altı farklı sıcaklık seçilmiştir ve tüm iklim bölgeleri için optimum faz değişim sıcaklıkları araştırılmıştır. Faz değişim sıcaklıkları ve faz stabilize malzemenin etkisini görmek için berrak tek cam (single clear glass – SG-1) içeren 1 m derinlikte güneş mekanı seçilmiştir. Optimum faz değişim sıcaklığı bulunduktan sonra, cam tipi değiştirilerek farklı iklim tipleri için optimum cam tipi tespit edilmiştir. Farklı ısıtma ve soğutma sistemlerinin işletme maliyetleri arasında fark oluşacağından ve bu farkı en aza indirmek amacıyla binanın ısıtma ve soğutma ihtiyacını karşılamak için yüksek verimli bir ısı pompası sisteme dahil edilmiştir ve böylece yapının ısıtma ve soğutma için harcadığı yıllık elektirik enerjisi ortaya çıkarılmıştır. Daha sonra bu enerji yardımıyla eşdeğer CO_2 salınımı bulunmuştur. Yapılan yıllık analizler sonucunda, güneş mekanının ısıtma ve soğutma ihtiyacını azaltmada önemli miktarda katkı sağladığı görülmüştür, bu da daha az enerji tüketimi ve CO_2 salınımını sağlamıştır. Kullanılan konfigürasyona bağlı olarak, gerekli toplam enerjinin 629 kWh kadar azaltılabileceği ve aynı zamanda CO_2 emisyonu salınımının 168 kg/yıl azaltılabileceği görülmüştür. Aynı zamanda, faz değişim malzemesi ilave edilmiş güneş mekanlarının ısıtma ve soğutma yükünden yıllık %20,86'ya kadar enerji tasarrufu sağlayabildiği görülmüştür.

Anahtar Kelimeler: Yıllık Enerji Analizi, CO_2 Emisyonu, Enerji Tasarrufu, Faz Değişim Malzemeleri, Güneş Mekanı.

1. INTRODUCTION

Recent studies indicate that global temperature values are increasing at an accelerating pace (Rathore and Shukla 2020). To reduce or even stop this increase, 196 member countries of the United Nations Framework Convention on Climate Change signed the Paris Agreement (Anon 2015) in 2015 and agreed to work to keep the rise of global average temperature well below 2 °C. As a result of this agreement, studies on the prevention of climate change and the conservation of energy have received remarkable attention from academic as well as industrial perspectives. It is found that global warming is predominantly caused by greenhouse gas emissions resulting from human activities such as excessive fossil fuel usage since the mid-twentieth century (Castellari and Kurnik 2017). As indicated in BP's Statistical Review of World Energy Report (Anon 2021b), residential and commercial buildings account for 29% of the primary energy consumption, while nearly 83.1% of this energy is generated by burning fossil fuels. In this regard, many countries updated their regulations about construction and energy usage of buildings to reduce the energy usage for residential and commercial buildings. These regulations have established new directives and constraints when constructing new buildings and renovating old ones. For example, according to the energy performance of buildings directive (EPBD) 2010/31/EU (European Parliament and of the Council of 19 May 2010), when a new building is constructed, it must be a nearly zero-energy building (European Parliament and of the Council of 19 May 2010). Based on the performed studies, to achieve energy efficiency in buildings, they should be constructed with a combination of factors, such as high-performance building fabric, high-efficiency equipment, active or passive solar system, energy-efficient lighting systems, and thermal storage (D'Agostino and Mazzarella 2019, Ionescu et al. 2015, Soares et al. 2013).

1.1 Literature Review

As one of the solar systems, sunspace is used very commonly in newly built buildings because of its attractive and fashionable design, the potential to reduce energy consumption, and multi-purpose utilization (Ma et al. 2021, Mihalakakou 2002, Oliveira Panão et al. 2012). Sunspaces can be considered in the category of both active and passive solar systems since solar radiation heats the sunspace which, in turn, heats the living space. Since sunspaces add little cost to the new building construction, it is more feasible to use in the plan stages of the new construction projects. However, the literature survey shows that they can still provide significant advantages to the old buildings. For example, Allesina et al. (2019) used a transparent sheet to modify an existing balcony to construct a low-cost sunspace, which only operates during the heating seasons. They built a small-scale experimental setup and conducted measurements and dynamic simulations. The sunspace was found to significantly reduce the heating energy demand in the heating season while it causes higher cooling energy consumption. The study showed that the temporary sunspace created with transparent sheet both performed better, and cost less than glazing replacement combined with better wall insulation. Chiesa et al. (2017) carried out an extensive study to determine the effectiveness of the sunspace utilization potential in Europe considering 50 different locations, and thus, thermal-climatic conditions. They showed that the sunspace integration to uninsulated buildings significantly decreased the required energy for heating for all types of glazing elements. However, they observed that the solar gains were small for the insulated houses. It was suggested to perform an economic feasibility analysis to investigate the cost-effectiveness of the sunspace. Xifeng et al. (2012) utilized a statistical method to examine the change in the mean indoor air temperature in a classroom that included a sunspace in a cold climate. During school hours, the mean temperature of rooms in the central part of the building with a sunspace was 6.6 °C higher compared to reference rooms that have no sunspace, resulting in efficient energy use and reduced costs of heating, ventilation, and air conditioning (HVAC) maintenance. Aelenei et al. (2014) studied implementing sunspace in existing residential houses in Portugal. The thermal performance of four configurations was considered in six different regions. They found that the fully integrated, south-facing sunspace with high reflectance shading performs better in all the cities, while for the other variables, their performance is dependent on climatic conditions. Ulpiani et al. (2019) built a well-insulated room with an integrated sunspace and investigated the effect of a mechanical ventilation system on the partition wall between the attached sunspace and the test building. They reported effective performance of the sunspace under various boundary conditions and a considerable temperature rise in the sunspace even on snowy days. López et al. (2018) studied the use of sunspace while using sand on the floor as thermal storage to increase the thermal inertia. The study showed that the temperature of the sand was usually higher than the indoor temperature of the air, and the presence of the sand caused a higher heat transfer during spring, autumn, and winter, whereas lower heat transfer in summer, leading to lower energy consumption in both heating and cooling seasons. In addition, they stated that most of the heat storage and heat release occurred in the top 10 cm of the sand layer. Another study by López et al. (2020) used a validated simulation tool to analyze the thermal behavior and energy reduction potential of a sunspace built for a project. The payback was found to be unreasonable for the three sunspace configurations tested. However, it was noted that the cost of the sunspace is usually lower than the profit gained through property appreciation if the sunspace is habitable. Ignjatović et al. (2015) investigated the application of the sunspace as a method of improving living conditions and energy performance with various design options and technical characteristics. Although the sunspace application affected only 2 - 3% of the total energy requirement of the whole building, it reduced the energy consumption of the room to which the sunspace was attached by 8 - 11%. Monge-Barrio and Sánchez-Ostiz (2015) 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 consider all-year-round climate conditions. Ma et al. (2020) 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 increased nearly twofold.

The literature review regarding sunspace integration in buildings shows that the use of sunspaces is a promising technique to conserve energy in detached houses despite potential disadvantages such as the high solar gain during the cooling season and high pay-back periods.

Another technique that has been implemented in buildings to save energy and provide thermal comfort is the utilization of phase change materials (PCMs). They are mainly incorporated in the walls (Devaux and Farid 2017, Li et al. 2021a), roofs (Li et al. 2015, Xamán et al. 2020), floors (Cesari et.al. 2022, Rathore and Shukla 2019), and even glazing systems (Jin et al. 2022, Li et al. 2020). Suitable melting/solidification temperatures of PCMs enable them to exploit their high latent heat for solar energy storage/release in building applications. For instance, Kuznik et al. (2008) performed numerical simulations of a wall containing PCM and reported that the use of a 1 cm PCM layer allowed double thermal inertia of the wall. In addition, the thermal fluctuations in the room were significantly reduced, meaning that the use of PCM provided thermal comfort along with energy-saving. In a subsequent experimental study, Kuznik and Virgone (2009) reported that the use of PCM reduced the indoor air temperature up to 4.2 °C. Lee et al. (2015a) investigated the effect of using a thin PCM layer in the wall on the heat transfer and time delay and found that the utilization of PCM resulted in approximately 6 h of time delay, as well as a 27% reduction in the heat transfer. Pasupathy and Velraj (2008) explored the potential benefit of using double-layer PCM on the roof of a building and found that PCM decreased temperature fluctuations. However, it was highlighted that the selection of the PCM is of great importance since the performance of the PCM is highly dependent on its thermophysical properties. Bhamare et al. (2020) evaluated a PCM integrated building roof application model at various inclination angles. Energy savings up to 16% could be reached with the PCM slab compared to the nonexistence of the PCM slab at a 2° inclination angle. Moreover, a nearly 2.4 °C decrease in the ceiling temperature was observed with PCM. Mazo et al. (2012) studied a floor application of PCM considering a radiant floor heat system integrated with PCM. According to the study, the PCM integrated radiant floor heating system provided an 18% reduction in energy costs due to the shift of loads from peak hours to off-peak hours of electricity demand. Li et al. (2016) performed a thermal performance analysis of a PCM-filled glazing unit to evaluate potential benefits. They observed that the photothermal performance of the PCM-filled glazing unit was strongly dependent on the phase state. It was reported that, with the extinction coefficient of 200 m^{-1}, the time to reach the interior surface to the highest temperature was 300 min earlier in the solid state, compared to the extinction coefficient of 5 m^{-1}. The above review proves the obvious advantages of the use of PCM in building components and confirms that the use of PCM in buildings is a popular research field.

Considering the merits of sunspace and thermal energy storage, some researchers combined sunspaces with various PCMs to evaluate the thermal performance of the overall system (Lu et al. 2018). For instance, Vukadinović et al. (2020) analyzed a detached residential building with a sunspace integrated with a thermal energy storage wall consisting of a thick concrete layer. The wall also contained a PCM layer. Three locations of PCM inside the thermal energy storage wall (near the exterior, near the interior, and in the middle) were tested. The annual building energy consumption was tracked for five cities in Serbia, located in regions with various climate conditions. The study revealed that the PCM improved the thermal inertia. Placing the PCM in the middle of the wall was preferred because it showed the best thermal performance compared to the other locations. Furthermore, it was reported that up to a 2.4% reduction in the annual energy demand of the building could be achieved by combining the sunspace with the additional PCM layer compared to the reference case, which was a sunspace without any PCM. In another study, Li et al. (2021b) studied a sunspace louver with or without PCM. It was found that, in terms of energy saving, PCM integration into the sunspace louver can be beneficial or harmful during the heating season depending on the design indoor temperature. A design indoor temperature of 18 °C was advantageous, whereas 16 °C or lower design temperatures were detrimental. Besides, the sunspace integration alone resulted in a nearly 23% saving in energy consumption. This saving could be further enhanced by up to 5% by integrating PCM into the louver.

1.2 Novelty and Objective of the Study

The literature survey presented above reveals that sunspace integration is a remarkably beneficial passive technique for energy saving. Furthermore, it can also provide a significant reduction in carbon emissions related to its energy-saving potential. The design of a combined sunspace-PCM system includes numerous parameters such as the type of the utilized glazing and phase transition temperature, PCM location, etc. These parameters need to be optimized for the highest possible energy saving and carbon emission reduction. In addition, the effectiveness of the sunspace should be examined throughout the whole year, as its thermal effectiveness can be different for heating and cooling applications. Moreover, climatic conditions in the location where the sunspaces are constructed also present an influential parameter for the design of the sunspace. It is therefore required to evaluate the sunspace effectiveness for the particular location. As revealed by the literature review, existing research works usually include only part of the perspectives to design the sunspace and evaluate its benefits and drawbacks. Furthermore, studies that seek to evaluate and optimize the design of combined sunspace-PCM systems are lacking.

Literature survey also suggests that even though there are numerous studies regarding sunspace, only a few studies were conducted on the climatic conditions of Turkey even though it is one of the biggest countries in Europe and contains multiple climatic conditions. Therefore, the present work aims for a comprehensive investigation into the design of combined sunspace-PCM systems in Turkey to find possible energy savings. The parameters considered include different glazing types, phase transition temperatures of the PCM, and PCM locations in the partitioned wall. Besides, the studies are performed a phase-stabilized material (PSM) to reveal the utilization of latent heat of PCM (Arıcı et al. 2020). Moreover, the active shading system was investigated to emphasize its significance in the sunspace systems.

2. METHODOLOGY

In this section, selected standards, calculation methods, parameters, properties of the materials, and details of the equipment were presented in detail to provide a better understanding to the reader of this thesis.

A detached house in five different locations in Turkey was considered. Annual thermal analyses were performed to evaluate the effect of the sunspace application. To investigate the effects of the sunspace in different climatic conditions, five different cities, each located in a different climatic zone of Turkey, were selected. The details of the considered cities are shown in Table 2.1 and climatic zones according to TS 825 are shown in Figure 2.1. United Kingdom National Calculation Methodology (UK-NCM) standards were used to determine indoor conditions and heat gain factors.

Table 2.1. Details of selected locations

Location	Latitude	Longitude	Elevation (m)	TS 825 Climate Zone	Köppen Classification
Antalya	36.87	30.73	54	1st zone	Cfa
Istanbul	40.97	28.82	37	2nd zone	Cfa
Ankara	40.12	33	949	3rd zone	Dfb
Sivas	39.75	37.02	1285	4th zone	Dfb
Erzurum	39.95	41.17	1758	5th zone	BSk

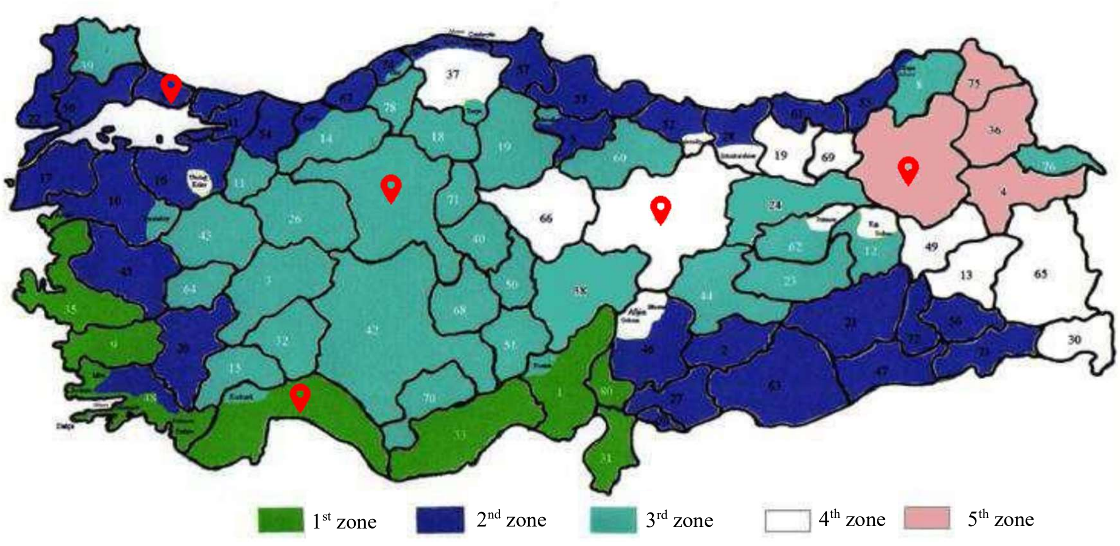
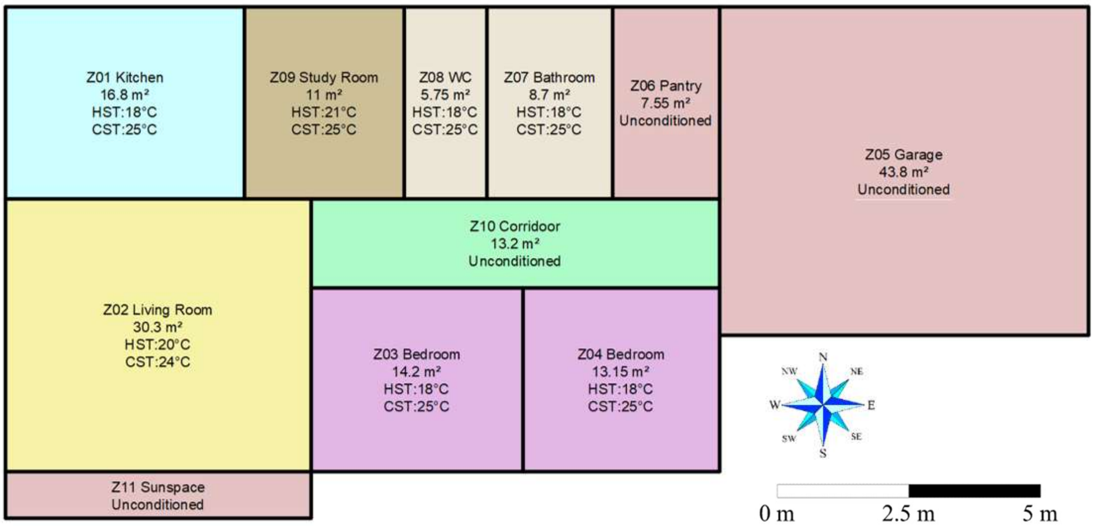


Figure 2.1. Climate zones according to TS 825

Thermal analyses were conducted by using EnergyPlus software. Required 3D geometry was created by Revit software by using a real construction plan for a detached house and the building height was selected as 3m. After the geometry was imported to the EnergyPlus software, HVAC zones were defined and required information such as building fabric, indoor air conditions, weather files, and algorithms were defined. 3D and plan view of the detached house can be seen in Figure 2.2. The building fabric was designed based on generally used materials in Turkey and the U-values of the construction elements are shown in Table 2.2. Since the PCM has different thermophysical properties in liquid and solid phases, the U-value for the partition wall is changing between 2.675 W/m²·K to 2.891 W/m²·K depending on solid/liquid percentages. Construction and properties for the partition wall and properties of PCM are shown in Figure 2.3., Table 2.3., and Table 2.4., respectively.

(a)



(b)

Figure 2.2. Three dimensional and plan view of the detached house
(a) Three dimensional view (b) Plan View

Table 2.2. U-values of the building components

Construction material	U-value (W/m²·K)
Outer wall	0.543
Internal partition	1.923
Sunspace partition without PCM	2.943
Sunspace partition with PCM	2.675-2.891
External door	5.429
Flat roof	0.25
Ground floor	0.253

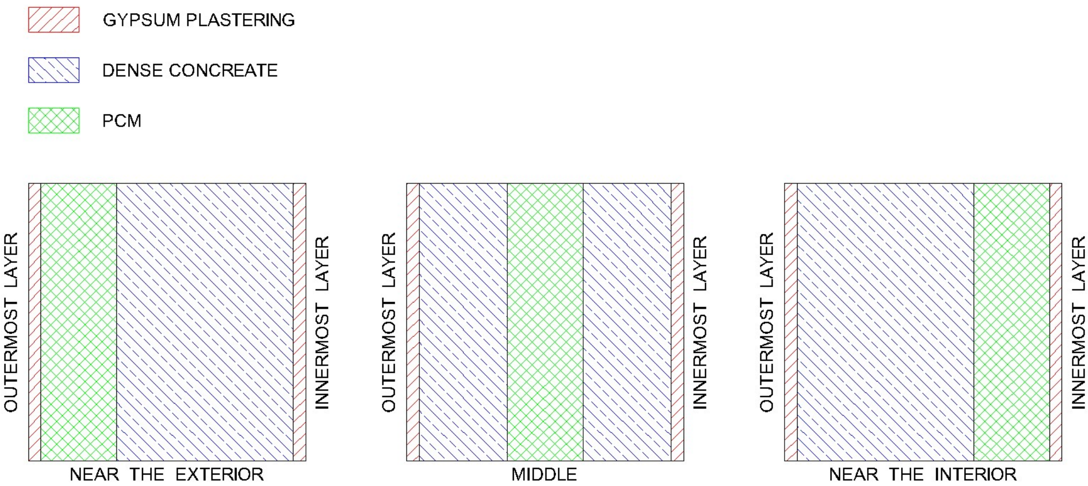


Figure 2.3. Construction of the partition wall

Table 2.3. Properties of the partition wall with PCM

	Layer 1 (Outermost)	Layer 2	Layer 3	Layer 4	Layer 5 (Innermost)
Construction material	Gypsum plastering	Dense concrete	PCM	Dense concrete	Gypsum plastering
Thickness (mm)	5	35	30	35	5
Thermal conductivity (W/m·K)	1.2	1.4	See Table 2.4	1.4	1.2
Density (kg/m^3)	2100	2100	See Table 2.4	2100	2100
Specific heat (J/kg·K)	1000	840	See Table 2.4	840	1000

Table 2.4. Properties of the PCM layer

		Peak melting temperature (°C)	Peak freezing temperature (°C)	Thermal conductivity (W/m·K)	Density (kg/m³)	Specific heat (J/kg·K)
19 °C	Solid	18	-	1.09	1540	3140
	Liquid	-	20	0.54		
21 °C	Solid	20	-	1.09		
	Liquid	-	22	0.54		
23 °C	Solid	22	-	1.09		
	Liquid	-	24	0.54		
25 °C	Solid	24	-	1.09		
	Liquid	-	26	0.54		
27 °C	Solid	26	-	1.09		
	Liquid	-	28	0.54		
29 °C	Solid	28	-	1.09		
	Liquid	-	30	0.54		

In the study, yearly dynamic energy analyses were conducted. The one-dimensional conduction finite difference model (CondFD) was implemented in the software as the conduction transfer function transformation (CTF) model used for the heat balance calculations has certain limitations (EnergyPlus 2013). Furthermore, the CTF model cannot be used for simulating the interior nodes of the materials and phase change phenomena. On the other hand, the CondFD model can be safely utilized for the simulation of phase change materials (Lee et al. 2015b, Sheeja et al. 2020). EnergyPlus offers two different schemes for the discretization of the conduction equation, namely, fully implicit and semi-implicit Crank-Nicholson. The fully implicit scheme was selected in this study. Thus, the discretized form of the conduction equation is shown below for a general interior node (Eq. 2.1).

$$c_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right) \tag{2.1}$$

Here, c_p is the specific heat capacity, ρ is the density, Δx is the spacing between the nodes in the modeled domain, Δt is the temporal time step. The node temperature is represented by T while the thermal conductivity is represented by k. Also, i is the node modeled, whereas i−1 and i+1 are the neighboring nodes. The current and next time steps are represented by j and j+1, respectively. The resulting linear equations were solved using an iterative method with under relaxation for increased stability (Eq. 2.2) (EnergyPlus 2013).

$$T_i^{j+1} = T_i^j + (T_i^{j+1} - T_i^j)F_{Relax} \tag{2.2}$$

Here F_{Relax} is the relaxation factor for temperature. Variable specific heat value was used to simulate the phase change process based on the updated node enthalpy in every iteration (Eq. 2.3). The specific heat of the material was determined by using the input tabulated data of enthalpy/temperature pairs.

$$c_p = \frac{h_i^{j+1} - h_i^j}{T_i^{j+1} - T_i^j} \tag{2.3}$$

The hysteresis physics occurring in the presence of the phase change process was captured by the specific heat and the independent variables given by Eq. 2.4.

$$c_p = f\left(T_i^{j+1}, T_i^j, \text{PhaseState}^{j+1}, \text{PhaseState}^j\right) \tag{2.4}$$

For calculating external convection, the DOE-2 model was selected. While the convection was calculated with the classic formula in Eq. 2.5, the convective heat transfer coefficient was calculated using Eq. 2.6-2.9 in the DOE-2 model. Eq. 2.6 was utilized for calculation of the heat transfer coefficient for very smooth surfaces such as glass while Eq. 2.7 was used for other surfaces. When there is no temperature difference on vertical surfaces, Eq. 2.8 was employed to calculate the natural convective heat transfer coefficient while Eq. 2.9 was used for horizontal surfaces.

$$Q_c = h_c A(T_{surf} - T_{air}) \tag{2.5}$$

$$h_{c,glass} = \sqrt{h_n^2 + [a \times V_z^b]^2} \tag{2.6}$$

$$h_c = h_n + R_f\left(h_{c,glass} - h_n\right) \tag{2.7}$$

$$h_n = 1.31|\Delta T|^{1/3} \tag{2.8}$$

$$h_n = \frac{9.482|\Delta T|^{1/3}}{7.283 - |\cos\Sigma|} \tag{2.9}$$

In the above equations (i.e. Eq.2.5 to 2.9), Q_c is the rate of exterior convective heat transfer, h_c is the exterior convection coefficient, A is the surface area, T_{surf} is the surface temperature, T_{air} is the air temperature, $h_{c,glass}$ is the convective heat transfer coefficient for very smooth surfaces such as glass, h_n is the natural convective heat transfer coefficient, V_z is the local wind speed calculated at the height above ground of the surface centroid, R_f is the surface roughness multiplier, $\sum$ is the surface tilt angle, ΔT is the temperature difference between the surface and air, while the a and b values are constant and changes with the wind direction. Details of surface roughness multiplier, and a and b constants are given in Appendix G.

For calculating interior convection, the Thermal Analysis Research Program (TARP) model was selected. Similar to the DOE-2 algorithm that was used for calculating external convection, TARP model also uses Eq. 2.8 and Eq. 2.9 to calculate the natural convective heat transfer coefficient for vertical and horizontal walls, respectively. Since there was no forced convection inside the house, the convective heat transfer coefficient (h_c) was equal to the natural convective heat transfer coefficient (h_n).

The annual thermal analysis was conducted with a series of different sets. For the first set, detached houses without sunspace in different climatic conditions were analyzed, and these cases were considered reference cases for these locations. For the second set, a sunspace with single clear glass was attached to the south wall of the living room and the effect of active shading was investigated in the climatic conditions of Istanbul. The length of the sunspace was chosen as 5.75m while the width of the sunspace was chosen as 1 m. For the active shading system, a 3 mm thick light opaque shade roll was used while the solar reflectance and solar transmittance values for this shade were selected as 0.5 and 0.05, respectively. The active shading system was operated between 6:00 AM to 6:00 PM from 31 March to 30 September to minimize the effect of overheating caused by the sunspace. For the third set, the partition wall construction was modified by moving the location of the PCM inside the partition wall, and analyses were conducted in the climatic conditions of Istanbul. For the fourth set, the effect of the phase change temperatures and latent heat was investigated by using six phase transition temperatures from 19 °C to 29 °C with 2°C increments. The analyses were also performed for the phase-stabilized material (PSM), which has the same properties as the PCM but can only use sensible heat since it cannot change its phase, in all climatic zones. To investigate the overall performance of the sunspaces, a heat pump was introduced to the system to minimize the unit price difference between heating and cooling applications. Seasonal energy efficiency rating (SEER) and seasonal coefficient of performance (SCOP) for heat pump were selected as 4.4 and 3.8, respectively. With the help of the SEER and SCOP, the required electricity to cover cooling and heating demand was calculated. After the best-case scenarios were determined for all climatic conditions, the glazing type of the sunspace was replaced with other glazing types in the final set. Properties of the used glazing types are shown in Table 2.5 and the sets considered in the thesis are summarized in Table 2.6.

After the analyses were completed, the energy costs of heating and cooling applications were found using the electricity prices in Turkey during October 2021 (0.071$/kWh). Also, CO_2 emissions for each case were determined using the CO_2 emission factor with a 24% allowance for the transmission/distribution losses (0.27322 kg-CO2/kWh) (Uludas et al. 2021, URL-2). Equations used for finding energy consumption (kWh/year), energy costs ($/year), and CO_2 emissions (kg-CO_2/year) were given in Eq. 2.10, Eq. 2.11, and Eq. 2.12, respectively. Here, cooling energy demand was represented by CED (kWh/year), and heating energy demand was represented by HED (kWh/year).

Table 2.5. Properties of the glazing elements

Window type	Abbreviation	Glass thickness (mm)	Air gap thickness (mm)	SHGC	U-value (W/m²·K)
Single clear glass	SG-1	6	-	0.81	6.121
Electrochromic single coloured glass	SG-2	6	-	0.254	6.121
Double clear glass	DG-1	6	13	0.697	2.708
Double reflective coating tinted glass	DG-2	6	13	0.342	2.696
Triple clear glass	TG-1	3	13	0.678	1.778
Triple glass with low-e film	TG-2	6	6	0.297	1.714

$$\text{Energy Consumption} = \text{CED} \times \text{SEER} + \text{HED} \times \text{SCOP} \tag{2.10}$$

$$\text{Energy Cost} = \text{Energy Consumption} \times \text{Electricity Price} \tag{2.11}$$

$$CO_2 \text{ Emission} = \text{Energy Consumption} \times CO_2 \text{ Emission Factor} \tag{2.12}$$

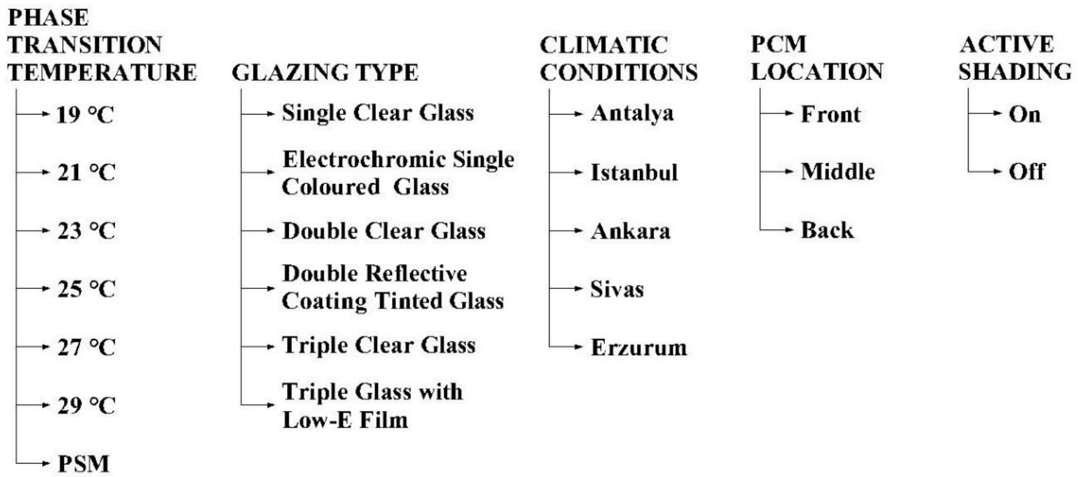


Figure 2.4. Investigated parameters

Table 2.6. Investigated sets

	Istanbul	Antalya	Ankara	Erzurum	Sivas
Reference case (Set 1)	✓	✓	✓	✓	✓
Active shading system (Set 2)	✓	-	-	-	-
Partition wall construction (Set 3)	✓	-	-	-	-
Phase transition temperatures and PSM (Set 4)	✓	✓	✓	✓	✓
Glazing type (Set 5)	✓	✓	✓	✓	✓

3. RESULTS AND DISCUSSION

In this thesis, annual thermal analyses for detached houses with sunspace were conducted to investigate the effects of the active shading system, PCM locations, phase transition temperatures and glazing types on the energy consumption of the buildings. To create a reference level for comparisons, houses without sunspace were considered for all locations. The sunspace width was selected as 1 m in all cases. SG-1 was selected as the glazing type for the investigation of the active shading system, location of the PCM, and phase transition temperature.

3.1. Effect of Active Shading System

To investigate the influence of the active shading system, climatic conditions of Istanbul were selected and the yearly energy consumption in the cases with/without active shading was compared. The obtained results presented in Figure 3.1. show the differences between the energy consumption of the cases with and without an active shading system. It was found that, with the use of the active shading system, all the cases show improvements, which can reach up to 4.8%. While the maximum improvement against the cases without an active shading system was achieved with the PSM case with 103 kWh yearly energy saving, the active shading only contributed 6 kWh energy saving with the 29 °C phase transition temperature. Similarly, 27 °C phase transition temperature only contributed to 24 kWh energy saving while other cases showed at least 87 kWh energy saving. As a general rule, it can be determined that while the performance of the active shading system was reduced with the increased phase transition temperature, they still contribute to the energy saving. Because of that, the active shading system was kept on for the further analyses.

3.2. Effect of PCM Location

Similar to active shading system analyses, climatic conditions of Istanbul were selected to investigate the effect of the location of the PCM inside the partition wall and three different positions (namely, near the exterior, middle, and near the interior) were investigated. In Figure 3.2., it is seen that the location of the PCM did not cause a significant change in the energy consumption (less than 10kWh/year). For most of the cases, this change was less than 0.5% of the required energy. To simplify further investigations, the PCM location was considered to be in the middle part of the wall in the following analyses.

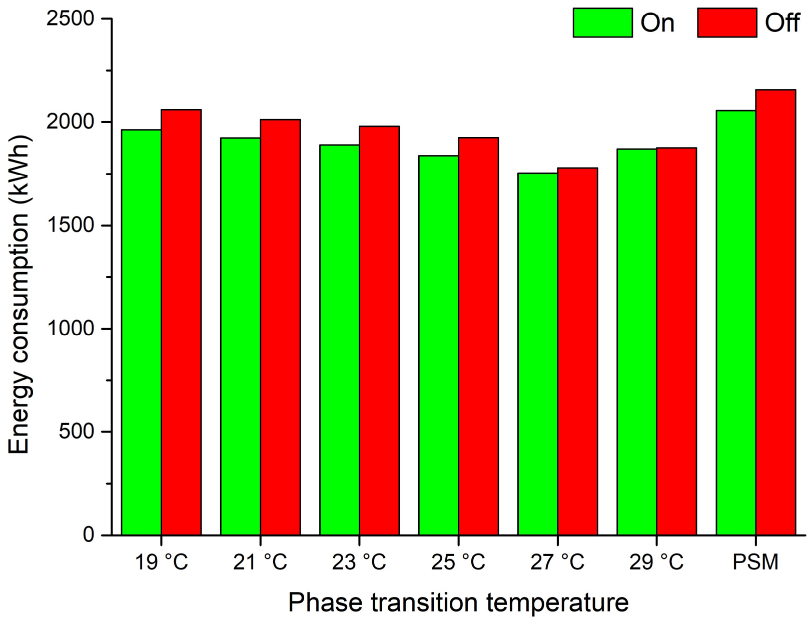


Figure 3.1. Effect of the active shading system on the energy consumption

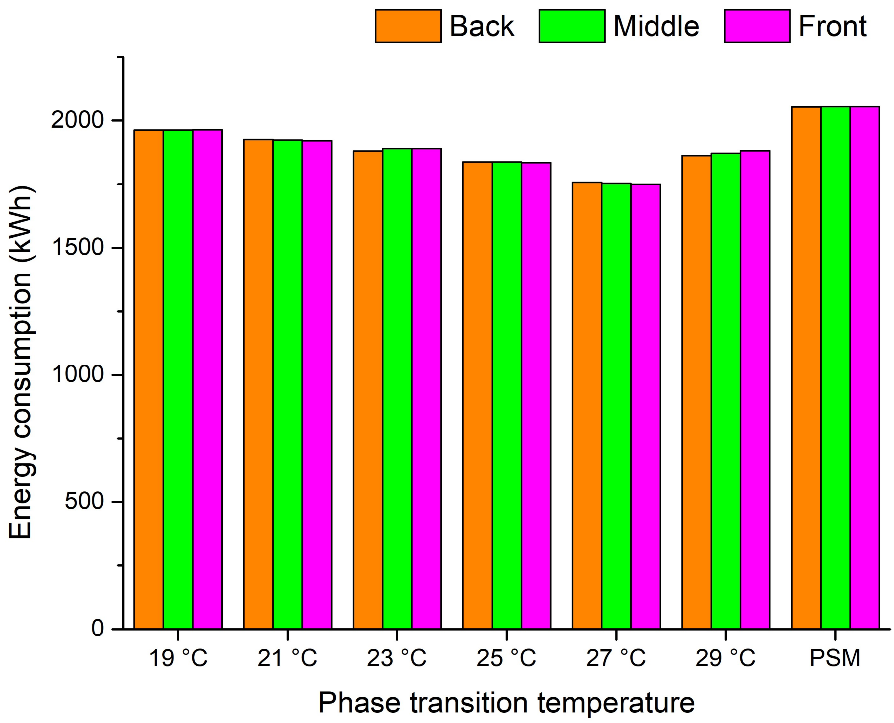


Figure 3.2. Effect of the location of the PCM inside the partition wall on the energy consumption

3.3. Effect of Phase Transition Temperature

To investigate the effect of the phase transition temperature, analyses were conducted in all the considered climatic conditions. To investigate the effect of the latent heat, also a PSM was introduced in addition to six phase transition temperatures from 19 °C to 29 °C with 2 °C increments. Energy consumption for both heating and cooling applications is shown in Figure 3.3. The optimal phase transition temperatures for different climatic conditions were different from each other. It was also seen that the optimum phase transition temperature has different values depending on heating and cooling applications. While higher phase transition temperatures contribute toward reducing cooling energy consumption, they are increasing the required heating energy. On the contrary, lower phase transition temperatures contribute toward reducing heating consumption while they are increasing the required cooling consumption. This means that, while the hotter climates such as Antalya require higher phase transition temperature, colder climates such as Erzurum require lower phase transition temperature since cooling energy consumption is higher in Antalya and heating energy consumption is higher in Erzurum.

Optimum phase transition temperatures for Antalya, Istanbul, Ankara, Sivas, and Erzurum were found as 29 °C, 27 °C, 25 °C, 25 °C, and 19 °C with energy consumption of 2319 kWh, 1754 kWh, 1992 kWh, 2634 kWh, and 3507 kWh, respectively. The optimum phase transition temperatures for heating applications were found to be 29 °C for Antalya, 21 °C for Istanbul, Ankara, and Sivas, and 19 °C for Erzurum with energy consumption of 187 kWh, 662 kWh, 1298 kWh, 1901 kWh, and 2918 kWh while the optimum phase transition temperatures for cooling applications were found to be 29 °C for Antalya, 27 °C for Istanbul, 25 °C for Ankara and Sivas and 19 °C for Erzurum was found with energy consumption of 2132 kWh, 1077 kWh, 678 kWh, 725 kWh, and 497 kWh, respectively. The highest improvement compared to the case without PCM was found in Istanbul with 11.55%, which was followed by Ankara with 11.17%. PSM cases shows the worst results which means that, in all PCM cases, the latent heat was successfully utilized as the only difference between PSM and PCM cases is the utilization of latent heat. Among the optimal phase transition temperatures, the highest latent heat utilization was observed in Istanbul at 14.62% while the least utilization was found in Erzurum at 7.3%.

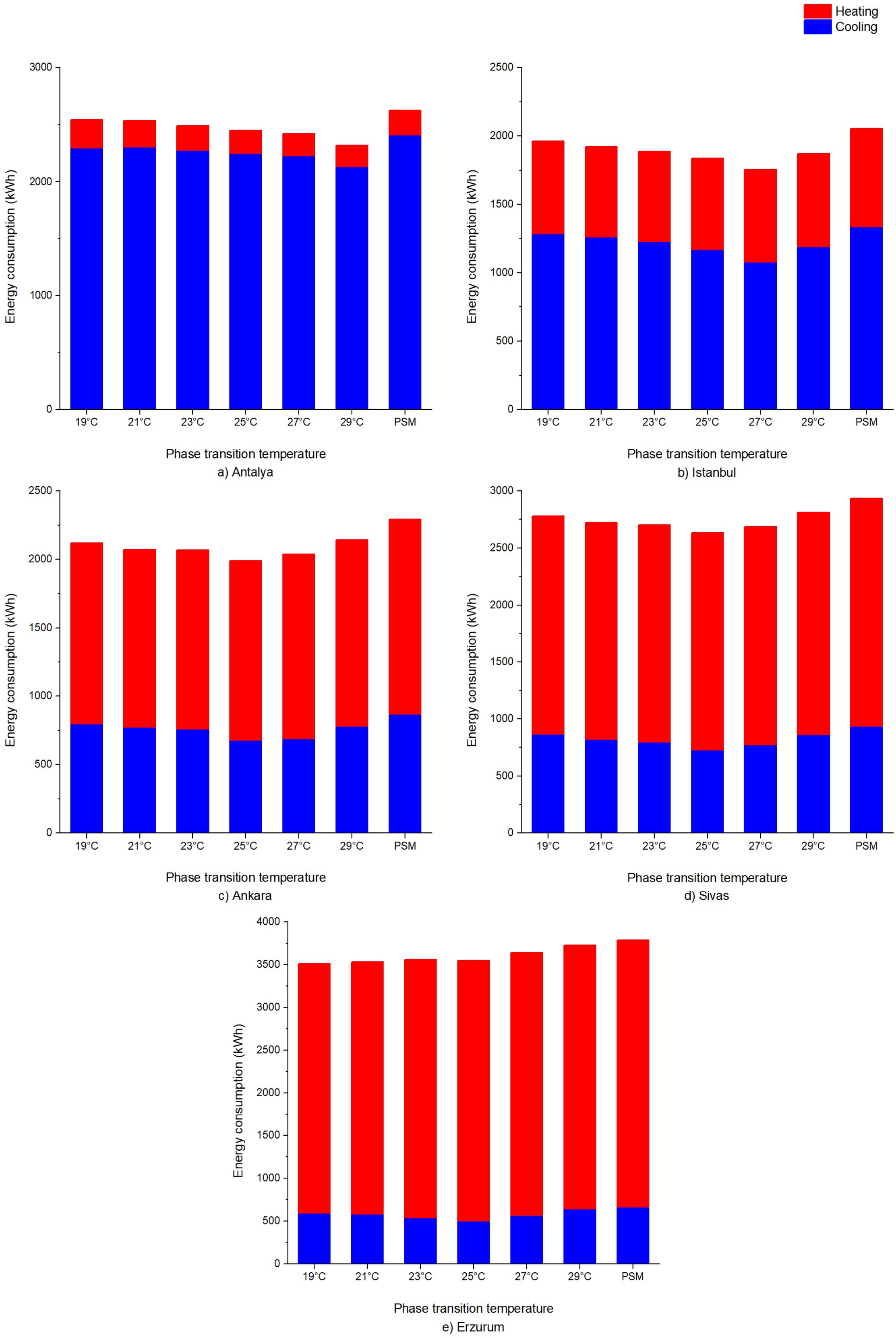


Figure 3.3. Effect of the phase transition temperature on the energy consumption

3.4. Effect of Glazing Type

To investigate the effect of glazing types on the energy consumption, cases with optimal phase transition temperatures were selected since they provided the lowest energy consumption. For glazing types, two single-layered, two double-layered, and two triple-layered glazing types were selected. While the U-values of the same layered glazing types are very close to each other, the SHGC is significantly different to reveal the effect of SHGC on the energy saving. Figure 3.4 shows the required heating and cooling consumptions in different climatic conditions for the used glazing types. As can be seen from Figure 3.4., similar to the phase transition temperatures, the optimum glazing type depends on the climatic conditions. For all the cases, SG-2 and TG-1 were determined as the best-case scenarios for cooling and heating applications, respectively. However, the optimum glazing types for, Antalya, Istanbul, Ankara, Sivas, and Erzurum were found as SG-2, TG-2, SG-1, SG-1, and TG-2, respectively. This difference between the optimum glazing types and the best glazing types for heating/cooling applications is caused by the efficiency difference between the heat pumps for cooling and heating applications. For example, for Ankara, the cooling demand for SG-2, TG-1, and SG-1 was calculated as 2634 kWh, 4108 kWh, and 2981 kWh while the heating demand was calculated as 5699 kWh, 4577 kWh, and 4997 kWh, respectively. When the heat pump was used to calculate energy consumption for these cases, energy consumption for SG-2, TG-1, and SG-1 were calculated as 2098 kWh, 2138 kWh, and 1992 kWh which shows that even though SG-1 was not the best case for either application, it provided the optimal results. Because the glazing type for cooling and heating application was found the same in all climatic conditions, it can be concluded that glazing with higher U-value and lower SHGC performs better in cooling applications while lower U-value and higher SHGC performs better in heating applications.

The highest improvements by changing the glazing type from SG-1 were noticed in Antalya with a rate of 3.17%, while Istanbul and Erzurum show slight improvements with 0.67% and 1.76%, respectively. Since the differences between glazing types can be very low (e.g., 9 kWh difference between SG-1 and TG-2 in Istanbul), the cost of the glazing types must also be considered when choosing the glazing system.

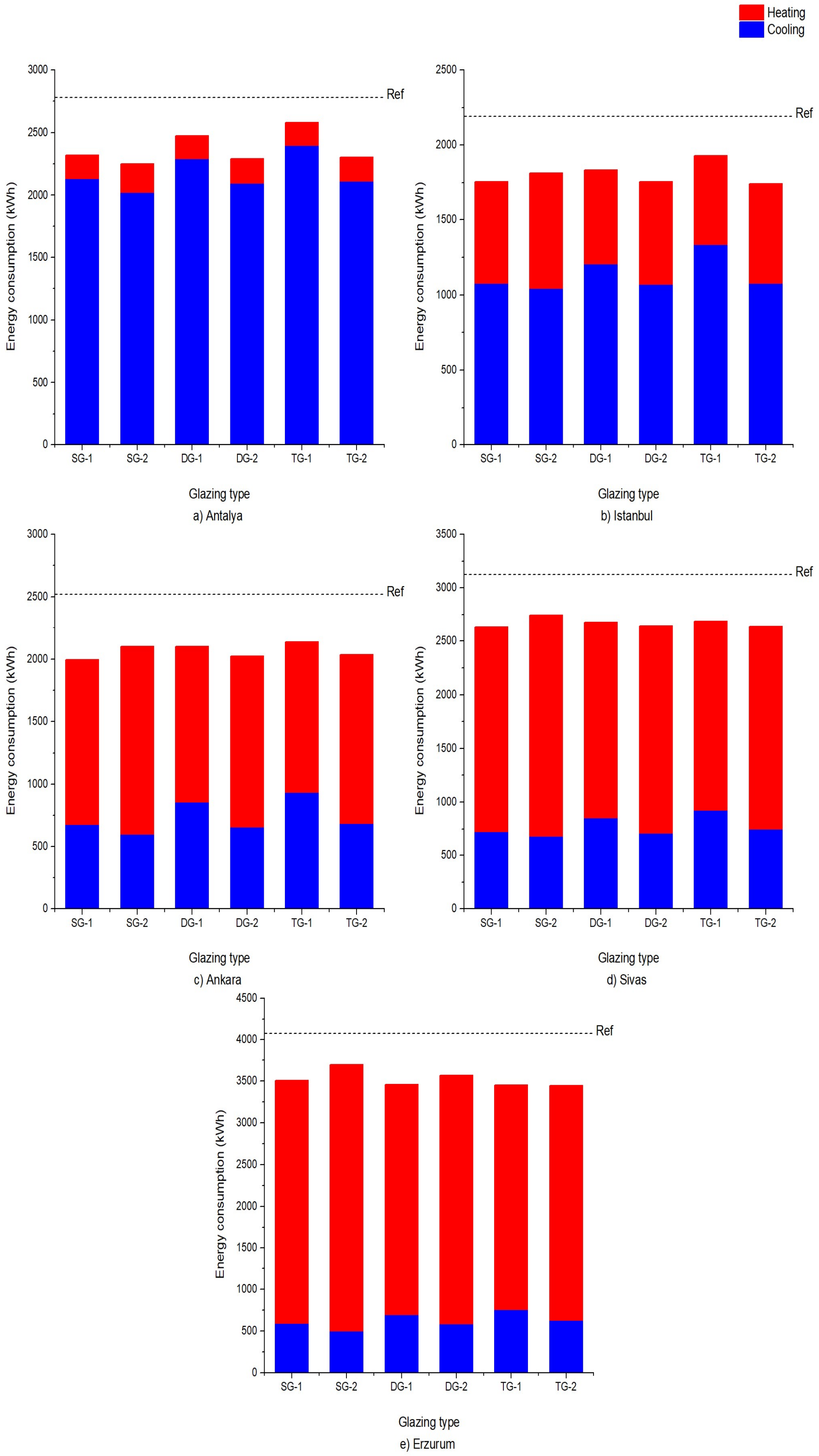


Figure 3.4. Effect of the glazing type on the energy consumption

3.5. Annual Cost and CO_2 Emission Analyses

With the help of the heat pump, annual cost and CO_2 emission analyses were conducted to investigate the effectiveness of the sunspace and PCM introduction. Resulting electricity consumption, annual cost and CO_2 emissions for all the cases are presented in APPENDIX E.

3.5.1. Annual Cost Analysis

Considering the wide range of parameters investigated within the present work, it is evident that the variation in these parameters can significantly affect energy consumption. Certainly, this influences the utility costs for the building. Thus, the energy cost can exhibit a notable variation depending on the design of the sunspace. Therefore, an economic analysis was carried out to reveal how much cost savings can be achieved by the use of sunspace without PCM, and PCM introduced sunspace.

For the reference houses in Antalya, Istanbul, Ankara, Sivas, and Erzurum, annual utility costs were found as 192 $/year, 156 $/year, 179 $/year, 222 $/year, and 289 $/year. When a sunspace without the PCM was integrated into the house, utility costs were reduced to 180 $/year, 141 $/year, 159 $/year, 204 $/year, and 266 $/year for the same locations. This results in a maximum of 10.9% of energy reduction. After introducing PCMs and optimizing the phase transition temperature (selecting the best-case scenario), energy costs were decreased to 165 $/year, 125 $/year, 141 $/year, 187 $/year, and 249 $/year for the same locations. It was found that the utility costs can be reduced up to 11.55% by introducing PCM to the sunspace.

To improve the cost reduction even further, glazing types of the sunspaces with optimum phase transition temperatures were analyzed and utility costs for the best glazing types were found as 160 $/year, 124 $/year, 141 $/year, 187 $/year, and 245 $/year for Antalya, Istanbul, Ankara, Sivas, and Erzurum, respectively. With these changes, utility costs were decreased by 15.4% to 20.9% in comparison to reference cases.

3.5.2. Annual CO_2 Emission Analysis

Heating and cooling applications directly impact the environment because of the harmful emissions during electricity production. In this thesis, CO_2 emissions, which are a prominent indicator of the environmental impacts of buildings, were the focal point of the environmental evaluation. Therefore, an environmental impact analysis was performed to reveal the order of reduction in CO_2 emissions by the decrease of energy requirement caused by the sunspace-PCM integration into the building.

For the reference cases in Antalya, Istanbul, Ankara, Sivas, and Erzurum, annual CO_2 emissions were calculated as 740 kg-CO_2/year, 599 kg-CO_2/year, 688 kg-CO_2/year, 853 kg-CO_2/year, and 1113 kg-CO_2/year, respectively. Similar to the annual cost analysis, when sunspace without PCM was introduced to the house, CO_2 emissions for Antalya, Istanbul, Ankara, Sivas, and Erzurum were reduced to 694 kg-CO_2/year, 542 kg-CO_2/year, 613 kg-CO_2/year, 786 kg-CO_2/year, and 1025 kg-CO_2/year, respectively. With the PCM addition to the partition walls, these emission rates were further decreased to 634 kg-CO_2/year, 479 kg-CO_2/year, 544 kg-CO_2/year, 720 kg-CO_2/year, and 958 kg-CO_2/year, respectively, for the same locations.

To improve the reduction in CO_2 emission even further, glazing types of the 1-meter sunspaces with optimum phase transition temperatures were analyzed and CO_2 emissions for the optimal glazing types were found as 615 kg-CO_2/year, 476 kg-CO_2/year, 544 kg-CO_2/year, 720 kg-CO_2/year and 941 kg-CO_2/year respectively, for the Antalya, Istanbul, Ankara, Sivas, and Erzurum. With the change of the glazing type, CO_2 reduction was increased up to 172 kg/year in comparison to reference cases while the minimum reduction was increased to 111 kg/year.

4. CONCLUSIONS

The effects of the sunspace and the PCM integration to the partition wall of a detached house on energy consumption, cost-saving, and CO_2 emissions were numerically explored in five different climate zones. For this purpose, six glazing types including single pane, double pane, and triple pane windows, six phase transition temperatures from 19 °C to 29 °C, a phase-stabilized case, an active shading system, and three partition wall constructions, where the PCM is in front, middle or back, were studied to determine the optimum configuration that leads to the highest energy saving. The obtained results were discussed comparatively considering various perspectives such as variation in heating/cooling and annual energy consumption, energy savings, cost savings, and environmental impacts. The main conclusions drawn from the work can be summarized as follows:

- Using an active shading system is an important part of the sunspace system. With the use of an active shading system in combination with PCM, energy consumption can be reduced by up to 4.76%.
- Changing the location of the phase change material inside the partition wall while active shading is on has a slight effect on the energy consumption, below 0.56%.
- The selection of appropriate phase transition temperature is highly dependent on climatic conditions. In general, from the energy consumption and CO_2 emission point of view, while lower phase transition temperature gives better results in colder climates, higher phase transition temperature gives better results in hotter climates.
- The most suitable climatic condition among the considered cities where the use of PCM is the most effective (i.e., the latent heat is exploited the most) is that of Istanbul where the energy requirement is reduced by 14.62% with the utilization of PCM compared to that of the PSM case.
- The maximum reduction rate in the energy consumption with introducing the phase transition temperature optimized PCM to 1-meter sunspace with SG-1 was seen in Istanbul with 11.55%, while the minimum reduction rate was found in Erzurum with 6.52%.

- Optimum cases for heating and cooling applications are different from each other. Therefore, all-year thermal analyses are required to find the optimal sunspace configuration.
- Sunspace integration to the house without PCM can reduce electricity consumption by up to 10.91%.
- It is seen that optimizing the glazing type for the PCM introduced sunspace can further reduce the energy consumption, by up to around 3%. However, since the effect of this parameter is lower compared to other parameters such as phase transition temperature, and upgrading the glazing type can be costly, conducting a feasibility analysis about changing the glazing type is recommended.
- A sunspace glass with a high U-value and low SHGC performed better in the summer season, whereas a glass with a low U-value and high SHGC performed better in winter. However, yearly energy analyses showed the optimal glazing type varies in different locations and can be different from the best glazing types for both winter and summer.

To sum up, the integration of PCM into the partition wall between the living room and the sunspace provided considerable advantages from both the heating and cooling perspectives. However, it was noted that an optimization study is necessary, especially to select an appropriate PCM phase change temperature which significantly affects the thermal performance of the sunspace. It was also shown that the selection of the appropriate glazing type is of great importance for the heating and cooling energy requirement. In general, it can be stated that the utilization of PCM in a glazed sunspace is a promising technique to enhance energy efficiency. In this context, future work can be dedicated to the exploration of the thermal performance of PCM-sunspace for various climatic conditions with the use of different PCM types, different sunspace designs (sunspace width), and different glazing types.

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APPENDICES

APPENDIX-A

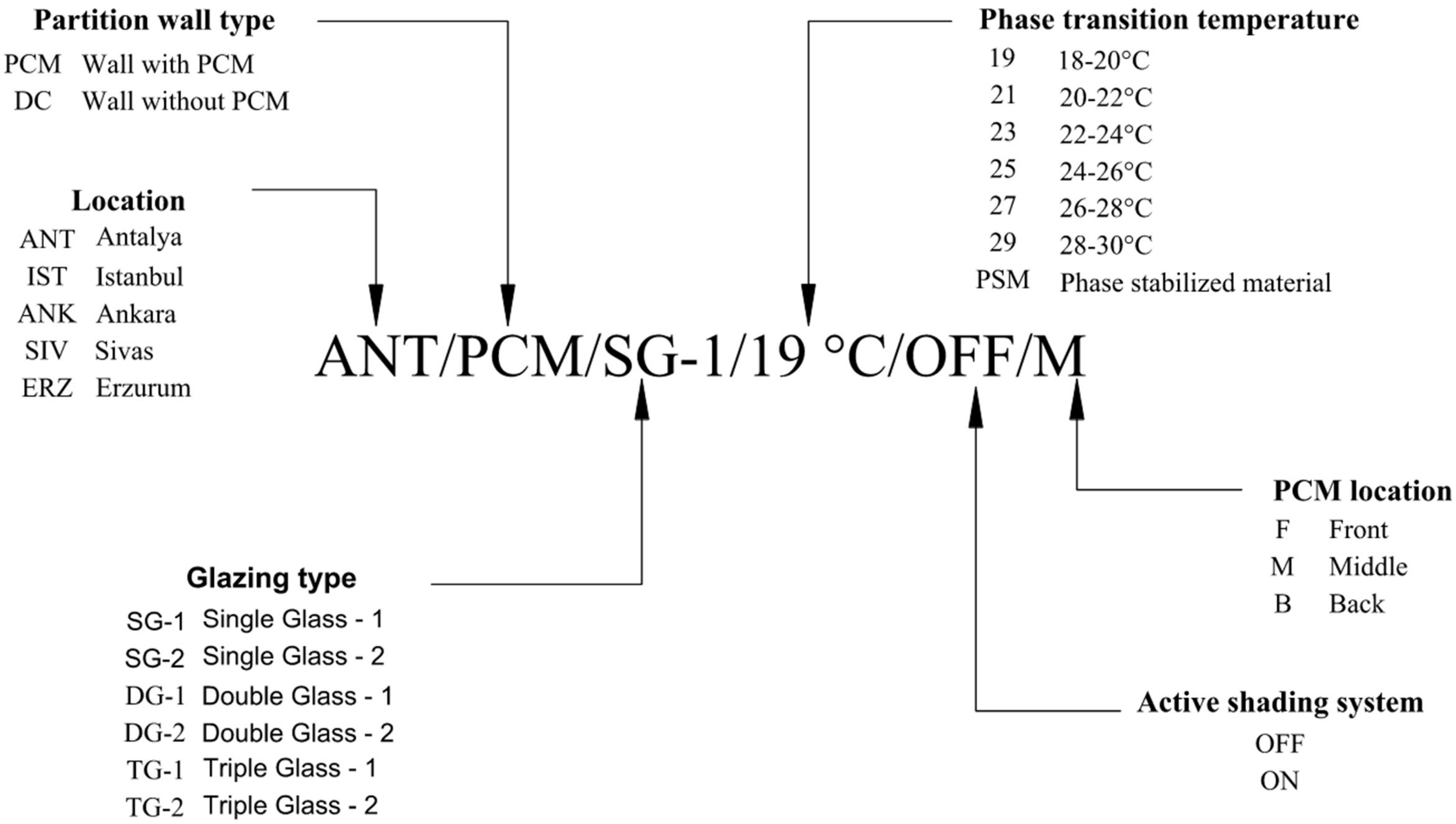

Figure A.1. Case Naming

APPENDIX-B

Table B.1. Seasonal Cooling Demand and Heating Demand Without Active Shading System

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
IST/PCM/SG-1/19/OFF/M	434	4231	1117	6	5787	473	0	206	1846	2525
IST/PCM/SG-1/21/OFF/M	442	4231	1115	6	5794	475	0	207	1850	2532
IST/PCM/SG-1/23/OFF/M	472	4084	933	10	5498	457	0	203	1887	2547
IST/PCM/SG-1/25/OFF/M	478	4084	949	10	5522	460	0	204	1879	2544
IST/PCM/SG-1/27/OFF/M	483	4076	968	10	5537	463	0	205	1876	2545
IST/PCM/SG-1/29/OFF/M	570	3538	958	18	5083	471	0	203	1901	2575
IST/PCM/SG-1/PSM/OFF/M	713	4317	1286	11	6327	515	0	222	1996	2734

APPENDIX-C

Table C.1. Seasonal Cooling Demand and Heating Demand for Different PCM Locations

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
IST/PCM/SG-1/19 °C/ON/F	509	4023	1118	0	5650	503	0	224	1850	2577
IST/PCM/SG-1/19 °C/ON/M	503	4024	1123	0	5649	505	0	224	1848	2577
IST/PCM/SG-1/19 °C/ON/B	499	4024	1128	0	5651	507	0	224	1849	2580
IST/PCM/SG-1/21 °C/ON/F	496	4018	1036	2	5551	477	0	218	1830	2525
IST/PCM/SG-1/21 °C/ON/M	498	4018	1031	2	5549	477	0	218	1820	2515
IST/PCM/SG-1/21 °C/ON/B	493	4022	1027	1	5543	476	0	219	1816	2511
IST/PCM/SG-1/23 °C/ON/F	422	3971	942	6	5341	475	0	207	1850	2532
IST/PCM/SG-1/23 °C/ON/M	416	3974	996	6	5392	473	0	206	1846	2525
IST/PCM/SG-1/23 °C/ON/B	407	3988	1001	6	5402	471	0	206	1839	2516
IST/PCM/SG-1/25 °C/ON/F	477	3801	846	10	5135	463	0	205	1876	2545
IST/PCM/SG-1/25 °C/ON/M	474	3811	845	10	5139	460	0	204	1879	2544
IST/PCM/SG-1/25 °C/ON/B	468	3809	838	10	5125	458	0	203	1887	2547
IST/PCM/SG-1/27 °C/ON/F	566	3215	951	18	4750	471	0	203	1901	2575
IST/PCM/SG-1/27°C/ON/M	571	3193	955	20	4739	470	0	203	1901	2573
IST/PCM/SG-1/27°C/ON/B	576	3163	960	22	4721	468	0	202	1902	2573
IST/PCM/SG-1/29 °C/ON/F	667	3429	1074	25	5194	469	0	202	1920	2591
IST/PCM/SG-1/29 °C/ON/M	685	3429	1092	29	5235	468	0	201	1919	2587
IST/PCM/SG-1/29 °C/ON/B	704	3429	1113	34	5280	468	0	201	1920	2588
IST/PCM/SG-1/PSM/ON/F	625	4061	1172	11	5867	517	0	222	1996	2736
IST/PCM/SG-1/PSM/ON/M	626	4063	1174	11	5873	517	0	222	1996	2736
IST/PCM/SG-1/PSM/ON/B	625	4063	1173	10	5871	517	0	222	1997	2737

APPENDIX-D

Table D.1. Seasonal Cooling Demand and Heating Demand for Different Phase Transition Temperatures and Glazing Types

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
ANT/Reference	1419	6332	2597	286	10635	147	0	135	825	1108
ANT/DC/SG-1	1351	6172	2470	210	10203	98	0	95	645	838
ANT/PCM/SG-1/19/ON/M	1241	6444	2399	14	10097	124	0	109	715	948
ANT/PCM/SG-1/21/ON/M	1255	6444	2388	39	10125	113	0	107	666	886
ANT/PCM/SG-1/23/ON/M	1163	6430	2332	78	10003	104	0	101	626	831
ANT/PCM/SG-1/25/ON/M	1229	6384	2136	125	9875	96	0	97	592	785
ANT/PCM/SG-1/27/ON/M	1197	6257	2146	189	9789	88	0	91	565	744
ANT/PCM/SG-1/29/ON/M	1365	5665	2082	268	9380	82	0	85	544	711
ANT/PCM/SG-1/PSM/ON/M	1442	6494	2503	166	10605	95	0	92	633	820
ANT/PCM/SG-2/29/ON/M	1259	5445	2062	121	8887	102	0	86	685	874
ANT/PCM/DG-1/29/ON/M	1375	6115	2312	283	10086	81	0	85	531	697
ANT/PCM/DG-2/29/ON/M	1358	5549	2076	242	9226	84	0	85	561	730
ANT/PCM/TG-1/29/ON/M	1381	6485	2391	290	10547	81	0	84	526	691
ANT/PCM/TG-2/29/ON/M	1363	5597	2079	253	9292	82	0	85	552	719
IST/Reference	699	4005	1300	32	6035	616	0	275	2227	3117
IST/DC/SG-1	567	3799	1150	18	5534	524	0	226	2007	2757
IST/PCM/SG-1/19 /ON/M	503	4024	1123	0	5649	505	0	224	1848	2577
IST/PCM/SG-1/21/ON/M	498	4018	1031	2	5549	477	0	218	1820	2515
IST/PCM/SG-1/23/ON/M	416	3974	996	6	5392	473	0	206	1846	2525
IST/PCM/SG-1/25/ON/M	474	3811	845	10	5139	460	0	204	1879	2544
IST/PCM/SG-1/27/ON/M	571	3193	955	20	4739	470	0	203	1901	2573
IST/PCM/SG-1/29/ON/M	685	3429	1092	29	5235	468	0	201	1919	2587

Table D.1. Seasonal Cooling Demand and Heating Demand for Different Phase Transition Temperatures and Glazing Types (Continue)

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
IST/PCM/SG-1/PSM/ON/M	626	4063	1174	11	5873	517	0	222	1996	2736
IST/PCM/SG-2/27/ON/M	527	3140	924	2	4593	556	0	236	2138	2931
IST/PCM/DG-1/27/ON/M	590	3710	973	26	5300	427	0	192	1778	2397
IST/PCM/DG-2/27/ON/M	570	3164	956	18	4708	478	0	203	1925	2607
IST/PCM/TG-1/27/ON/M	596	4232	1005	36	5869	417	0	180	1667	2264
IST/PCM/TG-2/27/ON/M	575	3177	961	19	4731	462	0	199	1874	2536
ANK/Reference	423	2650	876	41	3990	1077	6	1074	3964	6122
ANK/DC/SG-1	300	2494	710	22	3526	914	3	934	3627	5478
ANK/PCM/SG-1/19/ON/M	209	2662	625	0	3497	875	3	887	3273	5038
ANK/PCM/SG-1/21/ON/M	168	2604	627	1	3401	826	3	844	3261	4934
ANK/PCM/SG-1/23/ON/M	213	2524	593	3	3333	783	3	822	3375	4982
ANK/PCM/SG-1/25/ON/M	279	2208	489	6	2981	780	2	817	3397	4997
ANK/PCM/SG-1/27/ON/M	356	2088	574	10	3027	816	2	838	3477	5133
ANK/PCM/SG-1/29/ON/M	431	2298	676	15	3420	813	2	863	3515	5193
ANK/PCM/SG-1/PSM/ON/M	334	2730	740	12	3816	890	2	923	3607	5423
ANK/PCM/SG-2/25/ON/M	262	1890	480	2	2634	922	2	960	3814	5699
ANK/PCM/DG-1/25/ON/M	288	2763	724	6	3780	744	2	778	3195	4719
ANK/PCM/DG-2/25/ON/M	81	1523	1292	6	2901	1634	22	164	3367	5187
ANK/PCM/TG-1/25/ON/M	290	2982	830	6	4108	743	2	766	3066	4577
ANK/PCM/TG-2/25/ON/M	279	2250	491	5	3025	799	2	835	3480	5116
SIV/Reference	510	2890	710	6	4116	1425	0	1172	5716	8314
SIV/DC/SG-1	422	2807	574	1	3804	1235	0	1038	5378	7652
SIV/PCM/SG-1/19/ON/M	313	3015	482	0	3810	1154	0	986	5143	7282

Table D.1. Seasonal Cooling Demand and Heating Demand for Different Phase Transition Temperatures and Glazing Types (Continue)

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
SIV/PCM/SG-1/21/ON/M	324	2959	328	0	3611	1100	0	966	5157	7224
SIV/PCM/SG-1/23/ON/M	355	2787	355	0	3498	1104	0	962	5179	7244
SIV/PCM/SG-1/25/ON/M	395	2368	427	0	3189	1094	0	957	5203	7254
SIV/PCM/SG-1/27/ON/M	480	2396	515	0	3391	1091	0	961	5226	7278
SIV/PCM/SG-1/29/ON/M	553	2622	614	0	3790	1165	0	960	5291	7416
SIV/PCM/SG-1/PSM/ON/M	467	3053	597	0	4117	1211	0	1026	5355	7592
SIV/PCM/SG-2/25/ON/M	377	2215	413	0	3004	1272	0	1052	5510	7834
SIV/PCM/DG-1/25/ON/M	402	2913	433	0	3748	1054	0	915	4966	6935
SIV/PCM/DG-2/25ON/M	391	2318	425	0	3134	1185	0	947	5212	7344
SIV/PCM/TG-1/25/ON/M	433	3170	464	0	4068	1002	0	877	4830	6709
SIV/PCM/TG-2/25/ON/M	395	2466	429	0	3289	1148	0	930	5109	7186
ERZ/Reference	230	2068	706	0	3004	2746	2	2288	7853	12889
ERZ/DC/SG-1	170	1945	564	0	2679	2486	1	2070	7386	11942
ERZ/PCM/SG-1/19/ON/M	96	2031	465	0	2592	2217	1	1893	6976	11087
ERZ/PCM/SG-1/21/ON/M	124	2009	422	0	2555	2170	1	1971	7078	11220
ERZ/PCM/SG-1/23/ON/M	156	1768	452	0	2375	2200	1	1968	7303	11472
ERZ/PCM/SG-1/25/ON/M	189	1563	437	0	2189	2298	1	1974	7321	11593
ERZ/PCM/SG-1/27/ON/M	227	1749	517	0	2493	2376	0	1972	7327	11675
ERZ/PCM/SG-1/29/ON/M	254	1959	608	0	2821	2411	0	1985	7325	11721
ERZ/PCM/SG-1/PSM/ON/M	196	2150	578	0	2924	2444	0	2051	7361	11856
ERZ/PCM/SG-2/19/ON/M	95	1717	385	0	2197	2455	1	2110	7584	12150
ERZ/PCM/DG-1/19/ON/M	146	2377	528	0	3051	2164	0	1821	6522	10508
ERZ/PCM/DG-2/19/ON/M	115	2012	450	0	2577	2242	0	1924	7180	11346

Table D.1. Seasonal Cooling Demand and Heating Demand for Different Phase Transition Temperatures and Glazing Types (Continue)

Case Code	Cooling Demand (kWh)					Heating Demand (kWh)				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
ERZ/PCM/TG-1/19/ON/M	174	2542	612	0	3328	2158	0	1803	6280	10241
ERZ/PCM/TG-2/19/ON/M	125	2143	487	0	2755	2167	0	1824	6721	10712

APPENDIX-E

Table E.1. Annual Utility Costs and CO_2 Emissions

Case Code	Total Cooling Demand (kWh)	Total Heating Demand (kWh)	Energy Consumption (kWh)	Utility Costs ($/year)	CO_2 Emissions ($kgCO_2$/year)
ANT/Reference	10635	1108	2708	192	740
ANT/DC/SG-1	10203	838	2539	180	694
ANT/PCM/SG-1/19/ON/M	10097	948	2544	181	695
ANT/PCM/SG-1/21/ON/M	10125	886	2534	180	692
ANT/PCM/SG-1/23/ON/M	10003	831	2492	177	681
ANT/PCM/SG-1/25/ON/M	9875	785	2451	174	670
ANT/PCM/SG-1/27/ON/M	9789	744	2421	172	661
ANT/PCM/SG-1/29/ON/M	9380	711	2319	165	634
ANT/PCM/SG-1/PSM/ON/M	10605	820	2626	186	718
ANT/PCM/SG-2/29/ON/M	8887	874	2250	160	615
ANT/PCM/DG-1/29/ON/M	10086	697	2475	176	676
ANT/PCM/DG-2/29/ON/M	9226	730	2289	163	625
ANT/PCM/TG-1/29/ON/M	10547	691	2579	183	705
ANT/PCM/TG-2/29/ON/M	9292	719	2301	163	629
IST/Reference	6035	3117	2192	156	599
IST/DC/SG-1	5534	2757	1983	141	542
IST/PCM/SG-1/19 /ON/M	5649	2577	1962	139	536
IST/PCM/SG-1/21 /ON/M	5549	2515	1923	137	525
IST/PCM/SG-1/23 /ON/M	5392	2525	1890	134	516
IST/PCM/SG-1/25/ON/M	5139	2544	1837	130	502

Table E.1. Annual Utility Costs and CO_2 Emissions (Continue)

Case Code	Total Cooling Demand (kWh)	Total Heating Demand (kWh)	Energy Consumption (kWh)	Utility Costs ($/year)	CO_2 Emissions ($kgCO_2$/year)
IST/PCM/SG-1/27/ON/M	4739	2573	1754	125	479
IST/PCM/SG-1/29/ON/M	5235	2587	1871	133	511
IST/PCM/SG-1/PSM /ON/M	5873	2736	2055	146	561
IST/PCM/SG-2/27/ON/M	4593	2931	1815	129	496
IST/PCM/DG-1/27/ON/M	5300	2397	1835	130	501
IST/PCM/DG-2/27/ON/M	4708	2607	1756	125	480
IST/PCM/TG-1/27/ON/M	5869	2264	1930	137	527
IST/PCM/TG-2/27/ON/M	4731	2536	1743	124	476
ANK/Reference	3990	6122	2518	179	688
ANK/DC/SG-1	3526	5478	2243	159	613
ANK/PCM/SG-1/19/ON/M	3497	5038	2120	151	579
ANK/PCM/SG-1/21/ON/M	3401	4934	2071	147	566
ANK/PCM/SG-1/23/ON/M	3333	4982	2068	147	565
ANK/PCM/SG-1/25/ON/M	2981	4997	1992	141	544
ANK/PCM/SG-1/27/ON/M	3027	5133	2039	145	557
ANK/PCM/SG-1/29/ON/M	3420	5193	2144	152	586
ANK/PCM/SG-1/PSM/ON/M	3816	5423	2294	163	627
ANK/PCM/SG-2/25/ON/M	2634	5699	2098	149	573
ANK/PCM/DG-1/25/ON/M	3780	4719	2101	149	574
ANK/PCM/DG-2/25/ON/M	2901	5187	2024	144	553
ANK/PCM/TG-1/25/ON/M	4108	4577	2138	152	584

Table E.1. Annual Utility Costs and CO_2 Emissions (Continue)

Case Code	Total Cooling Demand (kWh)	Total Heating Demand (kWh)	Energy Consumption (kWh)	Utility Costs ($/year)	CO_2 Emissions ($kgCO_2$/year)
ANK/PCM/TG-2/25/ON/M	3025	5116	2034	144	556
SIV/Reference	4116	8314	3123	222	853
SIV/DC/SG-1	3804	7652	2878	204	786
SIV/PCM/SG-1/19/ON/M	3810	7282	2782	198	760
SIV/PCM/SG-1/21/ON/M	3611	7224	2722	193	744
SIV/PCM/SG-1/23/ON/M	3498	7244	2701	192	738
SIV/PCM/SG-1/25/ON/M	3189	7254	2634	187	720
SIV/PCM/SG-1/27/ON/M	3391	7278	2686	191	734
SIV/PCM/SG-1/29/ON/M	3790	7416	2813	200	769
SIV/PCM/SG-1/PSM/ON/M	4117	7592	2934	208	802
SIV/PCM/SG-2/25/ON/M	3004	7834	2744	195	750
SIV/PCM/DG-1/25/ON/M	3748	6935	2677	190	731
SIV/PCM/DG-2/25/ON/M	3134	7344	2645	188	723
SIV/PCM/TG-1/25/ON/M	4068	6709	2690	191	735
SIV/PCM/TG-2/25/ON/M	3289	7186	2639	187	721
ERZ/Reference	3004	12889	4075	289	1113
ERZ/DC/SG-1	2679	11942	3752	266	1025
ERZ/PCM/SG-1/19/ON/M	2592	11087	3507	249	958
ERZ/PCM/SG-1/21/ON/M	2555	11220	3533	251	965
ERZ/PCM/SG-1/23/ON/M	2375	11472	3559	253	972
ERZ/PCM/SG-1/25/ON/M	2189	11593	3548	252	969

Table E.1. Annual Utility Costs and CO_2 Emissions (Continue)

Case Code	Total Cooling Demand (kWh)	Total Heating Demand (kWh)	Energy Consumption (kWh)	Utility Costs ($/year)	CO_2 Emissions ($kgCO_2$/year)
ERZ/PCM/SG-1/27/ON/M	2493	11675	3639	258	994
ERZ/PCM/SG-1/29/ON/M	2821	11721	3726	265	1018
ERZ/PCM/SG-1/PSM/ON/M	2924	11856	3785	269	1034
ERZ/PCM/SG-2/19/ON/M	2197	12150	3697	262	1010
ERZ/PCM/DG-1/19/ON/M	3051	10508	3459	246	945
ERZ/PCM/DG-2/19/ON/M	2577	11346	3572	254	976
ERZ/PCM/TG-1/19/ON/M	3328	10241	3451	245	943
ERZ/PCM/TG-2/19/ON/M	2755	10712	3445	245	941

APPENDIX F

Table F.1. Details of the Climatic Conditions for Selected Cities

	Heating Degree Day @ 18.3°C	Cooling Degree Day @ 23.3°C	Heating Dry Bulb Temperature 99% (°C)	Humidity Ratio 99% (g/kg dry air)	Cooling Dry Bulb Temperature 1% (°C)	Mean Coincident Wet Bulb Temperature %1 (°C)	Extreme Annual Wind Speed 1% (m/s)
Antalya	995	14152	3.1	1.7	36.8	20.1	10.6
Istanbul	1811	4887	-0.2	2.5	30.6	21.2	11.2
Ankara	3169	4255	-11.2	0.9	32	16.9	8.8
Sivas	3467	2794	-14.4	1	30.7	17.3	8.1
Erzurum	4941	1753	-26.1	0.3	29	14.7	10.1

APPENDIX G

Table G.1. Details of Surface Roughness Multiplier

Roughness Index	Rf	Example Material
1 (Very Rough)	2.17	Stucco
2 (Rough)	1.67	Brick
3 (Medium Rough)	1.52	Concreate
4 (Medium Smooth)	1.13	Clear Pine
5 (Smooth)	1.11	Smooth Plaster
6 (Very Smooth)	1	Glass

Table G.2. Details of a and b Constants

Wind Direction	a	b
Windward	3.26	0.89
Leeward	3.55	0.617

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BIOGRAPHY

Murat Çağrı Uludaş finished primary school and high school in Kocaeli. He was accepted to the Department of Mechanical Engineering at the Faculty of Engineering, Kocaeli University, and graduated in 2016. After his graduation, he started working at Korfez ETA Engineering as a mechanical engineer. In 2019, he was accepted for the master's program at the Department of Mechanical Engineering at Kocaeli University, Graduate School of Natural and Applied Sciences. He relocated to the United Kingdom and opened Uludas Consultancy in 2020. He is still acting as director at Uludas Consultancy.