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THE EFFECTS OF GLAZING AREA INTERVENTIONS AND PCM APPLICATION IN BUILDING ENERGY RETROFITS

Hasan Tunay CENGİZ

MASTER OF SCIENCE THESIS
Department of Architecture
Building Physics Program

Advisor
Prof. Dr. Gülay ZORER GEDİK

Co-Advisor
Assist. Prof. Dr. Ezgi KORKMAZ

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A thesis submitted by Hasan Tunay CENGİZ in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 30.06.2021 in Department of Architecture, Building Physics Program.

Prof. Dr. Gülay ZORER GEDİK
Yıldız Technical University
Advisor

Assist. Prof. Dr. Ezgi KORKMAZ
Yıldız Technical University
Co-Advisor

Approved By the Examining Committee

Prof. Dr. Gülay ZORER GEDİK, Advisor
Yıldız Technical University _____

Prof. Dr. Gül KOÇLAR ORAL, Member
İstanbul Technical University _____

Assist. Prof. Dr. Suzi Dilara MANGAN, Member
Yıldız Technical University _____

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Hasan Tunay CENGİZ

Signature

Dedicated to UCSA

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LIST OF SYMBOLS

ac/h	Air Changes per Hour
ΔT	Change in Temperature
clo	Clothing Insulation Unit
f	Decrement Factor
kWh	Kilowatt-Hour
kWh/m^2	Kilowatt-Hour per Square Meter
L_f	Latent Heat of Fusion
L_s	Latent Heat of Sublimation
L_v	Latent Heat of Vaporization
lx	Luminous Flux per Unit Area
m	Mass
c	Specific Heat Capacity
L	Specific Latent Heat
ΔQ_l	Stored Energy in Latent Heat
ΔQ_s	Stored Energy in Sensible Heat
U	Thermal Transmittance (W/m^{2}K)
ϕ	Time Lag
V	Volume
W/m^{2}K	Watts per Square Meter-Kelvin

LIST OF ABBREVIATIONS

BES	Building Energy Simulation
DHW	Domestic Hot Water
EPS	Expanded Polystyrene
EU	European Union
GBPN	Global Building Performance Network
GHG	Greenhouse Gas
HSA	Horizontal Shadow Angle
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IWEC	International Weather for Energy Calculation
İDEP	Climate Change National Action Plan of Turkey
LHS	Latent Heat Storage
LTRS	Long-term Renovation Strategy
NZEB	Nearly Zero-energy Buildings
OECD	Organisation for Economic Co-operation and Development
PCM	Phase Change Material
PVC	Polyvinyl Chloride
RCP	Representative Concentration Pathway
SHGC	Solar Heat Gain Coefficient
SHS	Sensible Heat Storage
TES	Thermal Energy Storage
TMY	Typical Meteorological Year

TOKİ	Housing Development Administration of the Republic of Turkey
TPES	Total Primary Energy Supply
VSA	Vertical Shadow Angle
WMO	World Meteorological Organization
XPS	Extruded Polystyrene

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ABSTRACT

The Effects of Glazing Area Interventions and PCM Application in Building Energy Retrofits

Hasan Tunay CENGİZ

Department of Architecture
Master of Science Thesis

Advisor: Prof. Dr. Gülay ZORER GEDİK
Co-advisor: Assist. Prof. Dr. Ezgi KORKMAZ

The buildings and construction sector is responsible for 39% of CO_2 emissions in the world which have a direct impact on climate change. To mitigate these effects of the sector, the existing building stock needs to be improved. One of the methods for improving the building stock is to enhance the physical properties of the building envelopes with building energy retrofits.

Turkey's climate will gradually get warmer and drier with unstable precipitation with the effect of climate change. Furthermore, it is reported that the temperature increases in the summer period in the world between 2016-2100 will be higher than the increases in the winter period. Due to this trend, the importance of reducing the cooling loads of the buildings in the summer period is increasing.

The aim of this study is to show the effect of a series of building envelope interventions on the energy consumption of existing buildings located in different climates. The regions where the application example is located are İstanbul with temperate-humid and Diyarbakır with dry-hot climate, and the selected energy retrofit interventions are solar shading implementation, glass system replacement and phase change material application.

The thesis study consists of four chapters.

In the first chapter, the background of the subject is explained, the studies on the subject are evaluated, the aim, scope, methodology and hypotheses of the thesis are

explained.

In the second chapter, the concepts and variables used in the thesis are explained.

In the third chapter, the specifications of the application example building are explained, the energy consumption of the base case of the building is calculated, the properties of the energy retrofit interventions are explained in detail, and the energy consumption of each intervention is shown.

In the fourth chapter, the results and discussions of the thesis study are presented.

Keywords: Building energy retrofits, building energy efficiency, glazing area interventions, solar shading implementation, phase change materials

ÖZET

Bina Enerji İyileştirmelerinde Cam Alan Değişimlerinin ve FDM Uygulamasının Etkileri

Hasan Tunay CENGİZ

Mimarlık Anabilim Dalı
Yüksek Lisans Tezi

Danışman: Prof. Dr. Gülay ZORER GEDİK
Eş-Danışman: Dr. Öğr. Üyesi Ezgi KORKMAZ

Uluslararası Enerji Ajansı'nın Binalar ve Yapılar İçin Küresel Durum Raporu 2019'a göre bina ve inşaat sektörü, dünyada toplam enerji tüketiminin %36'sından ve CO_2 salımının %39'undan sorumludur. Bu salımların iklim değişikliğine doğrudan etkisi olduğu bilinmektedir. Sektörün enerji tüketimi ve sera gazı salımını azaltmak için mevcut yapı stokunun iyileştirilmesi gerekmektedir. Bu iyileştirme için uygulanabilecek yöntemlerden birisi, yıkıp yeniden yapmadan, enerji iyileştirme müdahaleleriyle binaların yapı kabuğu fiziksel özelliklerini güçlendirmektir.

İklim değişikliği etkisiyle Türkiye'nin ikliminin giderek daha sıcaklaşacağı ve kuraklaşacağı, bununla birlikte değişken yağışların görüleceği bilinmektedir. Ayrıca, IPCC'nin 5. Değerlendirme Raporu'na göre 2016-2100 yılları arasında dünyada yaz dönemindeki sıcaklık artışlarının, kış dönemindeki sıcaklık artışlarından fazla olacağı bildirilmektedir. Bu eğilimden ötürü, mevcut binaların iyileştirilmesi için yapılacak müdahalelerde, yaz dönemindeki soğutma yüklerinin düşürülmesinin önemi artmaktadır.

İklim değişikliğine uyum ve azaltım hedeflerinin dikkate alındığı bu çalışmanın amacı, farklı iklimlerde mevcut bir yapıya uygulanan bir dizi bina kabuğu müdahalesinin tekil olarak ve kombinasyonlarıyla birlikte uygulandığında binanın enerji tüketimine olan etkisini göstermektir. Uygulama örneğinin yapıldığı bölgeler ılıman nemli iklime sahip İstanbul ve sıcak kuru iklime sahip Diyarbakır şehirleri, seçilen iyileştirme müdahaleleri ise güneş kırıcı uygulaması, cam sistemi değişikliği ve faz değiştiren

malzeme uygulamasıdır.

Tez çalışması dört bölümden oluşmaktadır.

İlk bölümde, enerji tüketimi ve karbon salımıyla ilgili yaşanan sorunlar ortaya konulmuş, konuyla ilgili literatürde yapılan çalışmalar değerlendirilmiş, tezin amacı, kapsamı ve yöntemi anlatılmış ve çalışmanın hipotezleri listelenmiştir.

İkinci bölümde, tez çalışmasında kullanılan kavramlar ve değişkenler anlatılmıştır.

Üçüncü bölümde, tezin yöntemi listelenmiş, uygulama örneğinin özellikleri ve detayları açıklanmış, mevcut halinin enerji tüketimi hesaplanmış, enerji iyileştirme müdahalelerinin özellikleri detaylı olarak anlatılmış ve her bir müdahalenin tekil ve kombinasyonlarıyla oluşturduğu enerji tüketimleri gösterilmiştir.

Dördüncü bölümde, tez kapsamında elde edilen sonuç ve öneriler sunulmuştur.

Anahtar Kelimeler: Bina enerji iyileştirmeleri, binalarda enerji verimliliği, cam alan değişimleri, güneş kırıcı uygulaması, faz değiştiren malzemeler

1
INTRODUCTION

1.1 Literature Review

"*The greenest building is... one that is already built.*" [1].

The sun is the primary source that powers life on earth through heat. It continuously emits energy outward into space and some of this energy refracts into atmosphere. While the earth absorbs part of the solar radiation, it reflects the rest back to space as light and heat energy. Surface temperature of the earth is based on this absorbed-reflected energy balance. Natural or man-made sources can affect this balance. Greenhouse gases (GHG) are one of these sources that absorb and emit the solar radiation reflected from the surface of the earth and cause the heat to be trapped in the atmosphere [2]. It is known that the increase of GHG concentration contributes to the phenomenon called climate change which includes rising temperatures, extreme weather events, shifting wildlife populations and habitats and rising sea-levels [3].

According to the Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), the concentration of GHGs such as carbon dioxide, methane and nitrous oxide in the atmosphere has increased unprecedentedly since 1750s because of human activities. The increase in carbon dioxide concentration is by 40% compared to the pre-industrial era and based upon fossil fuel usage and net land use change emissions [4].

Fossil fuel combustion is still the primary method for energy generation in the world. Because of that energy consumption is one of the major causes of GHG emissions. As of 2019, percentages of total energy supply sources in Organisation for Economic Co-operation and Development (OECD) countries are [5];

- Oil by 35.3%
- Coal by 14.4%
- Natural gas by 29.1%

- Nuclear by 9.7%
- Bio-fuels and waste by 6.3%
- Hydro by 2.3%
- Geothermal, solar, wind, tide/wave/ocean, heat and other sources by 2.9%.

Moreover, according to 2018 data, 36% of this largely nonrenewable source based energy is consumed in buildings and construction sector, which is also responsible for 39% of energy based CO_2 emissions with residential buildings being the major contributor [6].

Because of the high existent concentration and continued emissions of GHGs, mainly CO_2, the effects of global warming could escalate in the future. According to Representative Concentration Pathway (RCP) scenarios of IPCC, surface temperature will increase at a minimum of 1.5°C at the end of the 21st century [4].

The United Nations Framework Convention on Climate Change (UNFCCC) treaty was signed in 1992 to stabilize GHG concentration in the atmosphere that would prevent interference with climate systems. From 1995, parties of the treaty met annually in meetings called Conference of Parties (COPs) to assess their progress in dealing with climate change. Kyoto Protocol was accepted at the third COP, and a promise made by EU-15 and 11 more countries in Europe to reduce greenhouse gas emissions by 8% lower than 1990 levels until 2008/2012 period [7]. The protocol was signed in 1997 and entered into force in 2005 because of the multilateral nature of the negotiations. Then in COP21, Paris Agreement entered into an agreement on 12 December 2015 by 195 nations, including Turkey to combat climate change [8].

In 2016, the total GHG emissions in Turkey were 496.1 million tonnes CO_2 equivalent, and 72.8% of this emission was energy-based with 40% of this energy consumption originates from households and commercial sector [9]. Moreover, according to the Ministry of Energy and Natural Resources data, Turkey's foreign dependency rate of energy demand in 2017 is 75.7% [10]. These statistics point out the need to increase energy efficiency in buildings.

To reduce the dependence on foreign energy sources and to provide direction for new building and retrofit projects, "Thermal Insulation Regulation in Buildings" entered into force in 2008 and insulated building envelopes became the norm in Turkey. "Energy Performance Regulation in Buildings" also came into force in 2008 and updated in 2010 following the European Parliament's directive 2010/31/EU as another guide for energy efficiency. The measures that were taken into consideration

in these regulations are mainly to increase performance of the buildings in winter conditions.

However, Climate Change National Action Plan (İDEP) of Turkey, released in 2011, reported that the expected increase in the annual average temperature in Turkey is by 2.5-4°C, in the Aegean and Eastern Anatolia regions by 4°C and in the inner regions by 5°C. According to the Plan, reported increases will affect the climate of Turkey to be warmer, more arid and with unstable precipitation [11]. According to the 2020 statistics of the Turkish State Meteorological Service, the average temperatures in Turkey increased linearly, supporting the İDEP. While the average temperature was 12.8°C in 2011, it increased to 14.6°C in 2020 [12].

In addition, seasonal differences are expected in temperature increases. According to the RCP scenarios of the fifth assessment of IPCC, temperature increases in the summer periods between 2016 and 2100 are expected to be higher than in the winter periods [13]. Long-term trends between 1950-2010 period shows statistically significant increasing trends especially in Marmara, Aegean, Mediterranean, Central Anatolia and South-eastern Anatolia in spring, summer and winter mean temperatures [14]. Because of these trends, relative decreases in the heating loads in the winter periods and serious increases in expected cooling loads in the summer periods could be predicted.

In order to reach the goal of adaptation and mitigation to climate change along with energy independence, it is necessary to make new constructions energy-efficient and improve the building physical properties of the existing buildings. According to the International Energy Agency (IEA) approximately 60% of the existing building stock could still be in use by 2050 [15]. In Turkey, the studies in the European Union (EU) harmonization process are leading the way on improving the built environment by urban renewal projects. However, the strategy implemented in Turkey is about demolishing and reconstruction the existing building stock which could cause inefficient resource uses, additional energy consumption and gentrification [16]. Building energy retrofits are a way to prevent this inefficiency and additional energy consumption. The primary goal in retrofitting existing structures is to reduce the operational impact of the building stock on the environment with no demolition and reconstruction.

Retrofit means improving the existing building stock with small or large interventions. These practices can greatly increase the thermophysical properties and enhance the energy performance of the buildings while helping reduce the carbon emissions, making existing buildings to be energy efficient and sustainable.

The thermophysical performance of a building depends on the total thermal transmittance (U-value), transparency ratio, time lag (ϕ) and decrement factor (f) of the solid component of the building envelope. In this context, it is known that the sheathing and insulation application, which is the main retrofit practice in Turkey, increases the energy efficiency of buildings in winter (steady-state) period. However, it is expected that climate change will escalate energy consumption during the summer (transient) period. For this reason, the retrofits to be made should prevent the buildings from overheating during the summer period. Therefore, in this study, two variables known to influence energy consumption during the summer period are considered: glazing areas and thermal mass.

Glazing areas are the most problematic areas in the building envelope because of their heat transfer specifications and greenhouse effect. Since glass is a dense and thin material, its thermal resistance is lower than solid surfaces, and hence heat loss is mostly from glass surfaces in winter. Moreover, in the summer, direct solar energy gains occur from glass surfaces and cause greenhouse effect which leads to overheating in interior spaces [17]. For this reason, in order for the retrofits to be made in the buildings to have an effect in the summer period, the first intervention should be made on glazing areas. There are two types of treatment in this sense:

- Glass system replacement
- Solar shading implementation.

Another important specification of the building envelope is its thermal mass, which handles retention and release of solar radiation [17]. It is known that adding phase change materials (PCM) to buildings increases the heat capacity during phase transition temperatures, which gives them potential to be used in passive cooling and heating of buildings in retrofit projects because of their thermal properties [18].

Using phase change materials in retrofit projects has been studied through numerical and experimental studies since the beginning of the century.

Koschenz and Lehmann designed a building component that could reduce the cooling loads of an existing office building by balancing the heat gain during the day. The component designed within the research is gypsum ceiling panels with micro-encapsulated paraffin added as PCM. These panels were first tested in the laboratory environment, then placed in the building, and the results were evaluated. According to the study, the ceiling layout comprising a mixture of 5 cm thick PCM (25% by weight) and gypsum reached the comfort temperature in standard office buildings.

It stated in this study that designed ceiling panels are suitable for lightweight buildings and increase the thermal mass of the building in order to compensate for large temperature changes [19].

Kuznik et al. evaluated the use of PCM in a lightweight construction building with low thermal inertia, high internal loads, and large temperature fluctuations. For the study, they selected two adjacent rooms for ease of comparability-one of which was a classical retrofit and the other one had PCM composite wallboard installed in its walls and ceiling. The two rooms observed for one year. Results show that, when inside air temperature fluctuates in the melting and freezing temperature of the PCM, application of PCM wallboards increases thermal comfort in the building [20].

Biswas et al. conducted a series of experiments to develop alternative methods of roof retrofits in buildings. The major purpose of the experiments is to contribute to energy efficiency through interventions in roof reconstructions. The three setups installed for this purpose are (i) a standard shingle roof, (ii) a roof with an infrared reflective coating, (iii) a photovoltaic (PV) cell integrated roof with PCM placed for heat storage. In the winter of 2009 and the summer of 2010, the temperature changes in the attic were measured. Collected data shows that, when compared to the standard shingle roof, PV-PCM integrated roof application reduced heating loads by 30% and cooling loads by 40% in the attic space [21].

Rodriguez-Ubinas et al. evaluated the relationship between window-to-wall ratio and the use of PCM in different climatic regions in Spain in retrofit projects. First, as an experiment, they set up two rooms with a long south-facing facade. They constructed interior walls of these rooms using gypsum wallboards; control room with a standard wallboard, other room with a micro-encapsulated PCM wallboard. Obtained measurement data were used to verify the subsequent simulation study. The primary result of the study is that passive design principles should be considered first in building retrofits, as it should be in newly designed buildings. The correct window-to-wall ratio and the use of PCM gypsum boards increased thermal comfort up to 49%. In addition, the study revealed that the use of PCM shows higher performance in regions with higher diurnal temperature changes [22].

Ascione et al. examined the effects of the use of PCM application on energy efficiency and thermal comfort in retrofit projects in five cities selected from different regions of Europe. The team modeled two identical office buildings in Ankara, Athens, Marseilles, Naples and Seville on EnergyPlus with and without PCM and analyzed the thermal behavior of these buildings between May and September with a series of simulations. PCM-impregnated gypsum boards were on the interior side of exterior

walls. In this study, they took many retrofit scenarios into consideration based on (i) the wall where the PCM was located, (ii) thickness, and (iii) melting temperature parameters of the PCM. Results of the study showed that melting temperature and thickness of the PCM were more important. Also, according to the study, the effect of PCM turned out to be more effective in semi-arid climates with hot dry summers (such as Ankara) compared to regions with a hot Mediterranean climate (such as Seville). Under these conditions, the indoor temperature was almost always remained at the comfort temperature in all buildings except Seville, and the need for heating, ventilation and air conditioning (HVAC) system usage were reduced to a few hours [23].

In a subsequent study, the same team evaluated intervention scenarios for an energy retrofit of a historic university building in Benevento, Italy. The measures in these scenarios include insulation, reduction of the infiltration, replacement of the glass systems in windows and raising the thermal inertia of the building by the use of PCM. First, they evaluated the measures singularly. According to this evaluation, low emissivity (low-E) glazing option showed better performance globally even though it was worse than solar control glazing in summer to reduce cooling loads and the use of PCM on both interior and exterior of building envelope achieved a total energy savings of 16.8% in summer. After that, they reviewed combined actions. It can be clearly seen that the most energy efficient option was the action where both windows replaced with low-E glazing and PCM added to the building, which achieved total energy savings of 39% annually [24].

Berardi and Soudian investigated the relationship between annual heat gain and PCM performance of a high-rise residential block using building energy simulation (BES) in Vancouver and Toronto. They investigated thermal behavior of the building in summer and winter periods using two commercial PCM products as a single composite material. PCMs with low melting temperature of 21.7°C for the heating period and high 23-25°C for the cooling period were selected and the effects of these products were compared using EnergyPlus as BES for units with different window-wall ratios. A significant reduction in heating loads has been achieved in the option, with a high window-to-wall ratio on the south-facing facade. In this option, the effect of PCM in reducing heating loads was negligible. However, it has been revealed that PCM application has a serious effect on the reduction of up to 56% in cooling loads [25].

According to the studies regarding climate change, architectural design practices, new constructions and interventions to existing buildings, should adapt the new norm, which is increasing temperatures and unpredictable weather whilst being more energy-efficient. One of the major methods of adaptation to changes is retrofitting the

existing building stock. The current study includes the facts that literature revealed in terms of architectural precautions for climate change focused in glazing areas and thermal mass of the building materials in retrofit projects. Therefore, in order to regulate the transmission of heat in and out of the building, the opportunities of solar shading devices and glass system changes and, to stabilize the diurnal temperature changes, the efficacy of using PCM are examined.

1.2 Objective of the Thesis

Building up towards energy efficiency is one solutions that is identified for its potential to reduce energy consumption related greenhouse gas emissions that contribute to climate change. Especially, improving aging building stock with retrofit projects is the key challenge the European Union is tackling. The EU is developing new directives and financing mechanisms to address this issue. According to the findings of Task 37 (Advanced Housing Renovation with Solar and Conservation Project) of the International Energy Agency (IEA), Solar Heating and Cooling Programme [26], among 60 retrofit demonstration projects, 13 of the projects reached the Passive House standard reducing their energy demand.

The scene is similar in Turkey. As a developing country, Turkey has a great deal of energy based GHG emission. Nevertheless, according to the World Bank, the construction sector in Turkey has a 30% energy savings potential.

To harvest this potential, Turkey established regulations in 2008 and "National Energy Efficiency Action Plan" in 2017. The measures taken for thermal performance in Turkey are focused on reducing the heating loads of buildings. However, because of climate change, Turkey is evolving into a warmer and unpredictable climate. Therefore, the reduction of the cooling loads as well as heating loads will become increasingly more important.

The aim of the current study is to reveal the effects of solar shading devices, glass system changes and PCM application on the energy consumption of the buildings and to examine the feasibility of these interventions in existing building retrofits in Turkey.

1.3 Hypothesis

High levels of energy efficiency can be achieved with minimal interventions to the building envelope in energy retrofit projects of existing buildings, especially in summer period. Based on this information, four hypotheses have been put forward in this thesis study.

The first hypothesis is that the solar shading application, which provides protection in the inter-equinox period, decreases the summer cooling loads and increases the heating loads in İstanbul and Diyarbakır climates. In Diyarbakır, where the average summer temperature is higher, the decrease in cooling loads is lesser than in İstanbul.

The second hypothesis is that the glass system change is the retrofit intervention with the most energy efficiency provided. If only solar control is aimed at the selection of the glass system, this choice can cause serious increases in energy loads in the winter period. For this reason, a comparison has been made between glass system types in the study.

The third hypothesis is that the use of PCM in retrofit projects provides energy efficiency during the heating and cooling periods in both climates, because of the insulation and heat storage properties of the material. The amount of energy efficiency is higher in Diyarbakır in the summer period where day-night temperature differences are higher than İstanbul.

The fourth hypothesis is that the energy retrofit combination in which all intervention methods are used together provides the highest energy efficiency for the summer period in both climatic regions.

1.4 Scope of the Thesis

This thesis is designed to express the energy savings of intervention options in existing building retrofits in changing climatic conditions because of climate change in Turkey. For this reason, a typical project which is built in different climates in Turkey is selected for the simulation study. Two different climatic zones and provinces have been selected for comparison. These provinces are İstanbul with a humid-temperate summer climate and Diyarbakır with a dry-hot summer climate.

The scope of the current study includes building envelope retrofit strategies; specifically insulation using PCM, replacement of glass system in the windows and solar shading implementation to glazing areas.

1.5 Thesis Methodology

To show the energy efficiency potential and to present a guideline for choosing the selected existing building retrofit interventions whether singular or combined, this thesis uses the methodology as represented below:

- An extensive literature review on existing building retrofits using mainly PCM as an insulation material with the property of adding thermal mass to the buildings to stabilize the interior temperature fluctuations has been made.
- An application example that is a frequently built residential block (TOKİ) in different climatic zones in Turkey has been chosen. The building envelope properties of the application example were defined, the climatic regions to be studied were determined, and the energy performance of the building was measured using building energy simulation software DesignBuilder according to these values.
- Retrofit strategies to apply to the selected building have been defined. The defined interventions are solar shading implementation and replacement of the glass system to glazing areas and installing PCM on external walls and ceilings of conditioned spaces. All the interventions have been analyzed singularly and with their combinations in the selected climatic regions.
- Analyses results have been evaluated.

2
GLAZING AREA INTERVENTIONS AND PHASE CHANGE MATERIAL (PCM) APPLICATION IN BUILDING ENERGY RETROFITS

2.1 Building Energy Retrofits

Sustainability is one of the major focuses in architectural design practices and new constructions for the time being. However, new designs and constructions are only one side of the formula because of the existing buildings in the built environment. The IEA predicts that 60% of the existing building stock will still be in use by the year 2050, which shows that new buildings will only make up for a small share in the near future [15]. Furthermore, new buildings will require either demolitions of old ones or new lands to be developed, which will cause indirect energy consumption and more embodied energy. Therefore, it is imperative to improve the physical conditions of the existing building stock.

Renovation is the broad term describing several interventions in a building. These interventions include whole measures as reconstruction, refurbishment, retrofit and partial treatments as maintenance and repairs. It is important to indicate that there is a general disagreement of the terms used in existing building interventions, especially for energy-efficiency interventions, between European Union and North America. One of the most important causes of this disagreement is the area of the application. A technical report of Global Building Performance Network (GBPN) states that the approach of deep retrofit, which North American experts prefer, defines interventions focused in building services efficiencies whereas deep renovation, energy renovation or building renovation takes building fabric efficiencies into account [27].

Furthermore, European Union is leading the way in energy efficiency by using the potential of existing buildings. By the Amending Energy Performance of Buildings Directive (EPBD) [28], EU member states are needed to establish long-term renovation strategies (LTRS) to develop their existing building stock into nearly zero-energy

buildings (NZEB) by 2050 where NZEB means "a building that has a very high energy performance... The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources [29]."

Nonetheless, in the current study, "building energy retrofit" term has been preferred to express energy efficiency improvements in existing buildings, since it is used more frequently in the literature on the subject throughout the world.

In Turkey, since thermal insulation and energy performance regulations were both came into force in 2008, it can be predicted that existing building stock before that year was designed and constructed under low or no energy regulation resulting poor building physics properties. This shows the potential of building retrofits in Turkey, where instead reconstruction of buildings seems to be the main solution.

Economidou categorizes building energy retrofits according to the location of the intervention and measures in a building: building envelope, building technical systems, renewable heat generation systems, renewable electricity generation systems and other energy related measures such as improving appliances [30].

- **Building Envelope**

  Building envelope is a common term for all components of a building that surround the conditioned area of the building and separate the conditioned areas from the unconditioned spaces or outside air [31]. It is the outermost and most easily accessible layer of the buildings. Therefore, improving the energy performance of the building envelope is one of the major methods for energy renovations. Especially interventions in non-transparent areas of the external walls are easily applied and therefore very common.

  Interventions in the envelope comprise (i) insulation of external walls, roofs and floors; (ii) replacement of windows and doors; (iii) draught-infiltration proofing; (iv) installation of solar shading systems; (v) employment of natural ventilation techniques, passive solar heating or cooling techniques [30].

- **Building Technical Systems**

  Building technical systems are active systems used for mainly heating, cooling, domestic hot water (DHW) and ventilation. These systems are technology driven and need to be retrofitted in time for efficiency. Therefore, these are one of the major elements involving building energy renovations for NZEB targets and hence energy efficiency [32]. Measures in this area include improvement of HVAC systems, replacement of boilers, lighting equipment, installation of heat recovery and building automation systems.

- **Renewable Heat Generation Systems**

  This type of retrofits are focused on integration of renewable heat generation systems to buildings. These systems can be on site or centralized in a built environment. Examples include solar collectors for hot water or heating, heat pump systems, biomass boilers and geothermal conversion for space heating.

- **Renewable Electricity Generation Systems**

  It is known that the largest portion of the electricity in the world is fossil fuel sourced. For this reason, implementation of on-site electricity generation from renewable sources is very important to reach mitigation goals of climate change and energy efficiency. Solar photovoltaics (PV), micro-hydro and micro-wind generation systems are the main practices.

- **Other Energy Related Measures**

  Improving appliances with more energy efficient and smart ones in buildings could be one of the cheapest and most practiced type of building retrofits. Although it is not a measure integrated into the building, it indeed increases the energy efficiency of the building as a whole.

2.2 Glazing Areas

Glazing areas in a building envelope have an important role of visually connecting and physically separating interior and exterior spaces. In this way, they have a large share in establishing a comfortable living environment for the dwellers. In order to meet the need for comfort, buildings are expected to be insulated against seasonal changes in the atmosphere. Thermal insulation and solar control measures cause reduced heating and cooling loads in the building.

Thermal transmittance of a building component (U-value) is used to measure its transmission of heat, which causes heat loss in winter period. U-value is the amount of heat flow in watts through 1 m^2 of a building component for 1 K air temperature difference between two sides of said component where lower values mean better insulation. It is inversely proportional to the thickness of the materials that makes up the component on a parallel path of the heat flow. Because architectural glass is generally a thin material, it could be problematic in building envelope for insulation in winter period.

Solar energy gains through glazing areas have a positive impact on heating loads during winter. However, they could contribute to overheating of the interior during

summer period because of the greenhouse effect. The reason behind this is the impermeability of the float glass material to certain wavelengths of radiation.

To improve the interior conditions, either the amount of solar radiation transmitted into the building should be limited or HVAC services should be installed to the building. But it is important to notice that installing HVAC systems results in additional energy consumption.

Two intervention types are included in the scope of the current study to increase the thermal performance of the glazing areas in a building envelope: solar shading implementation and glass material refurbishment.

2.2.1 Solar Shading Implementation

External solar shading is the most effective means of physically limiting or blocking solar radiation into the building through glazing areas. There are three major types of solar shading devices according to their relative positions to the windows on the building envelope: horizontal, vertical and egg-crate. Sun path diagrams are used in order to protect the other facades from direct solar radiation for a determined time period. Schematic diagrams for calculating the dimensions of the solar shading devices are shown in Figure 2.1.

- **Horizontal solar shading** devices are used mainly in equator-faced facades of the buildings. Some examples are horizontal louvres, awnings and eaves. To calculate the correct dimension of a horizontal solar shading device on a south-facing facade, vertical shadow angle (VSA) needs to be derived from the latitude (LAT) of the building. To exclude complete 6 months of summer radiation in an equator facing window, VSA is calculated as follows [17].

$$VSA = 90^{\circ} - LAT \tag{2.1}$$

- **Vertical solar shading** devices can be used in eastern and western sides of the building when the solar rays are with acute angle to the direction of the windows facing. Some examples are vertical fins and louvres. Vertical devices defined by their horizontal shadow angles (HSA) which is the angle between shadow line and the surface normal [17].

- **Egg-crate solar shading** devices are a combination of horizontal and vertical devices. They can be used when a facade needs both horizontal and vertical solar shading.

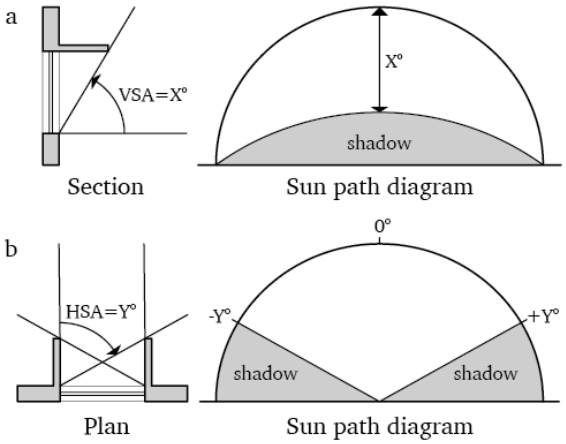


Figure 2.1 Solar shading device dimension calculation diagrams: a. horizontal, b. vertical [17]

2.2.2 Glass System Replacement

Architectural glass is an excellent conductor of heat because of its density and low thickness. In order to increase its thermal resistance, multi-pane glass systems became the norm in the construction sector. This insulation glasses have air or noble gasses (e.g. argon) in their cavities between glass panes. Double glazing units could reach U-values about 1.0 W/m^{2}K while triple glazing ones have 0.5-0.8 W/m^{2}K, giving them remarkable winter condition performances reducing heat losses [33]. It should be noted that U-values of the glass systems depend on the gases used and the thickness of the cavity. A typical detail of a multi-pane glass system is shown in Figure 2.2.

To take the performance of the glazing areas even further, two improvement approaches to the multi-glazing systems exist: low emissivity (Low-e) glass and solar control glass.

- **Low-e Glass**

  In multi-pane glass systems, biggest share of the heat losses consists of heat radiation from warm to cold areas, while the smaller part is from convection and conduction inside the gas cavity, which is unavoidable. Therefore, further improving the thermal performance of the glazing unit is to reduce the radiation heat losses. Towards this goal, a thin layer of noble metals or semiconductors is applied to the glass surfaces in the cavity during production. This layer allows the visible spectrum of the solar radiation to pass, but reflects the thermal infrared, reducing the radiation losses. The glass panes with this property are called Low-e glasses [34]. Low-e coatings are applied on surface position 2 and 3 (Figure 2.2). Coatings in position 2 are mainly to reduce overheating during

summer reflecting solar radiation. Conversely, position 3 coatings are to reflect the heat radiation of the objects back again to interior, keeping the energy inside of the building.

- **Solar Control Glass**

  To improve the thermal performance of a building in summer period, it is important to minimize solar gains through glazing areas which results in lowered daylight factor. There are two means of reducing total energy transmittance (g-value) of a glazing unit: tinted and reflective glass panes [33]. Solar control coatings are applied on surface position 2 (Figure 2.2).

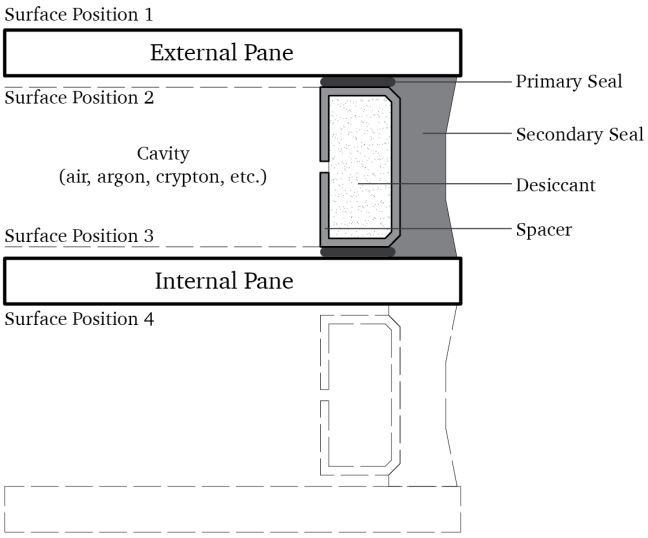


Figure 2.2 Typical detail of a multi-pane glass system [34]

2.3 Thermal Energy Storage Using PCM

Several energy storage systems are used to save the generated energy to be used in another time such as heat pumps to store thermal energy, springs and flywheels to store mechanical energy, batteries to store chemical energy. Thermal energy storage is one of the most important methods to use the heat generated by changing the temperature or changing the phase of the material [35]. Saving the generated heat to conserve energy is one key to reach energy efficiency, therefore involves environmental and economic aspects of sustainability.

2.3.1 Thermal Energy Storage

Thermal energy storage (TES) is to keep heat or cold for future use. In order to re-use this energy, this process should be reversible [36]. Thermal energy can be stored by

increasing or decreasing the temperature of a material, meaning altering its sensible heat, by changing the phase of a material, meaning altering its latent heat, or through the combination of said methods [35]. Also in chemistry, reversible chemical reactions can be used for energy storage, which are out of the current study's scope, thus they are not elaborated [37]. TES methods are summarized in Figure 2.3.

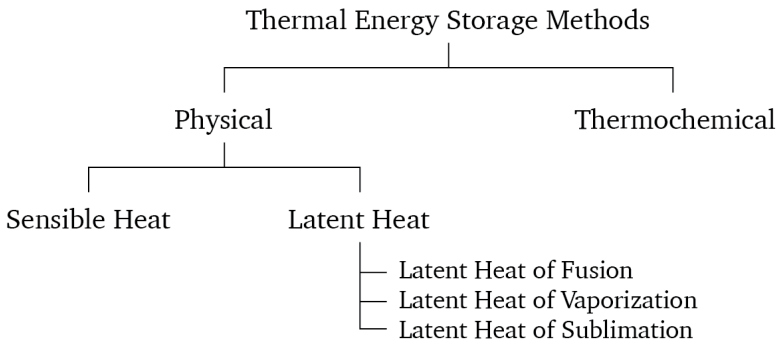


Figure 2.3 Thermal energy storage methods

2.3.1.1 Sensible Heat Storage

Sensible heat storage (SHS) is the method when heat energy is transferred to or from the storage material, temperature change can be observed directly. Temperature increase is proportional to the transferred heat and does not cause phase change. Stored energy amount in SHS (ΔQ_s) can be expressed as in equation 2.2:

$$\Delta Q_s = m \cdot c \cdot \Delta T = \rho \cdot c \cdot V \cdot \Delta T \tag{2.2}$$

where m is the mass and c is the specific heat of the storage material, ΔT is the change in temperature, ρ is the density and V is the volume of the material [36, 37]. The temperature-stored energy graph of SHS is shown in Figure 2.4.

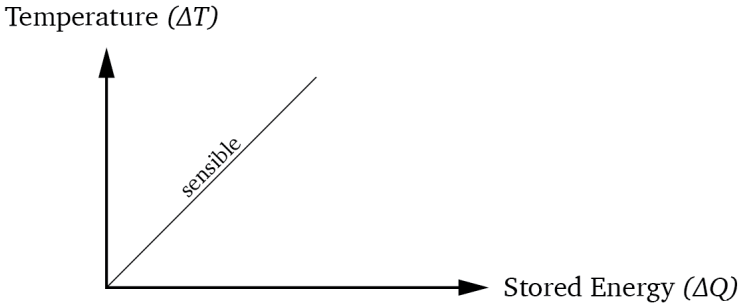


Figure 2.4 Sensible heat storage

2.3.1.2 Latent Heat Storage

Latent heat storage (LHS) is the method when heat energy is transferred to or from the storage material, it undergoes a phase change at a constant temperature. Stored energy amount in LHS (ΔQ_l) can be expressed as in equation 2.3:

$$\Delta Q_l = m \cdot L \tag{2.3}$$

where m is the mass and L is the specific latent heat of the storage material [38]. As phase change can be from solid to liquid, liquid to gaseous, solid to gaseous states, latent heat is called fusion (L_f), vaporization (L_v), sublimation (L_s) respectively. The temperature-stored energy graph of LHS is shown in Figure 2.5.

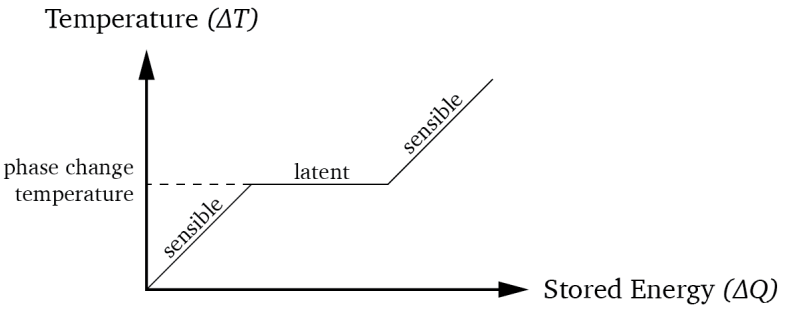


Figure 2.5 Latent heat storage

- **Latent Heat of Fusion (Solid-Liquid):** Melting-solidification usually causes small volume changes in the storage material (lower than 10%) in solid-liquid phase changes. If a suitable container which can encapsulate the excess volume caused by fusion is used, melting-freezing cycle at a constant temperature occurs. This temperature is called "melting point" or "phase change temperature" [36].

- **Latent Heat of Vaporization (Liquid-Gas):** Vaporization-condensation process usually has high enthalpy but also causes large volume changes in the storage material. Because of the vapor pressure release to the environment, latent heat of vaporization is not preferred for energy storage except only for water in an open system at ambient pressure [36].

- **Latent Heat of Sublimation (Solid-Gas):** Sublimation phase change has very high enthalpy, but similar to the vaporization, it causes large volume changes. Because of that, it is not used in TES [35].

2.3.2 PCM

Phase change materials (PCMs) take advantage of the latent heat of phase change (usually fusion) to control temperatures within a certain range. When a material melts, it absorbs energy from the environment at a constant temperature. Absorbed energy increases the energy of particles that make up the material, and this increase loosens the atomic bonds between said particles. Thus process ends up with the phase change to liquid state at the melting temperature. Inversely, solidification process is the process when material releases energy to the environment, particles lose energy and material changes its phase to solid state at the phase change temperature [18, 39].

If the melting temperature of PCM is proximal to the desired indoor comfort temperature, this endothermic-exothermic cycle can help stabilize the indoor temperature, decreasing heating and cooling loads and altering the interior surface temperatures of a building [40]. Hence, PCMs can increase heat capacity of the building with low thermal mass and thus they can be used as a key material for building energy retrofits.

2.3.2.1 PCM Types

PCMs are classified as (i) organic, (ii) inorganic compounds and (iii) eutectic mixtures according to their chemical composition. The classification of PCMs is shown in Figure 2.6.

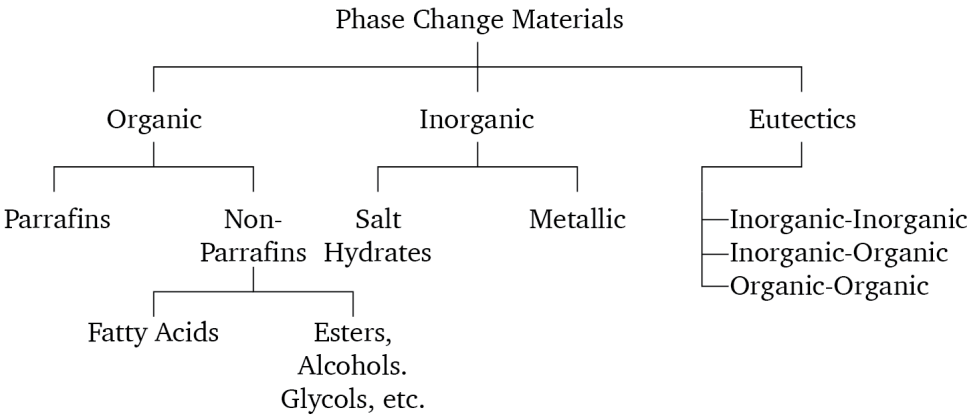


Figure 2.6 Classification of PCMs [41]

- **Organic PCMs:** Organic PCMs are non-toxic, non-corrosive and chemically stable compounds that have a high latent heat of fusion. They are divided into two groups: (i) paraffins and (ii) non-paraffins [40]. Paraffin group of

organic PCMs are mainly used in the electronics industry for thermal control [18]. Although paraffins are inexpensive, have suitable heat storage capacities of 120 to 210 kJ/kg and have a wide range of melting points between 20 to 70°C, but their use is limited because of their low conductivity (about 0.2 W/mK) and they experience large volume changes during phase change [40].

Non-paraffins include fatty acid esters, alcohols and glycols. Due to the lower melting points (16 to 65°C) of fatty acids, they are better suited for human comfort applications [18]. They are inflammable, undergo small volume changes while phase changing, have high heat of fusions (155-180 kJ/kg) and do not experience super-cooling (the case that a liquid or gas falls below the freezing point without solidification) while freezing, but are more expensive than paraffins [40, 42].

- **Inorganic PCMs:** Inorganic PCMs comprise salt hydrates. Salt hydrates are substances in which a salt (e.g. oxides, carbonates, sulphates, and nitrates) and water combine to a certain extent. They are nonflammable and have high latent heat storage capacity (about 240kJ/kg) and thermal conductivity (about 0.5 W/mK), but they may experience supercooling, the volume change during phase change is high and segregation is possible [43]. In addition, thermal storage capacities of salt hydrates decrease over time. This is because of the formation of low salts during the melting of the salt hydrates, and this reaction is irreversible [40]. Most inorganic PCMs are corrosive to metals and slightly toxic. These features may limit their use in thermal storage in buildings.

  They have melting points ranging from 10-900°C. Using inorganics at low temperatures where they overlap with paraffins is not common. However, the primary choice for high melting temperatures are inorganic PCMs. They are often used in solar energy applications (solar power plants) for energy storage [18].

- **Eutectic PCMs:** Eutectic systems are homogeneous mixtures comprising several substances that melt or solidify simultaneously at a single melting point that is lower than the melting point of either of the constituents [31].

  Eutectic PCMs are divided into three according to the properties of the materials they contain; (i) organic-organic, (ii) inorganic-inorganic and (iii) inorganic-organic eutectics. They have sharp melting points suitable for providing the desired operational temperature. They have larger volumetric thermal storage densities than the organics and unlike inorganics segregation does not occur. However, there is not enough information about the physical properties and some fatty organic-organic eutectics may not be suitable for

buildings because of their strong odors [42, 44].

2.3.3 PCM Containment Methods

PCMs are used in buildings to store heat energy as latent heat. During their phase change cycle, any volume loss can directly affect the performance of the building envelope and volume changes can damage their containers if directly embodied in a material such as concrete and gypsum.

In order to overcome these risks, containment methods are proposed for the PCMs to function properly [45]. Some of the containment methods are listed as:

- Bulk packaging in containers
- Foil packaging in blankets or sheets
- Impregnating directly to a carrier material
- Macro-encapsulation
- Micro-encapsulation.

A selection of PCM products is shown in Figure 2.7.



Figure 2.7 PCM product examples: a. PCM-filled glass, b. foil packaging in blanket, c. macro-encapsulation [46–48]

2.3.4 PCM Applications in Buildings

PCMs can be used in passive and active systems in buildings. Passive applications are implementation of the PCM directly to building component such as walls and ceilings, making use of the natural solar heat for heating and cooling. They can also be put into effect by inter-operating with active systems of a building such as HVAC systems.

Tyagi and Buddhi specify major application types and locations of PCM in a building. Some of the passive application items of their study are [49]:

- **Wallboards:** PCM enhanced wallboards are the most common solution for buildings. Especially interior side of the building envelope is the most frequently studied location in literature. PCM wallboards can be impregnated gypsum boards, concrete boards, etc. For existing buildings with low thermal inertia, installation of these boards could increase the thermal performance of the building significantly [50].
- **Ceiling:** Along with using PCM enhanced gypsum boards for ceiling cladding, placing macro-encapsulated PCM sheets above suspended ceilings are also studied for thermal control in buildings [51]. Ceiling panels are especially efficient compared to internal walls because the surface which PCM is going to work could not be covered while the building is operational.
- **Building blocks:** PCM impregnated building blocks could cause a high thermal inertia and high thermal performance without the need of using high mass materials [52]. But it is important to show that, when used within the structural concrete, PCM can affect the compressive strength, stability and fire resistance of the building component [53].
- **Trombe walls:** Trombe walls are equator-facing walls comprising an outer glass surface, a black painted concrete wall and air in between. They are used to storing solar energy and by heating the intermediate air release the heat to interior of the building [31]. According to Telkes and Askew as cited in Tyagi and Buddhi, adding PCM to the concrete wall of the trombe wall system has been studied since 1970s showing beneficial results [49, 54, 55].
- **Windows and shutters:** Using translucent PCM to overcome problems of glazing areas is still a research subject in the current literature showing that the problems with glazings filled with translucent PCM in its liquid state are lowering the visibility of the windows and ineffectiveness compared to regular glazing options on cloudy days [50, 56]. Another and widely used solution for solar heat gain problems of glazing areas is window shutters. Combining PCM with shutters has the opportunity not only to block solar radiation into the interior of the building but also using stored energy during daytime to be released in nighttime, especially in climates where daytime and nighttime temperatures are differentiated as in xeric places [49, 57]
- **Floors:** Floor areas are the area most exposed to solar radiation in a building's interior, making them convenient for passive solar heating. Integrating PCM

to floorboards and other elements of the building showed to be beneficial for reducing energy loads [58].

In the current study, for ease of application in building energy retrofit projects, foil packaged PCM blankets under gypsum board cladding are selected in the simulation stage. PCM application detail which is used in the current study is shown in Figure 2.8.

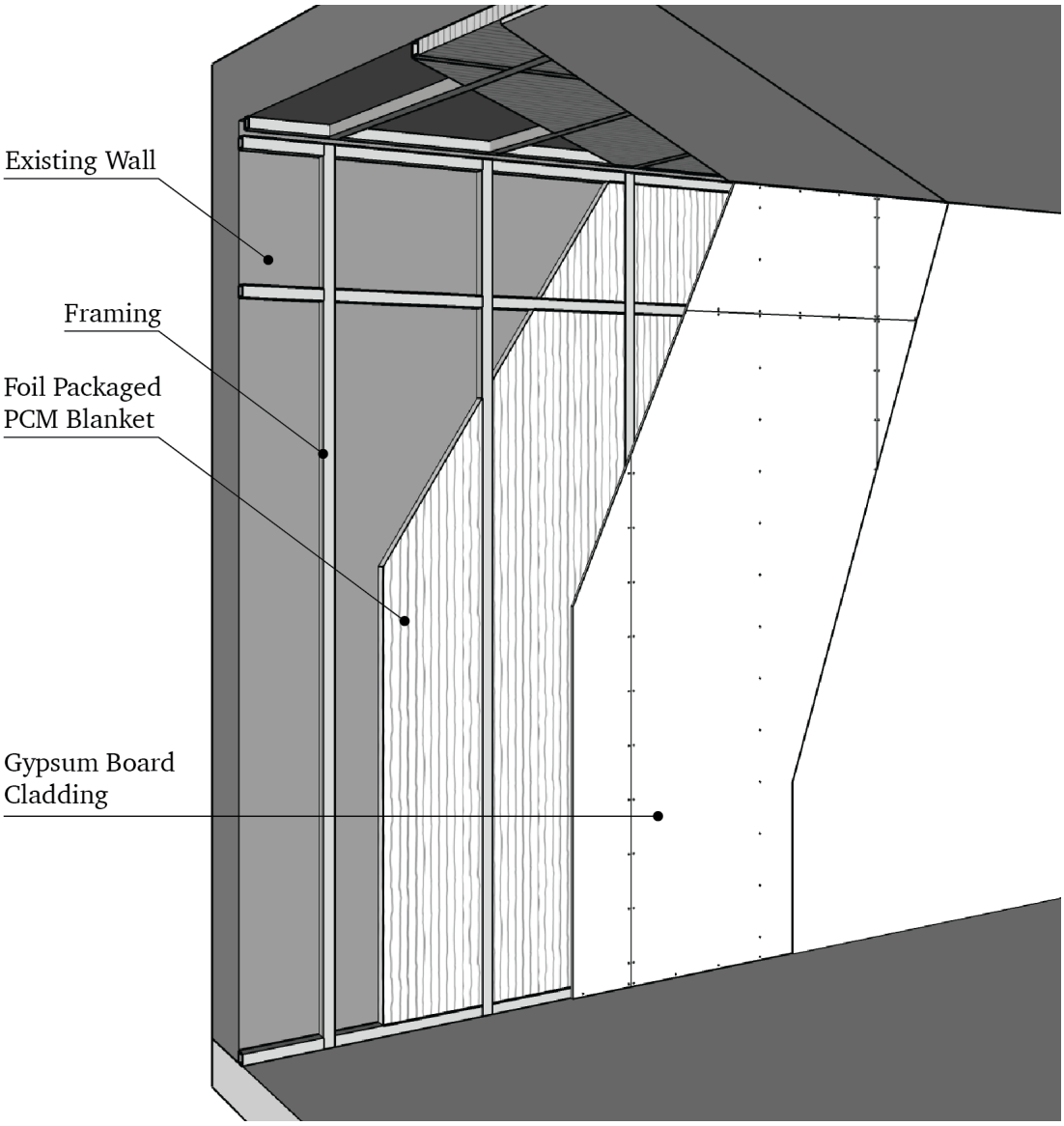


Figure 2.8 PCM application system detail in the thesis study

3
AN APPROACH FOR GLAZING AREA INTERVENTIONS AND PCM APPLICATION IN BUILDING ENERGY RETROFITS

Within the thesis study, it is aimed to increase the energy efficiency of existing buildings, especially in the summer period, in different climatic regions by evaluating the effects of retrofit decisions on energy consumption of the buildings. Another purpose of the thesis is to compare the performance of the phase change materials (PCM) application with other retrofit scenarios in two different climatic zones. Therefore, building envelope interventions and using PCM are evaluated individually and with their combinations in order to see the effects of these measures on their contribution to energy efficiency of the building in winter and summer periods.

Steps of the developed approach for this purpose are listed below.

1. **Determination of the application example:** The determined application example is a residential project which is frequently implemented in different climatic regions in Turkey.
2. **Determination of the building envelope properties of the application example:** Physical properties of the building envelope regarding heat transfer are determined based on the construction documents and the mechanical report of the selected application example.
3. **Determination of the climatic regions of the study:** Since energy efficiency is aimed at the summer period, the determined climate regions are the regions where cooling loads are predicted to be high. One region is temperate-humid, the other has a dry hot summer climate.
4. **Generating data and assumptions for energy performance analysis:** Heating and cooling setpoint and setback temperatures are determined based on

previous research studies on this subject. Heating, ventilation and air conditioning systems are determined based on the systems used in the region.

5. **Energy performance analysis of the existing building as a reference:** Heating, cooling, lighting and total loads of the current state of the building is calculated and its performance is evaluated using the selected building energy simulation (BES) software in the determined climatic regions.

6. **Determination of building envelope retrofit strategies:** The retrofit interventions to enhance the thermal performance of the building are determined within the techniques used in the region of the study. Subsequently, heating, cooling, lighting and total loads analyses are conducted using BES software for each climatic region in the study.

7. **Determination and implementation of the appropriate PCM:** The PCM, which compensates for the internal temperature fluctuations of buildings, and the application area of the material are determined, then energy consumption is calculated using BES software for each climatic region in the study.

8. **Developing retrofit strategies with combinations of selected interventions:** In order to have a clear reading of the effects caused by the use of interventions together, energy analyses are made for each combination and for all climatic regions.

9. **Evaluation of the analysis results:** The interventions are evaluated based on the calculated energy consumption of each scenario.

The steps of the approach is shown as a graphic in Figure 3.1.

3.1 Application Example of the Developed Approach

Within the current study, first, a typical project of the Housing Development Administration of the Republic of Turkey (TOKİ) was chosen. Most important factors in this selection process are (i) applicability of this project in any province of Turkey and (ii) constancy of the materials and construction techniques. In this context, the selected typical project makes up an application example for thesis study.

Subsequently, chosen TOKİ project was modelled using DesignBuilder building energy simulation (BES) software, which is used for heat transmission calculations in transient periods. Then the model was placed to both İstanbul and Diyarbakır provinces. The reason behind this location selection is to measure the performance

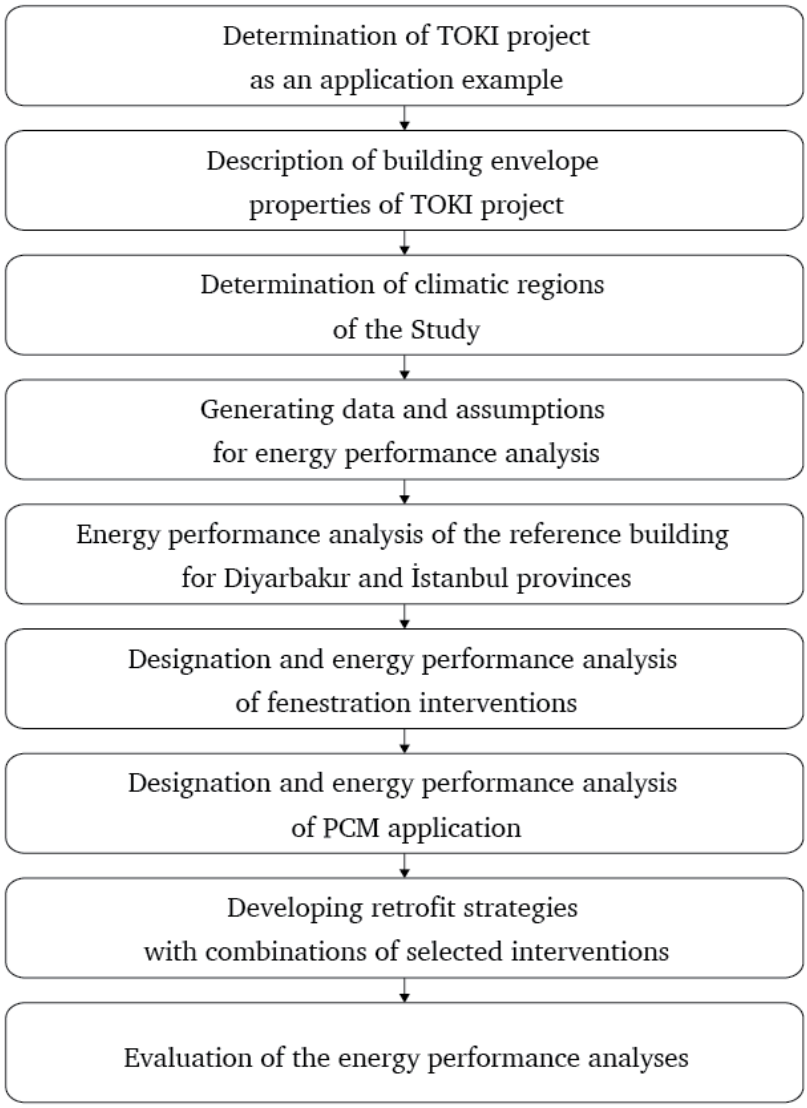


Figure 3.1 The steps of the approach

of the PCM in these climate conditions especially in summer period: İstanbul has a temperate humid summer, while Diyarbakır has a warm dry summer climate. After the selection, proposed base-case scenarios were analysed using BES software.

The primary reason for overheating in buildings in summer period is glazing areas. Therefore, enhancement of these areas of the building was selected as the first step of the retrofit interventions which include solar shading implementation, replacing existing 4+16+4 double-glazing with solar control and low-e glasses. In this way, overheating of the base-case buildings was averted.

Following glazing area interventions, PCM was selected according to its melting temperature and latent heat storage capacity and then applied to both interior surfaces of external walls and ceilings of conditioned spaces. After each singular intervention

scenario, energy consumption analyses were repeated and their contribution to energy efficiency of the building was evaluated. Using these singular intervention data, retrofit strategies were determined by combinations of these interventions and evaluated through BES results for selected climatic zones. The retrofit steps listed above is given in Figure 3.2.

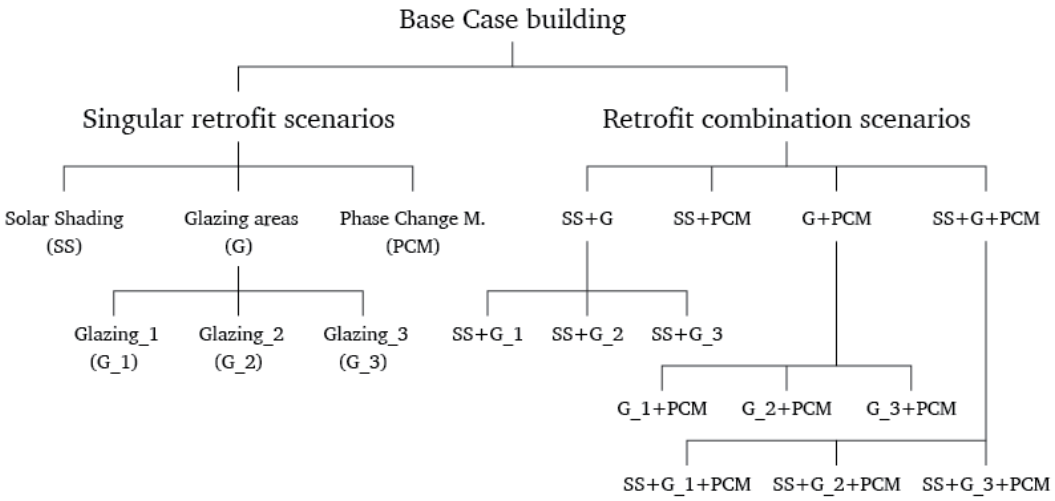


Figure 3.2 The determined retrofit steps of the study

3.1.1 Determination of TOKİ Project as an Application Example

One of the typical projects of TOKİ has been selected in order to compare the scenarios in two climate zone. Therefore, the KT type was selected. In this selection, up-to-datedness and compactness of the project were taken into consideration. The project is a building coded KT4, comprising a basement floor, ground floor and three normal floors, with two three-bedroom flats on each floor above basement. The floor plans and south elevation of the building are given in Figure 3.3 to 3.6.

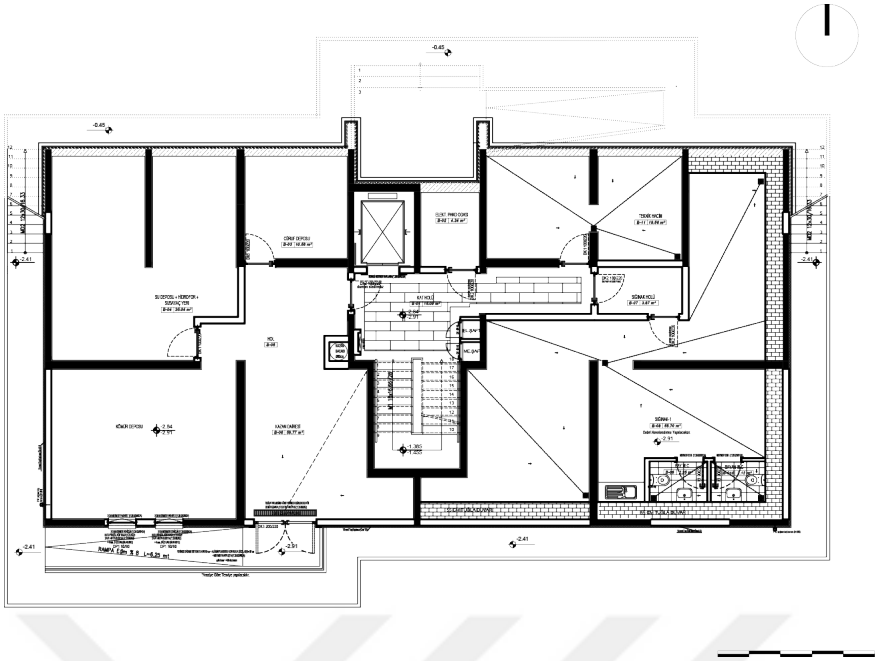


Figure 3.3 Basement plan of the TOKİ project



Figure 3.4 Ground floor plan of the TOKİ project

Construction documents of the KT4 architectural project were taken from the submitted project in the Oğuz neighborhood of Acıpayam district of Denizli Province with the registration number 2017/612944 [59]. General information about the project is listed below.

- Basement floor comprises technical areas, shelter and storage areas.

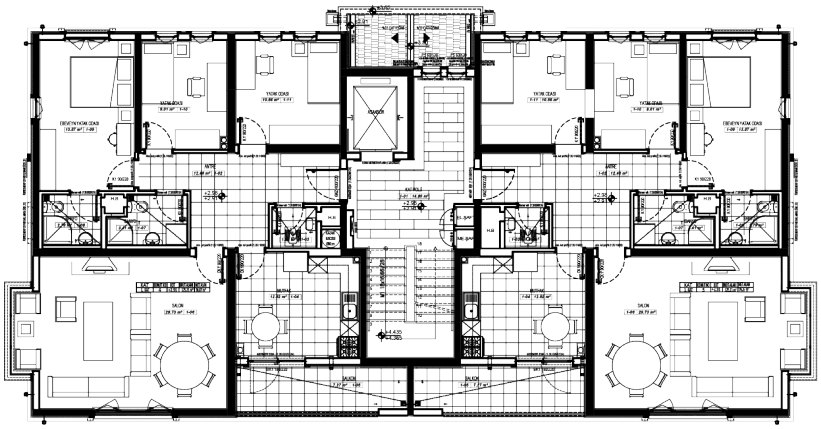


Figure 3.5 Normal floor plan of the TOKİ project



Figure 3.6 South elevation of the TOKİ project

- Plan schemes are mostly similar in the ground and above floors. Floors comprise two three-bedroom flats which are symmetrical in the east and west sections of the building. The living and kitchen areas face the south with 160 cm deep indented balconies which are accessible from the kitchens. Bedrooms of the flats are in the north. The only difference between ground and normal floors is the 80 cm width cantilevered portion in living rooms of the normal floors.

Besides this feature, space organizations are the same.

- Each flat has a gross floor area of 125,21 m^2 and net floor area of 96,07 m^2.
- Floor height is the same for each floor and 291 cm.

3.1.2 Description of Building Envelope Properties of TOKİ Project

In order to reveal the current energy consumption of the KT4 type residential block used in the study for İstanbul and Diyarbakır provinces, first the building envelope details of the building should be determined. Since there are incompatibilities between the architectural and the mechanical project in the tender documents of the selected project, the mechanical project was taken as a basis for the building envelope details. Every detail is named according to its location for convenience.

External wall types, roof slab and glazing areas were created using DesignBuilder BES software and surface-to-surface U-values of each detail were calculated. The names, descriptions and U-values of the details used in the project are summarized in Table 3.1.

Table 3.1 Building envelope details of the TOKİ project

Location	**Detail Name**	**Definition**	**U-value (W/m^2K)**
External walls	EW1	Brickwork, plaster	0,432
	EW2	Cast concrete, plaster	0,553
	EW3	Brickwork, artificial stone cladding	0,432
	EW4	Cast concrete, artificial stone cladding	0,548
	EW5	Brickwork, fibercement cladding	0,413
	EW6	Cast concrete, fibercement cladding	0,518
	BGW	Project below grade wall	0,511
Glazing areas	W	4+16+4 PVC windows	1,900
	ED	Aluminum doors	4,000
Roof	R	Cast concrete, stone wool insulation	0,359
Foundation	GF	Project foundation	0,452

3.1.2.1 External Walls

External walls are made of 200 mm reinforced concrete and AB class vertical core brick walls, with 60 mm expanded polystyrene (EPS) thermal insulation boards. The vertical core bricks with a density of 650 kg/m^3 used as the external wall body material in the project were created using the thermal conductivity calculation values table (Annex-E) of TS825 standard [60]. Under the gypsum plaster on the interior side of the brick walls, cement-lime render of 20 mm thickness is used. The calculated

U-values of the wall types named EW1 and EW2 are 0,432 and 0,553 W/m^{2}K, respectively. Thermal resistance calculations of the walls are given in Table 3.2 and 3.3.

Table 3.2 Thermal Resistance Calculation of EW1

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^{2}K/W)**	**U-value (W/m^{2}K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Cement-lime render	0,02	1,00	0,0200	
AB class vertical core brick	0,20	0,35	0,5714	0,432
EPS insulation	0,06	0,04	1,5000	
Cement render	0,02	1,60	0,0125	
External surface therm. res.			0,0400	
Overall thermal resistance			2,3131	

Table 3.3 Thermal Resistance Calculation of EW2

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^{2}K/W)**	**U-value (W/m^{2}K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Reinforced concrete	0,20	2,50	0,0800	
EPS insulation	0,06	0,04	1,5000	0,553
Cement render	0,03	1,60	0,0188	
External surface therm. res.			0,0400	
Overall thermal resistance			1,8080	

The wall types named as EW3 and EW4 are the types described as "local natural stone clad" in the project. The thermal conductivity calculation value (λ) of the natural stone cladding is 1,3 W/mK in the mechanical project and has a thickness of 20 mm. This value corresponds to "artificial stone cladding" in the building materials table (Annex-E) of TS825 standard. The calculated U-values of the artificial stone clad wall types named EW3 and EW4 are 0,432 and 0,548 W/m^{2}K, respectively. Thermal resistance calculations of the walls are given in Table 3.4 and 3.5.

Table 3.4 Thermal Resistance Calculation of EW3

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^2K/W)**	**U-value (W/m^2K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Cement-lime render	0,02	1,00	0,0200	
AB class vertical core brick	0,20	0,35	0,5714	0,432
EPS insulation	0,06	0,04	1,5000	
Artificial stone cladding	0,02	1,30	0,0154	
External surface therm. res.			0,0400	
Overall thermal resistance			2,3160	

Table 3.5 Thermal Resistance Calculation of EW4

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^2K/W)**	**U-value (W/m^2K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Cement-lime render	0,02	1,00	0,0200	
Reinforced concrete	0,20	2,50	0,0800	0,548
EPS insulation	0,06	0,04	1,5000	
Artificial stone cladding	0,02	1,30	0,0154	
External surface therm. res.			0,0400	
Overall thermal resistance			1,8246	

The wall types named as EW5 and EW6 are the types described as "fiber-cement cladding" in the project. This wall type is designed using fiber-cement boards with a thickness of 10 mm. The thermal conductivity calculation value (λ) of the selected material is 0,0820 W/mK with a density of 350 kg/m^3. The calculated U-values of the fiber-cement clad wall types named EW5 and EW6 are 0,413 and 0,518 W/m^2K, respectively. Thermal resistance calculations of the walls are given in Table 3.6 and 3.7.

Table 3.6 Thermal Resistance Calculation of EW5

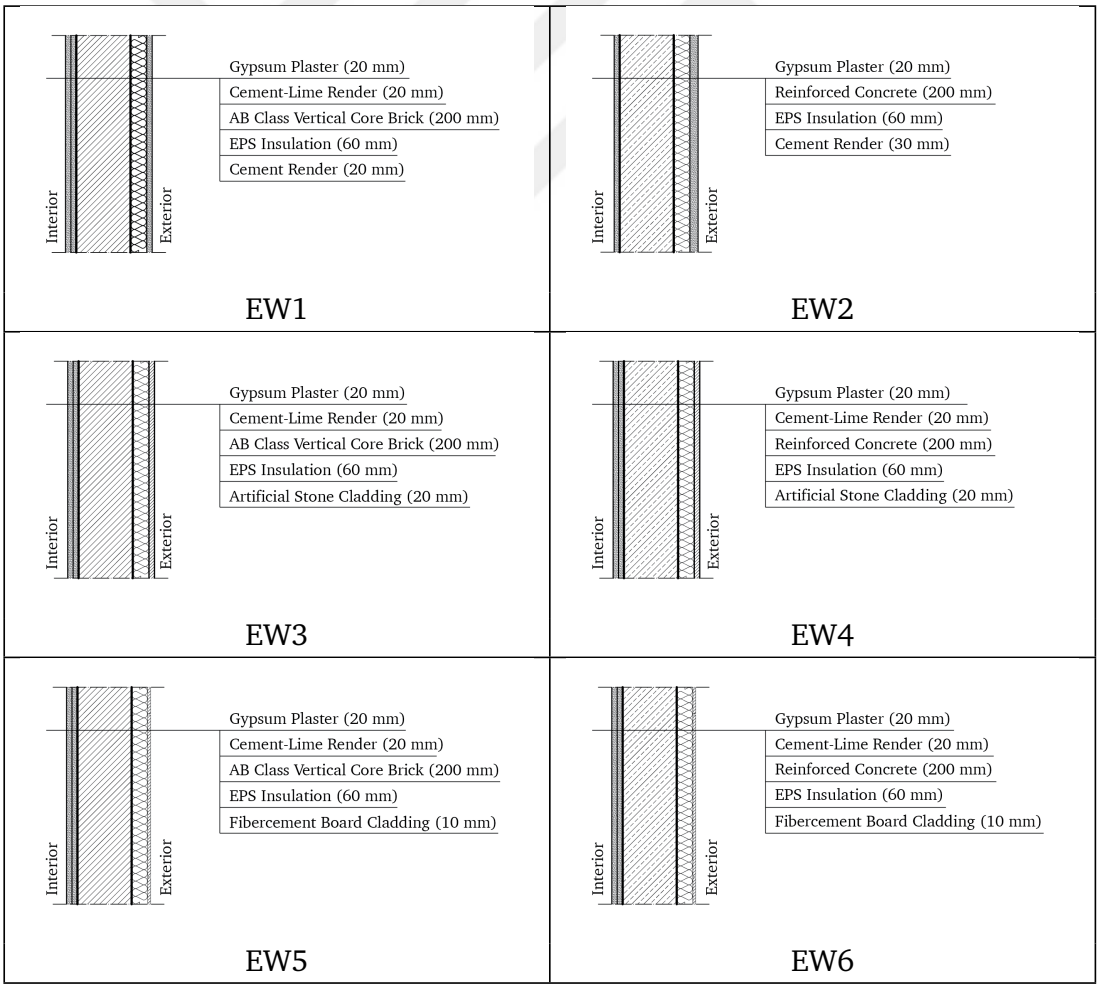
Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^2K/W)**	**U-value (W/m^2K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Cement-lime render	0,02	1,00	0,0200	
AB class vertical core brick	0,20	0,35	0,5714	0,413
EPS insulation	0,06	0,04	1,5000	
Fibercement board cladding	0,01	0,082	0,1220	
External surface therm. res.			0,0400	
Overall thermal resistance			2,4226	

Details of the external wall types in the project are given in Table 3.8.

Table 3.7 Thermal Resistance Calculation of EW6

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^2K/W)**	**U-value (W/m^2K)**
Internal surface therm. res.			$0,1300$	
Gypsum plaster	$0,02$	$0,51$	$0,0392$	
Cement-lime render	$0,02$	$1,00$	$0,0200$	
Reinforced concrete	$0,20$	$2,50$	$0,0800$	$0,518$
EPS insulation	$0,06$	$0,04$	$1,5000$	
Fibercement board cladding	$0,01$	$0,082$	$0,1220$	
External surface therm. res.			$0,0400$	
Overall thermal resistance			$1,9312$	

Table 3.8 External wall details of the application example



3.1.2.2 Below Grade Walls

The wall type named as BGW is the below grade wall of the project. In this type, unlike other details, waterproofing layers, extruded polystyrene (XPS) insulation and 85 mm thick brick wall are applied. The calculated U-value of the wall type is 0,511 W/m^{2}K. Thermal resistance calculation and detail of BGW is given in Table 3.9 and Figure 3.7, respectively.

Table 3.9 Thermal Resistance Calculation of BGW

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^{2}K/W)**	**U-value (W/m^{2}K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,02	0,51	0,0392	
Reinforced concrete	0,20	2,50	0,0800	
PVC waterproofing	0,006	0,19	0,0316	
XPS insulation	0,05	0,035	1,4286	0,511
AB class vertical core brick	0,085	0,35	0,2429	
PVC waterproofing	0,001	0,19	0,0053	
External surface therm. res.			0,0000	
Overall thermal resistance			1,9576	

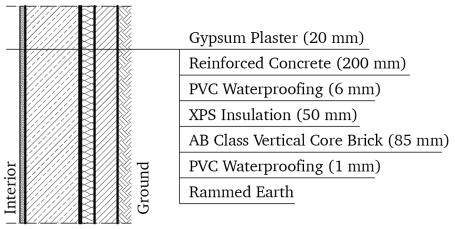


Figure 3.7 BGW detail

3.1.2.3 Glazing Areas

The windows system used in the project are defined as PVC windows with 4+16+4 mm low-e glazing system. U-values of the windows and aluminum profile external door are specified in the mechanical report as 1,9 W/m^{2}K and 4 W/m^{2}K, respectively. Other performance specifications of the glazing systems, except for the U-value, are accepted as default baseline values. These baseline values are compared with the examples of major manufacturers and validated [61, 62]. Therefore adopted daylight transmission, reflection and solar heat gain coefficient (SHGC) values of the window glass system are 80%, 17% and 75%, respectively.

3.1.2.4 Roof

The floor detail between the unconditioned roof-space and the interior is named as R. Stone wool insulation of 100 mm thickness is placed on the reinforced concrete slab. The calculated U-value of R is 0,359 W/m^{2}K. Thermal resistance calculation and detail of R are given in Table 3.10 and Figure 3.8, respectively.

Table 3.10 Thermal Resistance Calculation of R

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^{2}K/W)**	**U-value (W/m^{2}K)**
Internal surface therm. res.			0,1300	
Gypsum plaster	0,01	0,51	0,0196	
Reinforced concrete	0,14	2,50	0,0560	0,359
Mineral wool insulation	0,10	0,04	2,5000	
External surface therm. res.			0,0800	
Overall thermal resistance			2,7856	

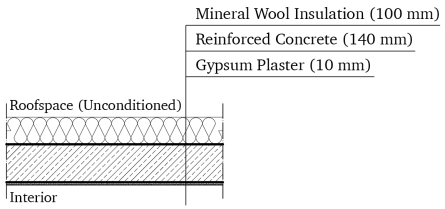


Figure 3.8 R detail

3.1.2.5 Foundation

The foundation detail and thermal resistance calculation of the project named as GF with a U-value of U=0,452 W/m^{2}K is given in Figure 3.9 and Table 3.11, respectively.

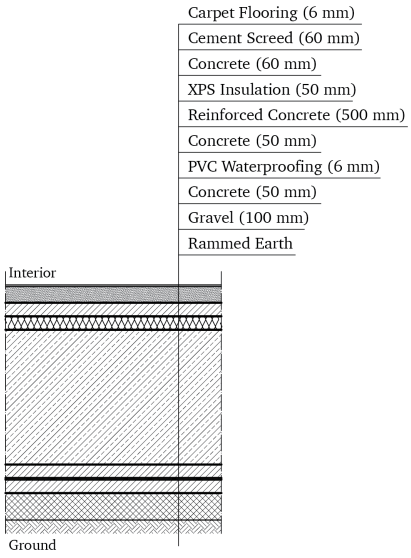


Figure 3.9 GF detail

Table 3.11 Thermal Resistance Calculation of GF

Layer	**Thickness (m)**	**Cond. (λ) (W/mK)**	**Resistance (m^{2}K/W)**	**U-value (W/m^{2}K)**
Internal surface therm. res.			0,1700	
Carpet flooring	0,006	0,06	0,1000	
Cement screed	0,06	1,40	0,0429	
Concrete	0,06	1,65	0,0364	
XPS insulation	0,05	0,035	1,4286	
Reinforced concrete	0,50	2,50	0,2000	0,452
Concrete	0,05	1,65	0,0303	
PVC waterproofing	0,006	0,19	0,0316	
Concrete	0,05	1,65	0,0303	
Gravel	0,10	0,70	0,1429	
External surface therm. res.			0,0000	
Overall thermal resistance			2,2130	

3.1.3 Determination of Climatic Regions of the Study

Since the aim of the study is to reduce the energy loads of the existing buildings, especially during summer, two climatic regions with high summer cooling loads are selected. When selecting the climatic regions of the study, day-night temperature differences are considered. Because it is known from the reviewed literature that melting-solidifying cycle of the PCM should be completed within a day in order to

achieve optimum performance. Furthermore, the cumulative effect of retrofit projects on energy efficiency due to the population density and applicability is also considered highly important. For these reasons, determined regions for the application example are İstanbul province with temperate-humid and Diyarbakır province with dry-hot summer climates.

Both cities have "dry-summer subtropical" Mediterranean climate according to the Köppen-Geiger Climate Classification system [63]. However, relative humidity in summer periods in İstanbul and Diyarbakır are 70% and 30%, respectively [64, 65]. This difference of relative humidities shows that day and night temperature differences are smaller in İstanbul than in Diyarbakır, meaning different energy performances of the retrofit interventions can be expected.

3.1.4 Generating Data and Assumptions for Energy Performance Analysis

3.1.4.1 Determining the Activity and Environmental Control Variables

Energy model of the KT4 building is prepared using DesignBuilder BES. Then the model, which is the baseline for current study, located both to İstanbul and Diyarbakır provinces. The activity variables in the model are defined separately for each space. Since the building comprises three-bedroom apartments, occupancy is defined as 4 people per apartment. Lighting variables are defined as default values of the software.

Setpoint and setback temperatures for heating and cooling are important for both the energy consumption of the building and thermal comfort of the users. For this reason, these values are determined based on the literature review, which can be seen in Table 3.12.

Table 3.12 Adopted setpoint and setback temperatures of reviewed literature

	Heating Setback Temp.	**Heating Setpoint Temp.**	**Cooling Setback Temp.**	**Cooling Setpoint Temp.**
Ingersoll and Huang[66]	15,6°C	21,1°C	-	-
Turner and Gruber[67]	18°C	21°C	-	-
Mozer et al.[68]	18°C	22,5°C	-	-
Tariku et al.[69]	17°C	21°C	-	-
Moon and Han[70]	15,6°C	22,2°C	27,8°C	25,6°C
Parker[71]	17,7°C	18,8°C	25,6°C	23,9°C
Martinaitis et al.[72]	18°C	20°C	-	-
Date et al.[73]	18°C	21°C		
Jacquet et al.[74]	17°C	21°C	-	-

After mentioned stages, the data and assumptions to be used in the calculation of energy loads have been made and are given in Table 3.13. The variables in the table belong only to the living rooms and vary in other spaces. For all locations, variables are given in the appendix Tables A.1 to A.4.

Table 3.13 Activity variable choices of living room spaces in application example

Occupancy density	$0,0188$ people/m^2
Metabolic activity	
Activity type	Eating/drinking
Activity factor	$0,90$
Clothing	Winter 1 clo, summer $0,50$ clo
Domestic hot water consumption	$0,000$ l/m^2-day
Environmental control	
Heating setpoint temperature	21°C
Heating setback temperature	17°C
Cooling setpoint temperature	26°C
Cooling setback temperature	28°C
Ventilation setpoint temperatures	
Natural ventilation, indoor min temperature control	24°C
Minimum fresh air	10 l/s-person
Lighting	150 lx

3.1.4.2 Determining Heating, Ventilation and Air Conditioning Variables

The HVAC (Heating, ventilation, and air conditioning) variables chosen for KT4 type building are summarized in Table 3.14. The architectural project does not have a defined air conditioning system. However, in order to calculate the cooling load required to keep the interior at a comfort temperature of 26°C, a split air conditioner with a seasonal CoP (coefficient of performance) 1,8 is designated in the simulation. In addition, domestic hot water (DHW) is only selected for bathroom and kitchen areas.

Table 3.14 HVAC variable choices of the simulation

HVAC setup	Radiator heating, split AC
Mechanical ventilation	Off
Heating Fuel Heating system seasonal CoP	On Natural gas 0,85
Cooling Fuel Cooling system seasonal CoP	On Electricity from grid 1,8
DHW (bathrooms and kitchens) DHW type Fuel DHW seasonal CoP Water delivery temperature	On Instantaneous hot water only Natural Gas 0,85 65°C
Natural ventilation Outside air Outdoor Temperature Limits	On 10 ac/h On

3.1.4.3 Determining the Climatic Data of the Locations of the Study

In order to get accurate results from simulation studies, it is necessary to determine the climate data correctly. In the current study, the method for obtaining climatic data of İstanbul and Diyarbakır is listed below.

- Climatic data of İstanbul is taken directly from the database of the DesignBuilder software. The building energy simulation software takes this data from IWEC (International Weather for Energy Calculation) for Europe WMO (World Meteorological Organization) Region 6 for Turkey [75].
- Since the climatic data of Diyarbakır is not ready in the database of the software, therefore it is taken from TurTMY (Typical Meteorological Year) data set which is based on the study of Pusat et al. on generation of typical meteorological year in Turkey [76].

3.1.5 Energy Performance Analysis of the Reference Building for Diyarbakır and İstanbul Provinces

The calculations made using the building energy simulation software are for a one-year period. DesignBuilder, the simulation software used within the thesis, is used for heat transfer calculation in periodic regimes in energy efficiency calculations, and displays the energy consumption in these periods through simulation. The calculated loads consist not only of heating and cooling but also of interior lighting loads. Calculation

of lighting loads is necessary because of the property of the luminaires to generate heat energy. Any retrofit intervention that affects the natural lighting of the building will also affect the artificial lighting periods, therefore affecting heating and cooling loads. The energy consumption values obtained from the simulations are shown in Table 3.15.

Table 3.15 Annual base case (BC) scenario loads of İstanbul and Diyarbakır provinces

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599,12	18120,21	11700,30	61419,63
BC_{Diy}	39194,00	50384,15	12186,53	101764,68

3.1.6 Designation and Energy Performance Analyses of Glazing Area Interventions

Retrofit options of the building are applied primarily for glass areas. Two different fenestration interventions are determined for the baseline building. The analyzed interventions are solar shading implementation and refurbishment of glass areas with solar control glass and low-e glass systems, respectively. While these interventions are effective in reducing cooling loads, the use of low-e glass is known also to reduce heating loads of the buildings.

3.1.6.1 Solar Shading Implementation

Glazing areas are one of the most important causes of overheating in summer period because of greenhouse effect. For this reason, it is important to prevent the interference of direct solar radiation into the building between the warm period of March and September equinoxes. Therefore, to design the most effective solar shading, sun path diagrams are prepared for each province and shadow angles are marked on the diagrams.

Determination of the shadow angle for south elevation is directly related to the latitude of the province. However, in order to determine the solar shading angles for east and west elevations of the building for each province, the studies of Akgöz and Berköz et al. have been taken as a guide [77, 78]. As can be seen in the diagrams in Figures B.1 and B.2 in Appendix B, the periods when the solar shading is preventing direct solar radiation have been decided by considering the periods when the artificial cooling is desired for İstanbul and Diyarbakır provinces.

- **Solar Shading Design for İstanbul Province**

  The sun path diagram of İstanbul Province is shown in Figure 3.10 and decisions made for each facade by implementing the study of Akgöz are listed below [77]:

  - For the east-facing facade, a horizontal solar shading device with a vertical shadow angle of (VSA) 42° is decided on using the heating and cooling periods diagram in Appendix B, Figure B.1. If vertical shading decision was made for this facade, most of the necessary radiation would be prevented during the winter period as well. Proposed shading device prevents direct solar radiation to enter the building after 09:30 on the June solstice and after 11:30 on the December solstice.
  - In order to prevent direct solar radiation between the equinox dates on the south-facing facade, the VSA is calculated using 90°-LAT(41°01')=48°99' formula based on the latitude of the city of İstanbul. This solar shading device prevents direct solar radiation to enter the building from the March equinox to the September equinox in the south-facing facade of the building. It allows beneficial solar radiation to enter the building from the September equinox to the March equinox.
  - The west-facing facades of the buildings are prone to overheating during the summer period due to high solar radiation as they receive the afternoon sun. For this reason, a horizontal solar shading with 28° VSA is decided on using the heating and cooling periods diagram in Figure B.1. It is found out with a series of simulation that vertical solar shades prevents desirable afternoon solar radiation in winter period for this orientation of the building. This finding is in line with the previous study about optimal shading device design by Zorer Gedik [79]. Proposed shading device allows direct solar radiation to enter the building after 18:00 on the June solstice and after 15:30 on the December solstice.

  Solar shading dimensions of study for İstanbul province are shown in Figure 3.11.

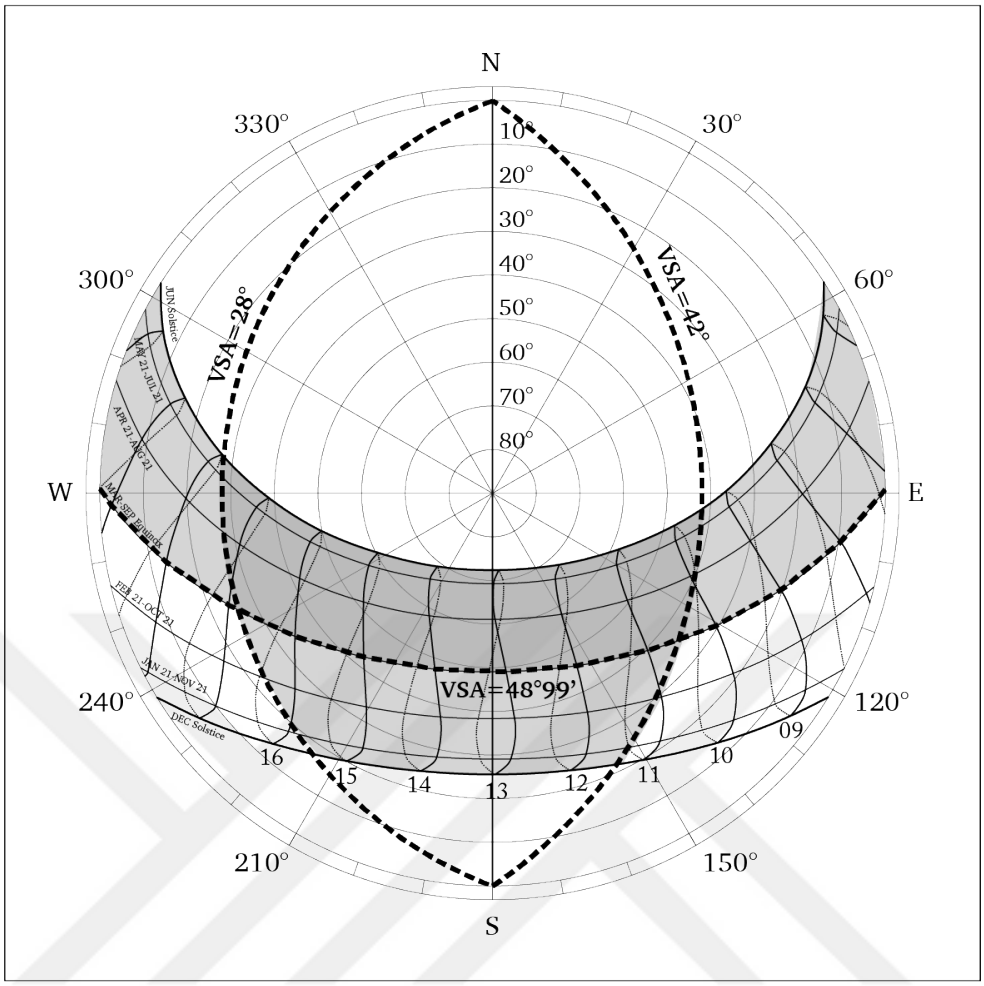


Figure 3.10 Sun path diagram of İstanbul province and HSA and VSA calculations for east, south and west elevations[80]

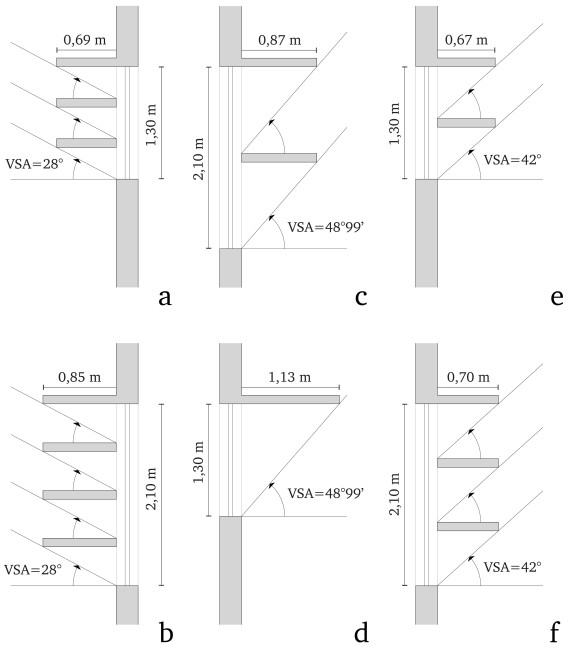


Figure 3.11 Solar shading dimensions for İstanbul province: a, b: west elevation, c, d: south elevation, e, f: east elevation

- **Solar Shading Design for Diyarbakır Province**

  The sun path diagram of Diyarbakır province is shown in Figure 3.12 and decisions made for each facade by implementing the study of Berköz et al. are listed below [78]:

  - For the east-facing facade, a vertical shadow angle of (VSA) 45° is decided on using the heating and cooling periods diagram in Appendix B, Figure B.2. Proposed shading device prevents direct solar radiation to enter the building after 09:00 on the June solstice and after 10:40 on the December solstice.
  - In order to prevent direct solar radiation between the equinox dates on the south-facing facade, the VSA is calculated using 90°-LAT(37°55')=52°45' formula based on the latitude of the city of Diyarbakır. This solar shading device prevents direct solar radiation to enter the building from the March equinox to the September equinox in the south-facing facade of the building. It allows beneficial solar radiation to enter the building from the September equinox to the March equinox.
  - The dates and times in the heating and cooling periods diagram in Figure B.2 show the requirement for a wide 53° VSA for the west-facing facade in Diyarbakır which is wider than the required VSA for İstanbul province. In order to verify and, if necessary, optimize the VSA for Diyarbakır study, a series of energy simulations have been carried out. According to the results, it was seen that the cooling and total loads of the building could be reduced further with a solar shading device which covers more than the required 53° VSA. This means blocking direct solar radiation for more in the afternoon period. Therefore, a horizontal solar shading device with a VSA of 8° is proposed, allowing direct solar radiation to enter the building after 19:00 on the June solstice and after 16:20 on the December solstice.

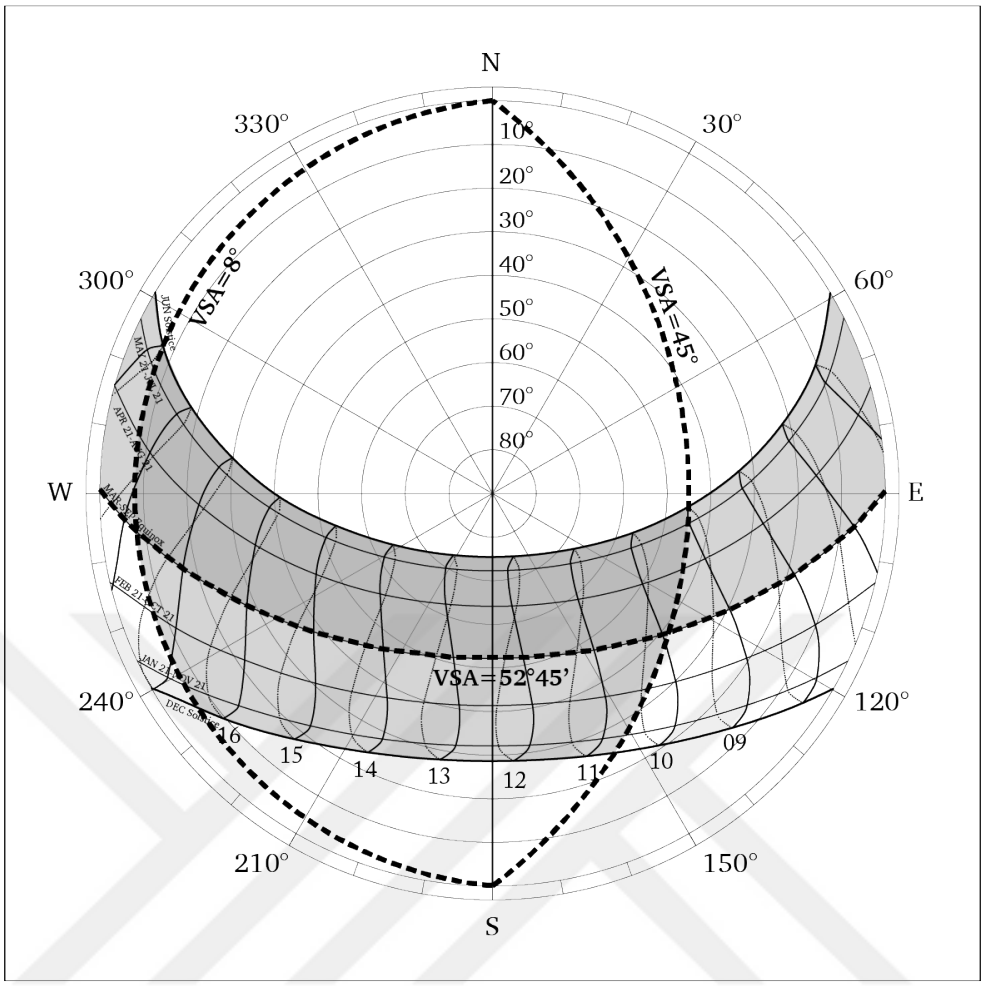


Figure 3.12 Sun path diagram of Diyarbakır province and HSA and VSA calculations for east, south and west elevations[81]

The energy consumption values after solar shading implementation to the baseline building obtained from the simulations are shown in Tables 3.16.

Table 3.16 Annual base case (BC) and solar shading (SS) scenario loads of İstanbul and Diyarbakır provinces

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599, 12	18120, 21	11700, 30	61419, 63
SS_{Ist}	36164, 54	11427, 21	12018, 03	59609, 78
BC_{Diy}	39194, 00	50384, 15	12186, 53	101764, 68
SS_{Diy}	45521, 14	42388, 33	12345, 91	100255, 38

3.1.6.2 Glass System Replacement

Another intervention to prevent energy performance problems in glazing areas during summer and winter periods is replacement of the glazing system. Two major glazing

system types are used to increase the energy efficiency of a building: solar control glasses to reduce cooling loads in summer period, low-e coated glasses to reduce both heating and cooling loads. These two systems can be used together or separately. Properties of the glass systems that are analyzed in the study are listed in Table 3.17.

Table 3.17 Performance values of glass systems used in the current study[62]

	Glazing system	**Daylight transmission**	**Reflection**	**SHGC**	**U-value (W/m^2K)**
G_BC	low-e	80%	17%	75%	1,900
G_1	low-e	79%	12%	56%	1,300
G_2	solar low-e	71%	10%	44%	1,300
G_3	tinted	51,8%	21,5%	38,5%	2,718

Glazing_1 (G_1) has a low-e coating and lower U-value than the base case glazing system (G_BC) which results in lower heat losses. On the other hand, Glazing_2 (G_2) has a solar low-e coating -meaning lower solar heat gain coefficient (SHGC)- and the same U-value with G_1. Because of that, G_2 is expected to reduce the cooling loads originated from direct solar heat gain more than G_1 which results in better summer performance. Glazing_3 (G_3), however, is a high performance solar control glass system, which is expected to show better performance in the summer period than both of its peers but because of its low U-value and SHGC (lowest of all the systems studied), worse performance in the winter period. G_3 consist of a tinted glass as external pane and has a reflective coating in the position 2 of the multi-pane system.

All three glass systems used in the study are $4 + 16 + 4$ mm systems in line with the existing building details of G_BC. Also, air is used in the cavity of the insulating glass units.

The energy consumption values after glass system replacement scenarios to the baseline building obtained from the simulations are shown in Tables 3.18.

Table 3.18 Annual base case (BC) and glass system replacement scenario loads of İstanbul and Diyarbakır provinces

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599,12	18120,21	11700,30	61419,63
G_1_{Ist}	33189,45	12098,17	11706,20	56993,82
G_2_{Ist}	36141,45	9113,96	11760,49	57015,90
G_3_{Ist}	43752,35	8647,44	11944,26	64344,05
BC_{Diy}	39194,00	50384,15	12186,53	101764,68
G_1_{Diy}	41007,74	44276,58	12189,00	97473,32
G_2_{Diy}	44346,54	41152,43	12211,88	97710,85
G_3_{Diy}	52150,03	42462,06	12293,53	106905,62

3.1.7 Designation and Energy Performance Analysis of PCM Application

As a secondary renovation intervention, PCM is applied to the building in order to balance diurnal indoor temperature fluctuations and thus reduce heating and cooling loads of the building in both İstanbul and Diyarbakır provinces.

3.1.7.1 Designation of the PCM

The first of the selection criteria of the PCM is its melting temperature. In this direction, in line with the thesis where reduction of cooling loads is examined, first the values of indoor air temperatures for both regions are calculated in summer period. Thermal comfort simulation is performed in July, when the solar radiation is the highest for both cities, and it is seen that the indoor air temperature fluctuates between 26°C and 28°C. According to the PCM literature, in order for the PCM to perform efficiently, it must have a melting temperature in this range.

The melting temperatures of PCMs defined both in the market and building energy simulation software are 21°C, 23°C, 25°C, 27°C and 29°C for the cooling period. In order to validate the selection criteria regarding melting temperatures, simulations with using all these PCM types are conducted. Results show and confirm that PCM with a melting point of 27°C has the highest energy efficiency performance in selected regions.

The second criterion in selection of PCM is its latent heat storage capacity, which is directly proportional to its thickness in same types of PCM. Specifications of the PCM that are evaluated in the second phase of the designation step are shown in Table 3.19.

Table 3.19 Specifications of evaluated PCM

PCM	Melting Temperature (°C)	Latent Heat Storage		Thickness (m)
		(BTU/h.ft^2)	(W/m^2)	
BioPCM M27Q27	27	27	85,17	0,0112
BioPCM M51Q27	27	51	160,88	0,0280
BioPCM M91Q27	27	91	287,07	0,0371
BioPCM M182Q27	27	182	574,14	0,0742

Listed materials are applied as macro-encapsulated blankets below a gypsum board layer. Since the thickness of the PCM, which is considered as a retrofit intervention, is important due to its effect on the net building area, the PCM type to be used is selected as M91Q27 with an optimal thickness of 3,71 cm. Selected PCM has a latent heat of 210-250 kJ/kg and thermal conductivity of 0,15-2,5 W/mK [82]. Thermal heat capacity graph of the PCM is shown in Figure 3.13.

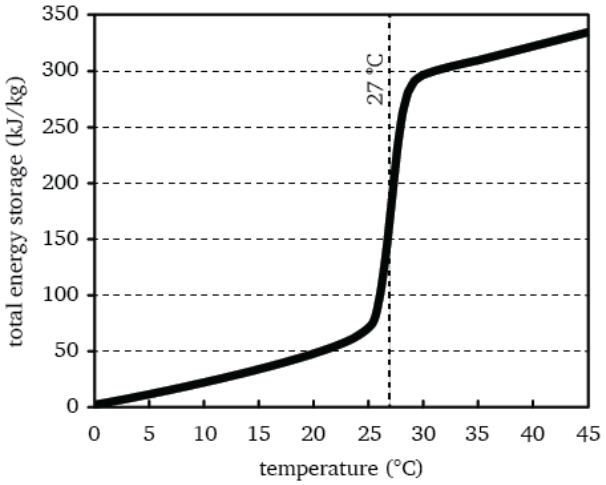


Figure 3.13 Thermal heat capacity graph of selected PCM [82]

3.1.7.2 Determination of the Surfaces for PCM Application

According to the reviewed literature, PCM is located generally to interior side of the external walls and ceiling surfaces of the interiors in the studies. To determine the surfaces of PCM application, series of simulation are conducted, showing that using both locations maximizes the performance of the material in cooling load reduction. Also, adding the material and gypsum board cladding to external wall construction changed the U-values of the building envelope, resulting reduced heating loads in winter period. These changed envelope details and their respective U-values are listed in Table 3.20.

Table 3.20 Changed building envelope details after PCM application

Location	**Detail Name**	**U-value (W/m^2K)**
External walls	EW1+PCM	0,395
	EW2+PCM	0,494
	EW3+PCM	0,395
	EW4+PCM	0,490
	EW5+PCM	0,379
	EW6+PCM	0,466
Roof	R+PCM	0,333

The energy consumption values after PCM application to the baseline building obtained from the simulations are shown in Table 3.21.

Table 3.21 Annual base case (BC) and PCM scenario loads of İstanbul and Diyarbakır provinces

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599, 12	18120, 21	11700, 30	61419, 63
PCM_{Ist}	29498, 82	17192, 26	11577, 58	58268, 66
BC_{Diy}	39194, 00	50384, 15	12186, 53	101764, 68
PCM_{Diy}	36701, 44	48275, 46	12049, 99	97026, 89

3.1.8 Developing Renovation Strategies with Combinations of Selected Interventions

After singularly analyzing the effect of the interventions on energy efficiency for both climatic regions, simulations are conducted for combinations of these interventions and results are obtained. Evaluated intervention combinations are listed below:

- Solar shading + Glazing_1
- Solar shading + Glazing_2
- Solar shading + Glazing_3
- Solar shading + PCM
- Glazing_1 + PCM
- Glazing_2 + PCM
- Glazing_3 + PCM
- Solar shading + Glazing_1 + PCM
- Solar shading + Glazing_2 + PCM
- Solar shading + Glazing_3 + PCM

The energy consumption values obtained for both provinces from each intervention combination are summarized and evaluated under the heading 3.1.9.2 Retrofit Combinations Scenario Loads.

3.1.9 Evaluation of the Energy Performance Analyses

3.1.9.1 Singular Retrofit Intervention Scenario Loads

The energy consumption values obtained after the retrofit interventions -solar shading implementation, glass system replacement and PCM application- to the application example for selected provinces are summarized in this heading. The values shown in the tables are the annual total energy loads of the conditioned areas in the building. The energy consumption values in İstanbul and Diyarbakır provinces are shown and compared with the base case scenario in Tables 3.22 and 3.23. The graphic expression of these values are shown in Figures 3.14 and 3.15. Afterwards, the effect of every retrofit scenario on energy efficiency of the building are listed.

- **Singular Retrofit Intervention Scenario Loads in İstanbul Province**

Table 3.22 Annual singular retrofit intervention scenario loads in İstanbul province

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599, 12	18120, 21	11700, 30	61419, 63
SS_{Ist}	36164, 54	11427, 21	12018, 03	59609, 78
G_1_{Ist}	33189, 45	12098, 17	11706, 20	56993, 82
G_2_{Ist}	36141, 45	9113, 96	11760, 49	57015, 90
G_3_{Ist}	43752, 35	8647, 44	11944, 26	64344, 05
PCM_{Ist}	29498, 82*	17192, 26	11577, 58	58268, 66

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

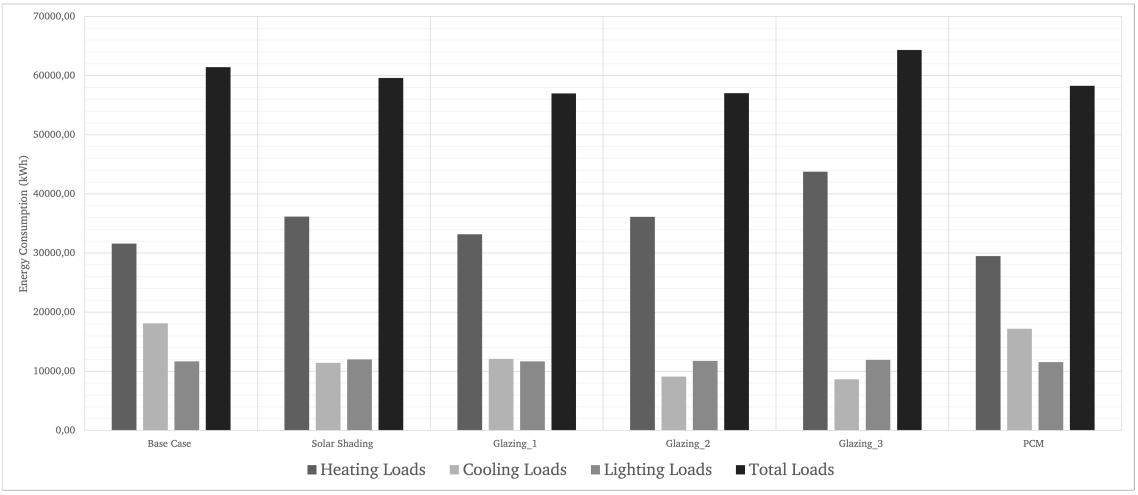


Figure 3.14 İstanbul singular retrofit intervention results summary

According to the values obtained from the building energy simulations, in İstanbul province;

- Solar shading implementation increased the heating loads by 14,45%, decreased the cooling loads by 36,94% and increased the lighting loads by 2,72% in the application example. Total annual energy consumption of the building decreased by 2,94%.
- Replacing the existing glass system with Glazing_1 increased the heating loads by 5,03%, decreased the cooling loads by 33,23% and increased the lighting loads by 0,05% in the application example. Total annual energy consumption of the building decreased by 7,21%.
- Replacing the existing glass system with Glazing_2 increased the heating loads by 14,37%, decreased the cooling loads by 49,70% and increased the lighting loads by 0,51% in the application example. Total annual energy consumption of the building decreased by 7,17%.
- Replacing the existing glass system with Glazing_3 increased the heating loads by 38,46%, decreased the cooling loads by 52,28% and increased the lighting loads by 2,09% in the application example. Total annual energy consumption of the building increased by 4,76%.
- Application of PCM with a melting point of 27°C on the interior side of the exterior walls and ceilings decreased the heating loads by 6,65%, the cooling loads by 5,12% and the lighting loads by 1,05% in the application example. Total annual energy consumption of the building decreased by 5,13%. Although the use of PCM is not the best performing option affecting total loads, it is the only scenario that reduces heating, cooling, and lighting loads all together.

- **Singular Retrofit Intervention Scenario Loads in Diyarbakır Province**

Table 3.23 Annual singular retrofit intervention scenario loads in Diyarbakır province

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
$\mathbf{BC_{Diy}}$	39194,00	50384,15	12186,53	101764,68
$\mathbf{SS_{Diy}}$	45521,14	42388,33	12345,91	100255,38
$\mathbf{G_1_{Diy}}$	41007,74	44276,58	12189,00	97473,32
$\mathbf{G_2_{Diy}}$	44346,54	41152,43	12211,88	97710,85
$\mathbf{G_3_{Diy}}$	52150,03	42462,06	12293,53	106905,62
$\mathbf{PCM_{Diy}}$	36701,44*	48275,46	12049,99	97026,89

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

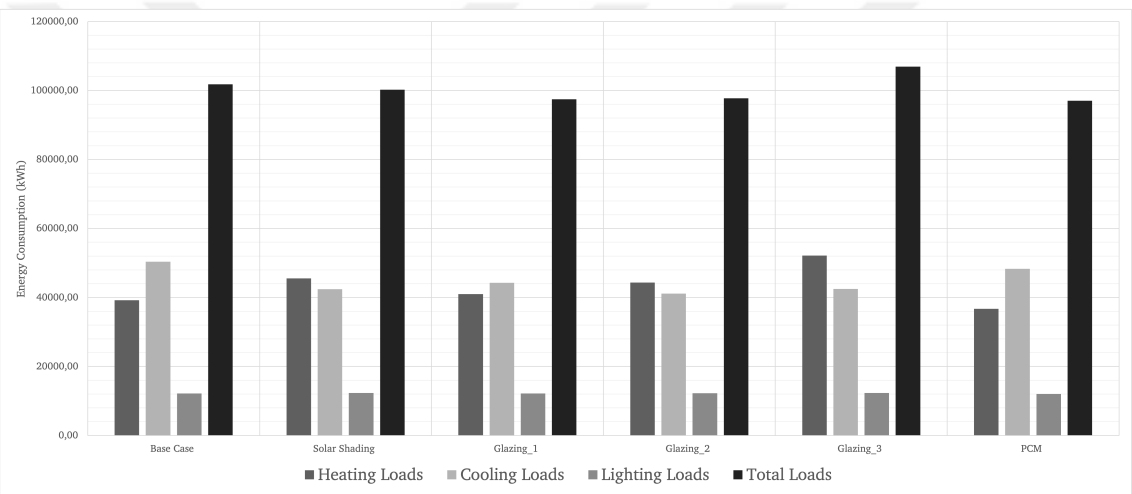


Figure 3.15 Diyarbakır singular retrofit intervention results summary

According to the values obtained from the building energy simulations, in Diyarbakır province;

- Solar shading implementation increased the heating loads by 16,14%, decreased the cooling loads by 15,87% and increased the lighting loads by 1,31% in the application example. Total annual energy consumption of the building decreased by 1,48%.
- Replacing the existing glass system with Glazing_1 increased the heating loads by 4,63%, decreased the cooling loads by 12,12% and increased the lighting loads by 0,02% in the application example. Total annual energy consumption of the building decreased by 4,22%.
- Replacing the existing glass system with Glazing_2 increased the heating loads by 13,15%, decreased the cooling loads by 18,32% and increased the

lighting loads by 0,21% in the application example. Total annual energy consumption of the building decreased by 3,98%.

– Replacing the existing glass system with Glazing_3 increased the heating loads by 33,06%, decreased the cooling loads by 15,72% and increased the lighting loads by 0,88% in the application example. Total annual energy consumption of the building increased by 5,05%.

– Application of PCM with a melting point of 27°C on the interior side of the exterior walls and ceilings decreased the heating loads by 6,36%, the cooling loads by 4,19% and the lighting loads by 1,12% in the application example. Total annual energy consumption of the building decreased by 4,66%. Similar to the results in İstanbul, the use of PCM is not the best performing option affecting total loads, but it is the only scenario that reduces heating, cooling, and lighting loads all together.

3.1.9.2 Retrofit Combinations Scenario Loads

After examining singular interventions, the effects of combinations of interventions on the energy consumption of the building are shown using the building energy simulations results. The values shown in the tables are the annual total energy loads of the conditioned areas in the building. The energy consumption of combination retrofit scenarios in İstanbul and Diyarbakır provinces are shown and compared with the base case scenario in Tables 3.24 and 3.25. The graphic expression of these values are shown in Figures 3.16 and 3.17.

- **Retrofit Combinations Scenario Loads in İstanbul Province**

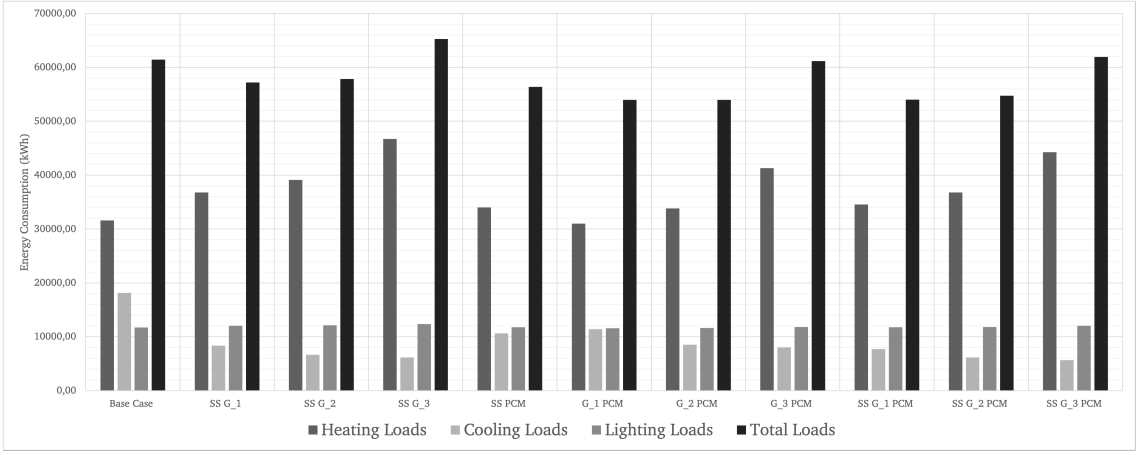


Figure 3.16 İstanbul retrofit combinations results summary

According to the values obtained from the building energy simulations, in İstanbul province;

Table 3.24 Annual retrofit combinations scenario loads in İstanbul province

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Ist}	31599,12	18120,21	11700,30	61419,63
$SS+G_1_{Ist}$	36796,74	8356,63	12022,93	57176,30
$SS+G_2_{Ist}$	39084,89	6647,93	12103,05	57835,87
$SS+G_3_{Ist}$	46710,41	6156,67	12374,17	65241,25
$SS+PCM_{Ist}$	34009,56	10630,14	11750,08	56389,78
G_1+PCM_{Ist}	30975,66	11403,01	11583,48	53962,15*
G_2+PCM_{Ist}	33828,28	8508,39	11637,69	53974,36
G_3+PCM_{Ist}	41310,37	8012,61	11821,30	61144,28
$SS+G_1+PCM_{Ist}$	34537,43	7720,56	11758,94	54016,93
$SS+G_2+PCM_{Ist}$	36764,02	6166,83	11821,42	54752,27
$SS+G_3+PCM_{Ist}$	44244,87	5660,59*	12048,36	61953,82

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

- Combination of solar shading implementation and Glazing_1 increased the heating loads by 16,45%, decreased the cooling loads by 53,88% and increased the lighting loads by 2,76% in the application example. Total annual energy consumption of the building decreased by 6,91%.
- Combination of solar shading implementation and Glazing_2 increased the heating loads by 23,69%, decreased the cooling loads by 63,31% and increased the lighting loads by 3,44% in the application example. Total annual energy consumption of the building decreased by 5,83%.
- Combination of solar shading implementation and Glazing_3 increased the heating loads by 47,82%, decreased the cooling loads by 66,02% and increased the lighting loads by 5,76% in the application example. Total annual energy consumption of the building increased by 6,22%.
- Combination of solar shading implementation and application of PCM with a melting point of 27°C increased the heating loads by 7,63%, decreased the cooling loads by 41,34% and increased the lighting loads by 0,43% in the application example. Total annual energy consumption of the building decreased by 8,19%.
- Combination of Glazing_1 and application of PCM with a melting point of 27°C decreased the heating loads by 1,97%, the cooling loads by 37,07% and the lighting loads by 1,00% in the application example. Total annual energy consumption of the building decreased by 12,14%.
- Combination of Glazing_2 and application of PCM with a melting point of 27°C increased the heating loads by 7,05%, decreased the cooling loads by 53,04% and the lighting loads by 0,54% in the application example. Total

annual energy consumption of the building decreased by 12, 12%.

- Combination of Glazing_3 and application of PCM with a melting point of 27°C increased the heating loads by 30, 73%, decreased the cooling loads by 55, 78% and increased the lighting loads by 1, 03% in the application example. Total annual energy consumption of the building decreased by 0, 45%.
- Combination of solar shading, Glazing_1 and application of PCM with a melting point of 27°C increased the heating loads by 9, 30%, decreased the cooling loads by 57, 39% and increased the lighting loads by 0, 50% in the application example. Total annual energy consumption of the building decreased by 12, 05%.
- Combination of solar shading, Glazing_2 and application of PCM with a melting point of 27°C increased the heating loads by 16, 35%, decreased the cooling loads by 65, 97% and increased the lighting loads by 1, 04% in the application example. Total annual energy consumption of the building decreased by 10, 86%.
- Combination of solar shading, Glazing_3 and application of PCM with a melting point of 27°C increased the heating loads by 40, 02%, decreased the cooling loads by 68, 76% and increased the lighting loads by 2, 97% in the application example. Total annual energy consumption of the building increased by 0, 87%.

- **Retrofit Combinations Scenario Loads in Diyarbakır Province**

Table 3.25 Annual retrofit combinations scenario loads in Diyarbakır province

	Heating loads (kWh)	**Cooling loads (kWh)**	**Lighting loads (kWh)**	**Total loads (kWh)**
BC_{Diy}	39194, 00	50384, 15	12186, 53	101764, 68
SS+G_1_{Diy}	46018, 72	38987, 50	12350, 60	97356, 82
SS+G_2_{Diy}	48483, 60	37305, 90	12393, 78	98183, 28
SS+G_3_{Diy}	56452, 81	38408, 75	12554, 01	107415, 57
SS+PCM_{Diy}	42922, 92	40371, 24	12120, 80	95414, 96
G_1+PCM_{Diy}	38394, 74	42254, 87	12052, 47	92702, 08
G_2+PCM_{Diy}	41622, 70	39217, 12	12075, 45	92915, 27
G_3+PCM_{Diy}	49327, 83	40487, 32	12157, 44	101972, 59
SS+G_1+PCM_{Diy}	43291, 56	37094, 99	12124, 42	92510, 97*
SS+G_2+PCM_{Diy}	45673, 91	35523, 99*	12156, 99	93354, 89
SS+G_3+PCM_{Diy}	53534, 98	36562, 42	12274, 73	102372, 13

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

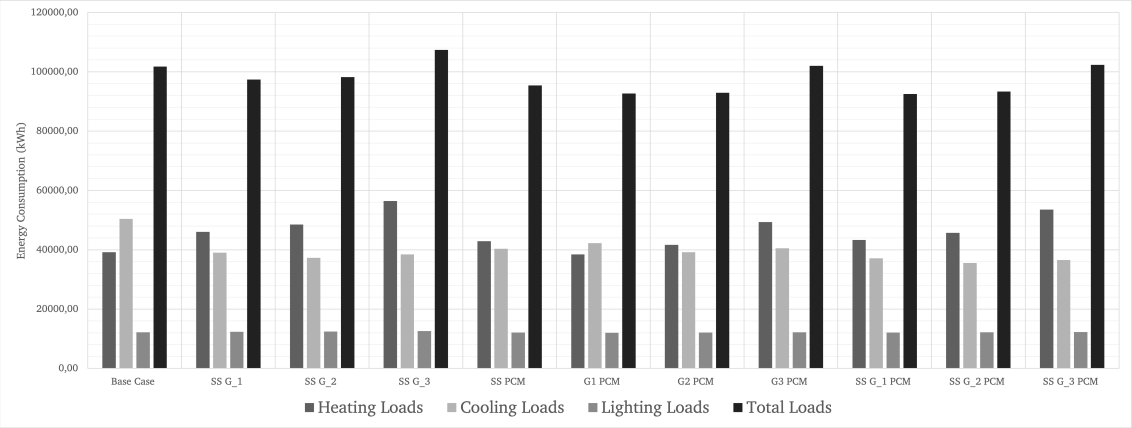


Figure 3.17 Diyarbakır retrofit combinations results summary

According to the values obtained from the building energy simulations, in Diyarbakır province;

- Combination of solar shading implementation and Glazing_1 increased the heating loads by 17,41%, decreased the cooling loads by 22,62% and increased the lighting loads by 1,35% in the application example. Total annual energy consumption of the building decreased by 4,33%.
- Combination of solar shading implementation and Glazing_2 increased the heating loads by 23,70%, decreased the cooling loads by 25,96% and increased the lighting loads by 1,70% in the application example. Total annual energy consumption of the building decreased by 3,52%.
- Combination of solar shading implementation and Glazing_3 increased the heating loads by 44,03%, decreased the cooling loads by 23,77% and increased the lighting loads by 3,02% in the application example. Total annual energy consumption of the building increased by 5,55%.
- Combination of solar shading implementation and application of PCM with a melting point of 27°C increased the heating loads by 9,51%, decreased the cooling loads by 19,87% and increased the lighting loads by 0,54% in the application example. Total annual energy consumption of the building decreased by 6,24%.
- Combination of Glazing_1 and application of PCM with a melting point of 27°C decreased the heating loads by 2,04%, the cooling loads by 16,13% and the lighting loads by 1,10% in the application example. Total annual energy consumption of the building decreased by 8,91%.
- Combination of Glazing_2 and application of PCM with a melting point of 27°C increased the heating loads by 6,20%, decreased the cooling loads by

22, 16% and the lighting loads by 0, 91% in the application example. Total annual energy consumption of the building decreased by 8, 70%.

- Combination of Glazing_3 and application of PCM with a melting point of 27°C increased the heating loads by 25, 86%, decreased the cooling loads by 19, 64% and the lighting loads by 0, 24% in the application example. Total annual energy consumption of the building increased by 0, 20%.
- Combination of solar shading, Glazing_1 and application of PCM with a melting point of 27°C increased the heating loads by 10, 45%, decreased the cooling loads by 26, 38% and increased the lighting loads by 0, 51% in the application example. Total annual energy consumption of the building decreased by 9, 09%.
- Combination of solar shading, Glazing_2 and application of PCM with a melting point of 27°C increased the heating loads by 16, 53%, decreased the cooling loads by 29, 49% and increased the lighting loads by 0, 24% in the application example. Total annual energy consumption of the building decreased by 8, 26%.
- Combination of solar shading, Glazing_3 and application of PCM with a melting point of 27°C increased the heating loads by 36, 59%, decreased the cooling loads by 27, 43% and increased the lighting loads by 0, 72% in the application example. Total annual energy consumption of the building increased by 0, 60%.

The graphic expression of energy consumption of the base case and all retrofit scenarios in both cities is shown in Figures 3.18 and 3.19, and the change in loads is shown in Tables 3.26 and 3.27.

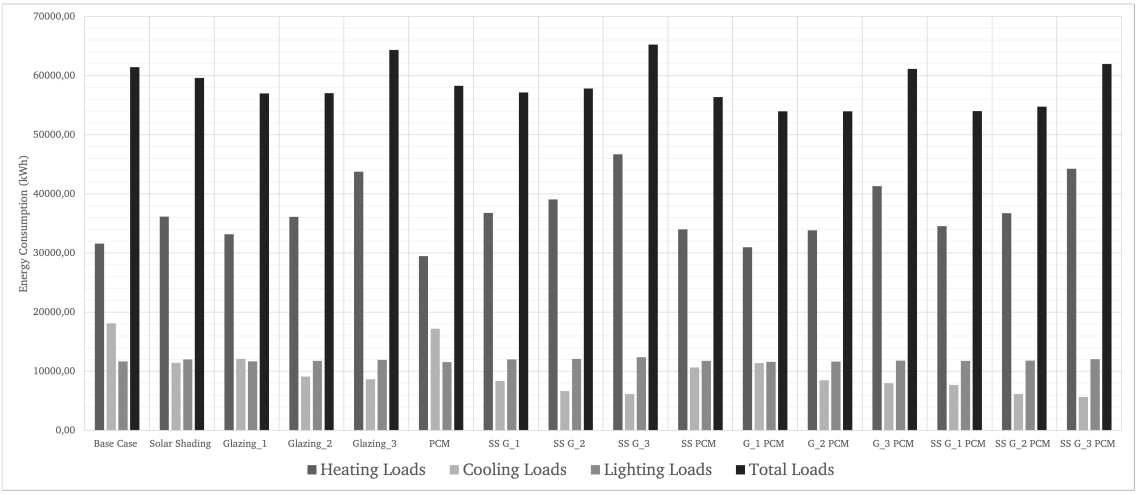


Figure 3.18 İstanbul results summary

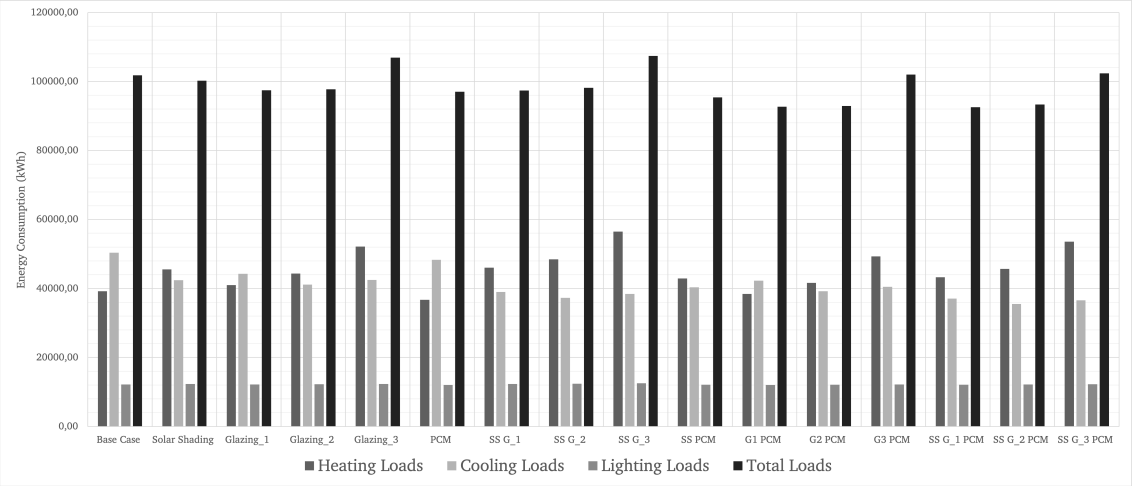
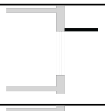
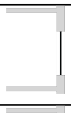
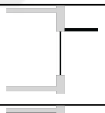
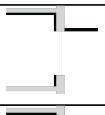
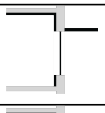
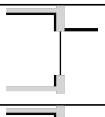
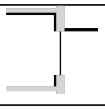


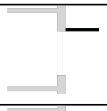
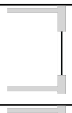
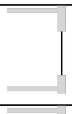
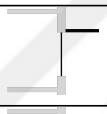
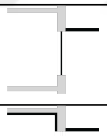
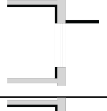
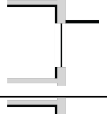
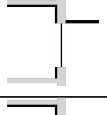
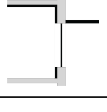
Figure 3.19 Diyarbakır results summary

Table 3.26 Energy consumption change ratios caused by the retrofit scenarios in İstanbul province

Retrofit scenario	Schematic section	Heating loads	Cooling loads	Lighting loads	Total loads
BC_{Ist}		–	–	–	–
SS_{Ist}		▲14, 45%	▼36, 94%	▲2, 72%	▼2, 94%
G_1_{Ist}		▲5, 03%	▼33, 23%	▲0, 05%	▼7, 21%
G_2_{Ist}		▲14, 37%	▼49, 70%	▲0, 51%	▼7, 17%
G_3_{Ist}		▲38, 46%	▼52, 28%	▲2, 09%	▲4, 76%
PCM_{Ist}		▼6, 65%*	▼5, 12$	▼1, 05%	▼5, 13%
$SS+G_1_{Ist}$		▲16, 45%	▼53, 88%	▲2, 76%	▼6, 91%
$SS+G_2_{Ist}$		▲23, 69%	▼63, 31%	▲3, 44%	▼5, 83%
$SS+G_3_{Ist}$		▲47, 82%	▼66, 02%	▲5, 76%	▲6, 22%
$SS+PCM_{Ist}$		▲7, 63%	▼41, 34%	▲0, 43%	▼8, 19%
G_1+PCM_{Ist}		▼1, 97%	▼37, 07%	▼1, 00%	▼12, 14%*
G_2+PCM_{Ist}		▲7, 05%	▼53, 04%	▼0, 54%	▼12, 12%
G_3+PCM_{Ist}		▲30, 73%	▼55, 78%	▲1, 03%	▼0, 45%
$SS+G_1+PCM_{Ist}$		▲9, 30%	▼57, 39%	▲0, 50%	▼12, 05%
$SS+G_2+PCM_{Ist}$		▲16, 35%	▼65, 97%	▲1, 04%	▼10, 86%
$SS+G_3+PCM_{Ist}$		▲40, 02%	▼68, 76%*	▲2, 97%	▲0, 87%

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

Table 3.27 Energy consumption change ratios caused by the retrofit scenarios in Diyarbakır province

Retrofit scenario	Schematic section	Heating loads	Cooling loads	Lighting loads	Total loads
BC_{Diy}		–	–	–	–
SS_{Diy}		▲16, 14%	▼15, 87%	▲1, 31%	▼1, 48%
G_1_{Diy}		▲4, 63%	▼12, 12%	▲0, 02%	▼4, 22%
G_2_{Diy}		▲13, 15%	▼18, 32%	▲0, 21%	▼3, 98%
G_3_{Diy}		▲33, 06%	▼15, 72%	▲0, 88%	▲5, 05%
PCM_{Diy}		▼6, 36%*	▼4, 19%	▼1, 12%	▼4, 66%
$SS+G_1_{Diy}$		▲17, 41%	▼22, 62%	▲1, 35%	▼4, 33%
$SS+G_2_{Diy}$		▲23, 70%	▼25, 96%	▲1, 70%	▼3, 52%
$SS+G_3_{Diy}$		▲44, 03%	▼23, 77%	▲3, 02%	▲5, 55%
$SS+PCM_{Diy}$		▲9, 51%	▼19, 87%	▼0, 54%	▼6, 24%
G_1+PCM_{Diy}		▼2, 04%	▼16, 13%	▼1, 10%	▼8, 91%
G_2+PCM_{Diy}		▲6, 20%	▼22, 16%	▼0, 91%	▼8, 70%
G_3+PCM_{Diy}		▲25, 86%	▼19, 64%	▼0, 24%	▲0, 20%
$SS+G_1+PCM_{Diy}$		▲10, 45%	▼26, 38%	▼0, 51%	▼9, 09%*
$SS+G_2+PCM_{Diy}$		▲16, 53%	▼29, 49%*	▼0, 24%	▼8, 26%
$SS+G_3+PCM_{Diy}$		▲36, 59%	▼27, 43%	▲0, 72%	▲0, 60%

*Dark grey cells indicate the scenarios with the lowest annual energy consumption.

This study aims to reveal the importance of improving the existing building stock with various energy retrofit interventions and to show the relationship between the effects of these interventions and the climatic conditions of the locations of the buildings. For this reason, two climatic zones with different characteristics are selected, three different intervention methods are determined, and their effect on the energy consumption of the building are examined individually and together with their combinations. The intervention methods chosen in the study are; solar shading implementation, replacement of the existing glass system, and PCM application on interior surfaces of exterior walls and ceilings in conditioned interiors.

Considering singular interventions, the significance of glass system change in reducing cooling loads can be seen clearly. Glazing_3, which is designed only for reducing cooling loads, having the highest reflectivity and U-value but the lowest SHGC, is the glass system that reduces the cooling loads the most in İstanbul province. However, the same system does not show the best cooling loads performance in Diyarbakır, where summer cooling loads are 2,78 times that of İstanbul in the base case scenario. Instead, the glass system with the highest cooling loads performance in Diyarbakır, where the outside temperature is much higher than the desired indoor comfort temperature is Glazing_2 .

Considering the effect of singular intervention scenarios on total loads, the intervention that decreases the total loads the most in İstanbul is the replacement of the existing glass system with Glazing_1, while it is the PCM application in Diyarbakır. It should also be noted that although not in the scope of the study, PCM application is the only intervention that reduces heating loads for both cities, singularly.

Options that reduce cooling loads the most in retrofit combinations scenarios are; "Solar shading-Glazing_3-PCM" and "Solar shading-Glazing 2-PCM" for İstanbul and Diyarbakır provinces, respectively. With these combinations, a cooling loads reduction of 68,76% in İstanbul and 29,49% in Diyarbakır is achieved.

Considering the effect of retrofit combinations on total loads, the interventions that decreased the total loads the most for İstanbul and Diyarbakır provinces are "Glazing_1-PCM" and "Solar shading-Glazing_1-PCM", respectively. With these combinations, a decrease of 12,14% in İstanbul and 9,09% in Diyarbakır is achieved. Considering the total loads, there does not seem to be any need for solar shading implementation in İstanbul.

4
RESULTS AND DISCUSSION

The built environment contributes directly and indirectly to energy-based greenhouse gas emissions which cause climate change. In order to reduce the contribution of buildings to climate change, the energy consumption of the building stock must be reduced while also adapting to the changing climatic conditions due to the effects of this phenomenon. The general approach to improve the aging built environment in this direction is to demolish and rebuild the problematic area. However, this method can cause inefficient resource use, additional energy consumption and gentrification. Therefore, within the scope of this thesis, retrofit interventions to improve the building envelope properties of existing buildings are studied.

Also, it is known that improvements for the summer period will also gain importance due to the gradual increase in summer temperatures with the effect of climate change [14]. The models created within the scope of the thesis study shows that when the correct interventions are selected, the necessary optimization can be made for cooling loads. The aim of the study is to examine the use of solar shading devices and glass systems to prevent direct solar radiation, and the effects of PCM application on the energy consumption of buildings in building energy retrofit projects.

In the study conducted for existing buildings in İstanbul and Diyarbakır provinces where summer temperatures are known to be high, it is observed that the retrofit interventions made on glazing areas to reduce cooling loads were also effective in reducing the total loads of the buildings. However, as the interventions made in the building envelope to reduce the cooling loads limit the beneficial solar radiation during the winter period, the heating loads increased as expected. For this reason, it has been suggested to use phase change materials (PCM) that contribute to the thermal mass of the building by adding it to the building envelope and help to keep the interior constant at the desired temperatures.

It should be noted that, in this thesis, retrofit interventions aimed at reducing cooling loads are examined. The interventions to reduce the heating loads have not been

examined, but the effects of these interventions on heating, cooling, lighting and total loads have been shown.

Evaluations of the simulation results according to the hypotheses of the study are;

1. In the study, the solar shading implementation, which provides protection only in the inter-equinox dates, reduced the cooling loads in both cities during the summer period. Although the heating loads have increased as predicted, the overall energy efficiency of the buildings has increased throughout the year. Annual cooling loads in İstanbul and Diyarbakır provinces decreased by 6693,00 and 7995,82 KWh, respectively. However, as the average summer temperature of Diyarbakır is much higher than that of İstanbul, the percentage decrease in cooling loads is less in Diyarbakır (15, 87%) than İstanbul (36, 94%).

2. In the study, three different types of glass systems were determined as retrofit interventions. Glazing_1 is a low-e coated glass system with a higher performance in winter than in summer. Glazing_2 type glass system has a solar low-e coating resulting higher summer performance. Glazing_3, on the other hand, is only intended to reduce cooling loads during the summer period.

   In singular retrofit interventions in both cities, low-e coated glass systems have shown high performance in reducing both annual cooling and annual total energy consumption of the building. This is because low-e coatings are intended to reduce energy consumption in both summer and winter periods. Due to the solar control properties of these systems, they performed worse than the existing glass system of the building in the winter period, but they caused lower energy consumption in total loads than the existing system in both cities because of their superior performance in the summer period.

   Glazing_3, a tinted glass system for solar control only, has been the worst option amongst singular intervention scenarios in both cities due to its very low performance during the winter period. However, in the summer period, it is the most effective glass system in reducing cooling loads in İstanbul by 52, 28%. In Diyarbakır province however, it did not show a similar performance. The reason for this is that tinted glass systems absorb most of the solar radiation coming to its surface, increasing its surface temperatures and releases absorbed solar radiation back to the environment in the evening hours [33]. Hence, the need for cooling in Diyarbakır increases, where the average temperatures in the summer season are already higher [65]. The system that reduces the cooling loads the most in this city is the Glazing_2 with solar low-e system.

   When all the singular retrofit interventions are compared, it can be said that

glass system replacement is the most effective intervention type in İstanbul. In Diyarbakır, the option with the best performance in total loads has been the PCM application.

3. For both locations, the use of PCM indoors has provided energy efficiency in summer and winter periods. The singular PCM application scenario is one of the rare scenarios where a decrease in heating, cooling and lighting loads for both cities is observed. But it is important to note that the effect of the material in the summer period is more than its effect in the winter period. Because the melting point of the PCM was determined according to the summer comfort temperature.

   The effect of the PCM application varied by provinces in singular retrofit interventions. In Diyarbakır, where day and night temperature differences are higher in summer compared to İstanbul, therefore, high performance is obtained from the material by ensuring that the PCM completes the melting-freezing cycle, the material's contribution to reducing the cooling loads in the summer period has been higher. In this city, applying PCM as a singular retrofit intervention is the best performing option to reduce the total loads.

   The enhancing effect of PCM has become apparent when combined with other retrofit interventions. This proves that the use of PCM, as mentioned in the literature, will perform better after improving the passive properties of the building [22]. First, passive standards in the buildings should be improved, then the efficiency of the building could be further increased with the use of PCM.

   For this reason, the scenarios with the highest performance in total loads for both locations are retrofit intervention combinations using PCM. The scenarios with the lowest energy consumption for İstanbul and Diyarbakır provinces were "Glazing_1-PCM" and "Solar shading-Glazing_1-PCM" options, respectively.

4. Scenarios in which all retrofit interventions to reduce cooling loads (solar shading, glass system replacement, PCM application) are used together have been the cases where the best performance was achieved in the summer period for both cities.

   In İstanbul province, the "Solar shading-Glazing_3-PCM" scenario reduced the energy consumption of the building in summer period by 68,76%. However, this scenario is not the most energy efficient case for this location throughout the year. The "Glazing_1-PCM" scenario has the highest performance among the combinations studied, with a decrease of 12,14% in total loads throughout the year. Considering the efficiency in total loads, it has been observed

that, the best performance can be achieved only by glass system replacement and PCM application in İstanbul province without the need of solar shading implementation.

In Diyarbakır, the "Solar shading-Glazing_3-PCM" scenario reduced cooling loads by 29,49% in the summer period. However, as in İstanbul, this scenario is not the best scenario in energy consumption throughout the year. The "Solar shading-Glazing_1-PCM" had the highest performance among the combinations studied, with a 9,09% reduction in total loads throughout the year.

Except for the examined hypotheses, the aspects that can be read from the simulation results are as follows.

- Fixed solar shading devices, designed to reduce the cooling loads to the maximum, significantly reduced the energy consumption of the building in the summer period in both cities, while increasing the heating loads in the winter period. The most obvious indicator of this increase is that the scenario with the lowest annual total loads for the İstanbul province is an option that does not comprise of solar shading.
- In both cities, Glazing_1 reduced their annual total energy loads more than Glazing_2. This also applies to combination scenarios with these glass systems. The difference in performance caused by the solar heat gain coefficient (SHGC) values of Glazing_1 and Glazing_2 is more pronounced in Diyarbakır where winters are harsher than İstanbul. This situation reveals the importance of SHGC value as well as U-value in glass systems. Although the U-value of both glazing systems is lower than the existing system, they have increased the heating loads of the application example compared to the existing ones.
- The use of a solar control glass for the summer period reduced cooling loads for both cities, while increasing the energy consumption of the building in most of the retrofit scenarios studied.
- Using only PCM as a retrofit intervention resulted in a cooling load drop in the range of $4-5\%$ in İstanbul and Diyarbakır. However, because it's an additional layer to the building envelope, PCM application caused the heating loads of the building to decrease as well. Among all retrofit scenarios, the only options where heating loads are reduced compared to the existing building loads are "PCM" and "Glazing_1-PCM".
- Scenarios where only solar shading implementation and glass system changes were applied were the most inefficient scenarios among the combination

scenarios, with a 6,91% decrease in annual total load in Istanbul, 4,33% in Diyarbakır at best.

- The scenario in which Glazing_1 and PCM are used together is the one with the highest performance in total loads for İstanbul province with a decrease of 12,14%. The same scenario is the second best scenario for Diyarbakır with a total loads decrease of 8,91%.

4.1 Limitations of the Study

The solar shading devices used on the south-facing facades were designed as fixed devices for the ease of application. They are designed to prevent all the solar gains in the inter-equinox period from March to September, as the study focuses on cooling loads. Because of the fixed quality of the devices, the prevention includes some dates that may require artificial heating, thus increasing heating loads in solar shading scenarios. This situation can be prevented with "active" solar shading systems whose size or angle can be changed, which are not examined within the scope of this study.

The architectural project on which the studies are carried out is a project implemented by the Housing Development Administration (TOKİ) in many parts of Turkey. The reason for this choice is that the project should serve as a basis for comparative simulation studies. The building envelope details of the project have the quality that meets and in some areas goes beyond the TS825 standard for the winter period [60]. The impact of retrofit interventions on an existing building to be selected from the built environment would be much more pronounced than in the project of the study.

4.2 Recommendations for Future Studies

This study focused on the effect of retrofit interventions on energy consumption of the buildings. However, in future studies, the economic impact of retrofit interventions should also be revealed.

In most scenarios where PCM is used, energy consumption has decreased throughout the year for both winter and summer conditions. It is important to indicate that, the costs of the services for heating and cooling may differ depending on the energy sources used in the location. This situation should be taken into account in studies where cost of the PCM and energy consumption loads will be evaluated using invoice expenditures.

To increase the performance provided by the use of PCM, a composite building

component comprised of more than one layer of PCM which is effective in both winter and summer periods, similar to that in the study of Berardi et al., can be used in energy retrofit projects [25].

In order to show the effect of retrofit interventions more clearly, it will be beneficial to conduct future studies with experiments and applications in existing buildings as well as simulation applications.

A
BUILDING ENERGY SIMULATION VARIABLES

DesignBuilder, the building energy simulation (BES) software used within the scope of the thesis, is used for heat transfer calculation in transient periods in energy efficiency calculations, and displays the energy consumption in these periods through simulation. The simulations in the thesis are calculated using DesignBuilder v6.1.8.021 which was released on 11 January 2021 [83]. All simulations are conducted using "Finite Difference" solution algorithm for the BES to be able to calculate the effects of the PCM.

The activity variables which are omitted in the thesis body for each space in the energy model that are omitted in the thesis body are shown in Table A.1 to A.4.

Table A.1 Activity variable choices of bedroom spaces

Occupancy density	0,0229 people/m^2
Metabolic activity	
Activity type	Bedroom (dwelling)
Activity factor	0,90
Clothing	Winter 1 clo, summer 0,50 clo
Domestic hot water consumption	0,000 l/m^2-day
Environmental control	
Heating setpoint temperature	21°C
Heating setback temperature	17°C
Cooling setpoint temperature	26°C
Cooling setback temperature	28°C
Ventilation setpoint temperatures	
Natural ventilation, indoor min temperature control	24°C
Minimum fresh air	10 l/s-person
Lighting	100 lx

After the simulations conducted using selected variables and solution algorithm, the software produces result tables that are detailed from general to specific as output. The total energy consumption per total area and per conditioned area of the building can be read in site and source energy table where source energy is unconverted

Table A.2 Activity variable choices of kitchen spaces

Occupancy density	0,0237 people/m^2
Metabolic activity	
Activity type	Work involving walking etc.
Activity factor	0,90
Clothing	Winter 1 clo, summer 0,50 clo
Domestic hot water consumption	1,050 l/m^2-day
Environmental control	
Heating setpoint temperature	21°C
Heating setback temperature	17°C
Cooling setpoint temperature	26°C
Cooling setback temperature	28°C
Ventilation setpoint temperatures	
Natural ventilation, indoor min temperature control	24°C
Minimum fresh air	12 l/s-person
Lighting	300 lx

Table A.3 Activity variable choices of bathroom spaces

Occupancy density	0,0187 people/m^2
Metabolic activity	
Activity type	Light office work
Activity factor	0,90
Clothing	Winter 1 clo, summer 0,50 clo
Domestic hot water consumption	1,050 l/m^2-day
Environmental control	
Heating setpoint temperature	21°C
Heating setback temperature	17°C
Cooling setpoint temperature	26°C
Cooling setback temperature	28°C
Ventilation setpoint temperatures	
Natural ventilation, indoor min temperature control	24°C
Minimum fresh air	12 l/s-person
Lighting	150 lx

primary energy obtained from raw materials. Source energy is used to evaluate the environmental performance of buildings. Site energy, on the other hand, is a measurable type of energy that is converted from source energy and includes the losses from this conversion and distribution.

The intensity of electricity, natural gas and other fuels, district cooling, heating, domestic hot water use of the building is shown in the normalized metrics table.

The cooling loads of the building are taken directly from the normalized metrics table

Table A.4 Activity variable choices of corridor spaces

Occupancy density	0,0155 people/m^2
Metabolic activity	
Activity type	Light manual work
Activity factor	0,90
Clothing	Winter 1 clo, summer 0,50 clo
Domestic hot water consumption	0,000 l/m^2-day
Environmental control	
Heating setpoint temperature	21°C
Heating setback temperature	17°C
Cooling setpoint temperature	26°C
Cooling setback temperature	28°C
Ventilation setpoint temperatures	
Natural ventilation, indoor min temperature control	24°C
Minimum fresh air	10 l/s-person
Lighting	100 lx

of the simulation output. However, space heating loads are derived from the end-uses table, since domestic hot water is included in heating loads in normalize metrics table. Then, total heating and cooling loads of the building are given for the different province scenarios of the study.

B
PERIODS REQUIRING ARTIFICIAL HEATING AND COOLING

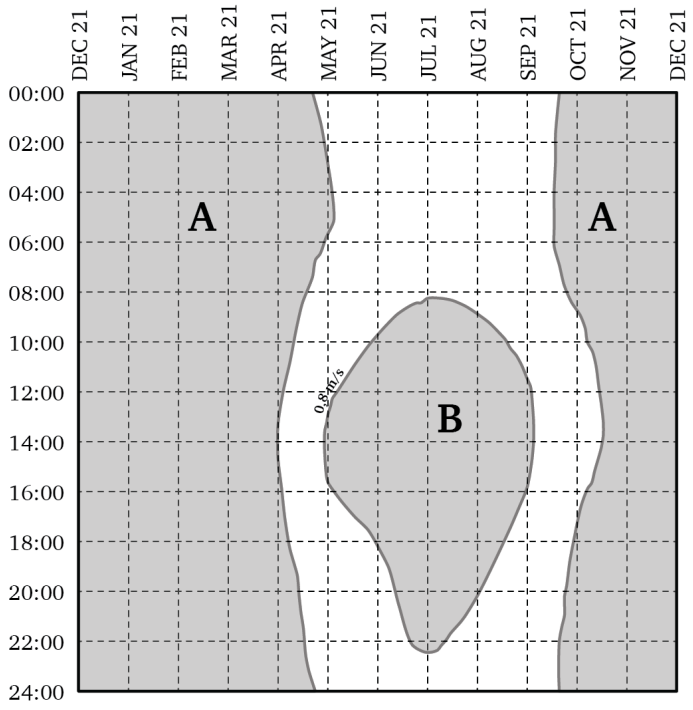


Figure B.1 The periods when artificial heating (A) and cooling (B) is desired for the İstanbul province [77]

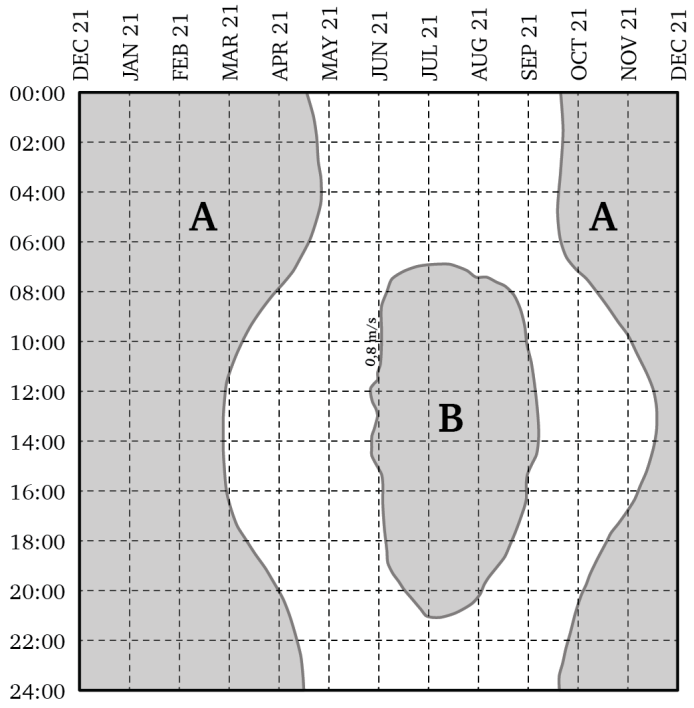


Figure B.2 The periods when artificial heating (A) and cooling (B) is desired for the Diyarbakır province [78]

REFERENCES

[1] C. Elefante, "The greenest building is... one that is already built," in *Forum Journal*, National Trust for Historic Preservation, vol. 21, 2007, p. 26.

[2] S. H. Schneider, "The greenhouse effect: Science and policy," *Science*, vol. 243, no. 4892, pp. 771–781, 1989.

[3] Intergovernmental Panel on Climate Change and J. T. Houghton, *IPCC first assessment report*. WMO, 1990.

[4] T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley, *et al.*, "Climate change 2013: The physical science basis," *Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, vol. 1535, 2013.

[5] International Energy Agency, "Key world energy statistics 2020," Tech. Rep., 2020, Accessed May 2020. [Online]. Available: https://www.iea.org/reports/key-world-energy-statistics-2020.

[6] International Energy Agency, "2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector," Tech. Rep., 2019, Accessed May 2020. [Online]. Available: https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

[7] United Nations Framework Convention on Climate Change, *Kyoto protocol - targets for the first commitment period | unfccc*, Accessed May 2020. [Online]. Available: https://unfccc.int/process/the-kyoto-protocol.

[8] United Nations Framework Convention on Climate Change, *Timeline - unfccc – 20 years of effort and achievement*, Accessed May 2020. [Online]. Available: http://unfccc.int/timeline/.

[9] Türkiye Istatistik Kurumu, *Turkiye istatistik kurumu - istatistiklerle çevre, 2016*, Accessed July 2020. [Online]. Available: http://www.tuik.gov.tr/PreHaberBultenleri.do?id=27685.

[10] Türkiye Petrolleri, "Ham petrol ve doğal gaz sektör raporu," 2019.

[11] Çevre ve Şehircilik Bakanlığı, "klim değişikliği ulusal eylem planı 2011-2023," Ankara, Tech. Rep., Jul. 2011, Accessed August 2020. [Online]. Available: http://www.dsi.gov.tr/docs/iklim-degisikligi/ideptr.pdf?sfvrsn=2.

[12] Turkish State Meteorological Service, *Turkey average temperatures*, Accessed May 2021. [Online]. Available: https://www.mgm.gov.tr/FILES/resmi-istatistikler/parametreAnalizi/Turkiye-Ortalama-Sicaklik-2020.pdf.

[13] R. K. Pachauri, M. R. Allen, V. R. Barros, J. Broome, W. Cramer, R. Christ, J. A. Church, L. Clarke, Q. Dahe, P. Dasgupta, *et al.*, *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Ipcc, 2014.

[14] M. Türkeş, "Küresel iklim değişiklikleri ve başlıca nedenleri ile Dünya'da ve Türkiye'de gözlenen ve öngörülen iklim değişiklikleri ve değişkenliği," *"Küresel İklim Değişikliği ve Etkileri" Engin Ural Anısına*, pp. 71–115, 2016.

[15] International Eneregy Agency, *Transition to Sustainable Buildings*. 2013, p. 284. DOI: https : / / doi . org / https : / / doi . org / 10 . 1787 / 9789264202955 - en. [Online]. Available: https : / / www. oecd - ilibrary. org / content / publication / 9789264202955-en.

[16] C. N. Uzun, "The impact of urban renewal and gentrification on urban fabric: Three cases in turkey," *Tijdschrift voor economische en sociale geografie*, vol. 94, no. 3, pp. 363–375, 2003.

[17] S. Szokolay, *Introduction to Architectural Science: The Basis of Sustainable Design*. Elsevier/Architectural Press, 2008, ISBN: 9780750687041. [Online]. Available: https://books.google.com.tr/books?id=VjwYnQ8q8I4C.

[18] A. S. Fleischer, *Thermal energy storage using phase change materials: fundamentals and applications*. Springer, 2015.

[19] M. Koschenz and B. Lehmann, "Development of a thermally activated ceiling panel with pcm for application in lightweight and retrofitted buildings," *Energy and buildings*, vol. 36, no. 6, pp. 567–578, 2004.

[20] F. Kuznik, J. Virgone, and K. Johannes, "In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard," *Renewable Energy*, vol. 36, no. 5, pp. 1458–1462, 2011.

[21] K. Biswas, W. Miller, P. Childs, J. Kosny, and S. Kriner, "Performance evaluation of a sustainable and energy efficient re-roofing technology using field-test data," in *International Roofing Symposium, Washington, DC: National Roofing Contractors Association. Retrieved from http://staticcontent. nrca. net/masterpages/technical/symposium/pdf/15_bi swas_paper. pdf*, 2011.

[22] E. Rodriguez-Ubinas, B. A. Arranz, S. V. Sánchez, and F. N. González, "Influence of the use of pcm drywall and the fenestration in building retrofitting," *Energy and Buildings*, vol. 65, pp. 464–476, 2013.

[23] F. Ascione, N. Bianco, R. F. De Masi, F. de'Rossi, and G. P. Vanoli, "Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season," *Applied Energy*, vol. 113, pp. 990–1007, 2014.

[24] F. Ascione, N. Bianco, R. F. De Masi, F. de'Rossi, and G. P. Vanoli, "Energy retrofit of an educational building in the ancient center of benevento. feasibility study of energy savings and respect of the historical value," *Energy and Buildings*, vol. 95, pp. 172–183, 2015.

[25] U. Berardi and S. Soudian, "Benefits of latent thermal energy storage in the retrofit of canadian high-rise residential buildings," in *Building Simulation*, Springer, vol. 11, 2018, pp. 709–723.

[26] S. Herkel and F. Kagerer, "Advances in housing retrofit—processes, concepts and technologies," *SHC Germany*, pp. 19–21, 2011.

[27] Global Buildings Performance Network, "What is a deep renovation definition," *URL http://www. gbpn. org/sites/default/files/08. DR_TechRep. low_. pdf*, 2013.

[28] European Union Directive, "844 of the european parliament and of the council of 30 may 2018 amending directive 2010/31/eu on the energy performance of buildings and directive 2012/27/eu on energy efficiency," *EU: Brussels, Belgium*, 2018.

[29] European Council, "Directive 2010/31/eu of the european parliament and of the council of 19 may, 2010 on the energy performance of buildings," *Official Journal of the European Union*, vol. 153, pp. 13–35, 2010.

[30] M. Economidou, *Energy renovation*, Accessed Oct 2020. [Online]. Available: https://e3p.jrc.ec.europa.eu/articles/energy-renovation.

[31] C. J. Cleveland and C. Morris, *Dictionary of energy*. Elsevier, 2009.

[32] C. Becchio, P. Dabbene, E. Fabrizio, V. Monetti, and M. Filippi, "Cost optimality assessment of a single family house: Building and technical systems solutions for the nzeb target," *Energy and Buildings*, vol. 90, pp. 173–187, 2015.

[33] B. Weller, S. Unnewehr, S. Tasche, and K. Härth, *Glass in building: principles, applications, examples*. Walter de Gruyter, 2012.

[34] J. D. Musgraves, J. Hu, and L. Calvez, *Springer Handbook of Glass*. Springer Nature, 2019.

[35] I. Dincer and M. A. Rosen, *Thermal Energy Storage Systems and Applications, Second Edition*. Wiley, 2010.

[36] H. Mehling and L. F. Cabeza, *Heat and cold storage with PCM*. Springer, 2008, vol. 308.

[37] N. V. Khartchenko and V. M. Kharchenko, *Advanced energy systems*. CRC Press, 2013.

[38] J.-P. Ansermet and S. D. Bréchet, *Principles of thermodynamics*. Cambridge University Press, 2019.

[39] F. Pacheco-Torgal, C. G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, and J. Kurnitski, *Cost-effective energy efficient building retrofitting: Materials, technologies, optimization and case studies*. Woodhead Publishing, 2017.

[40] R. Baetens, B. P. Jelle, and A. Gustavsen, "Phase change materials for building applications: A state-of-the-art review," *Energy and buildings*, vol. 42, no. 9, pp. 1361–1368, 2010.

[41] M. K. Rathod and J. Banerjee, "Thermal stability of phase change materials used in latent heat energy storage systems: A review," *Renewable and sustainable energy reviews*, vol. 18, pp. 246–258, 2013.

[42] A. Sharma, V. V. Tyagi, C. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable energy reviews*, vol. 13, no. 2, pp. 318–345, 2009.

[43] F. Kuznik, D. David, K. Johannes, and J.-J. Roux, "A review on phase change materials integrated in building walls," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 379–391, 2011.

[44] M. Kenisarin and K. Mahkamov, "Solar energy storage using phase change materials," *Renewable and sustainable energy reviews*, vol. 11, no. 9, pp. 1913–1965, 2007.

[45] J. Kośny, *PCM-enhanced building components: an application of phase change materials in building envelopes and internal structures*. Springer, 2015.

[46] Glassx, *Glassx-store*, Accessed March 2021. [Online]. Available: https://www.glassx.ch/de/produkte/glassx-store/.

[47] Phase Change Solutions, *Enrg blanket*, Accessed March 2021. [Online]. Available: https://phasechange.com/enrgblanket/.

[48] PCM Products, *Encapsulated pcms*, Accessed March 2021. [Online]. Available: https://www.pcmproducts.net/Encapsulated_PCMs.htm.

[49] V. V. Tyagi and D. Buddhi, "Pcm thermal storage in buildings: A state of art," *Renewable and sustainable energy reviews*, vol. 11, no. 6, pp. 1146–1166, 2007.

[50] S. E. Kalnæs and B. P. Jelle, "Phase change materials and products for building applications: A state-of-the-art review and future research opportunities," *Energy and Buildings*, vol. 94, pp. 150–176, 2015.

[51] M. Jaworski and S. Abeid, "Thermal conductivity of gypsum containig phase change material (pcm) for builiding applications," *Journal of Power Technologies*, vol. 91, no. 2, pp. 49–53, 2011.

[52] R. Collier and D. Grimmer, "Experimental evaluation of phase change material building walls using small passive test boxes," Los Alamos Scientific Lab., NM (USA), Tech. Rep., 1979.

[53] T.-C. Ling and C.-S. Poon, "Use of phase change materials for thermal energy storage in concrete: An overview," *Construction and Building Materials*, vol. 46, pp. 55–62, 2013.

[54] M. Telkes, "Thermal storage for solar heating and cooling," in *Proceedings of the Workshop on Solar Energy Storage Subsystems for the Heating and Cooling of Buildings, Charlottesville (Virginia, USA)*, 1975.

[55] G. Askew, "Solar heating utilization a paraffin's phase change material," in *Proceedings of the second national passive solar conference, Philadelphia, PA*, 1978.

[56] F. Goia, M. Perino, and V. Serra, "Improving thermal comfort conditions by means of pcm glazing systems," *Energy and Buildings*, vol. 60, pp. 442–452, 2013.

[57] E. M. Alawadhi, "Using phase change materials in window shutter to reduce the solar heat gain," *Energy and Buildings*, vol. 47, pp. 421–429, 2012.

[58] X. Jin and X. Zhang, "Thermal analysis of a double layer phase change material floor," *Applied Thermal Engineering*, vol. 31, no. 10, pp. 1576–1581, 2011.

[59] Elektronik Kamu Alımları Platformu, Accessed August 2020. [Online]. Available: https://ekap.kik.gov.tr/EKAP/.

[60] Turkish Standard, *Ts 825 thermal insulation requirements for buildings*, 2013.

[61] Pilkington, *Architectural glass product guide*, Accessed April 2021. [Online]. Available: https://assetmanager-ws.pilkington.com/fileserver.aspx?cmd=get_file&ref=bpna01&cd=cd.

[62] Isicam, *Isicam sistemleri*, Accessed November 2020. [Online]. Available: http://www.isicam.com.tr/tr/.

[63] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the köppen-geiger climate classification updated," *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.

[64] Turkish State Meteorological Service, *Istanbul weather averages*, Accessed December 2020. [Online]. Available: https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=undefined&m=ISTANBUL.

[65] Turkish State Meteorological Service, *Diyarbakir weather averages*, Accessed December 2020. [Online]. Available: https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=undefined&m=DIYARBAKIR.

[66] J. Ingersoll and J. Huang, "Heating energy use management in residential buildings by temperature control," *Energy and buildings*, vol. 8, no. 1, pp. 27–35, 1985.

[67] C. S. Turner and K. Gruber, "Residential thermostat management practices: An investigation of setback behavior," *Proceedings of the ACEEE: Summer Study on Energy Efficiency in Buildings, Human Dimensions*, vol. 2, pp. 2–151, 1990.

[68] M. Mozer, R. Dodier, D. Miller, M. Anderson, J. Anderson, D. Bertini, M. Bronder, M. Colagrosso, R. Cruickshank, B. Daugherty, *et al.*, "The adaptive house," in *IEE Seminar Digests*, IET, vol. 11059, 2005, pp. v1–39.

[69] F. Tariku, M. Kumaran, P. Fazio, *et al.*, "Thermostat setback effect in whole building performance," in *Proceedings of Building Physics Symposium, Leuven, Belgium*, 2008, pp. 1–5.

[70] J. W. Moon and S.-H. Han, "Thermostat strategies impact on energy consumption in residential buildings," *Energy and Buildings*, vol. 43, no. 2-3, pp. 338–346, 2011.

[71] D. S. Parker, "Determining appropriate heating and cooling thermostat set points for building energy simulations for residential buildingsin north america," 2013.

[72] V. Martinaitis, E. K. Zavadskas, V. Motuzienė, and T. Vilutienė, "Importance of occupancy information when simulating energy demand of energy efficient house: A case study," *Energy and Buildings*, vol. 101, pp. 64–75, 2015.

[73] J. Date, A. K. Athienitis, and M. Fournier, "A study of temperature set point strategies for peak power reduction in residential buildings," *Energy Procedia*, vol. 78, pp. 2130–2135, 2015.

[74] S. Jacquet, C. Le Bel, and D. Monfet, "In situ evaluation of thermostat setback scenarios for all-electric single-family houses in cold climate," *Energy and Buildings*, vol. 154, pp. 538–544, 2017.

[75] EnergyPlus, *Weather data by location - energyplus*, Accessed June 2021. [Online]. Available: https://energyplus.net/weather-location/europe_wmo_region_6/TUR//TUR_Istanbul.170600_IWEC.

[76] S. Pusat, İ. Ekmekçi, and M. T. Akkoyunlu, "Generation of typical meteorological year for different climates of turkey," *Renewable Energy*, vol. 75, pp. 144–151, 2015.

[77] E. Akgöz, *Enerji etkin bina tasarım parametreleri için uygun değerlerin belirlenmesi: Istanbul örneği*, 2004.

[78] E. Berköz, M. Küçükdoğu, *et al.*, "Enerji etkin konut ve yerleşme tasarımı (energy efficient housing and settlement design)," *TÜBİTAK, INTAG*, vol. 201,

[79] G. Zorer Gedik, "An approach to designing an optimal shading device," *Architectural Science Review*, vol. 45, no. 4, pp. 285–293, 2002.

[80] Gaisma, *Gaisma, istanbul sun path diagram*, Accessed November 2020. [Online]. Available: https://www.gaisma.com/en/location/istanbul.html.

[81] Gaisma, *Gaisma, diyarbakir sun path diagram*, Accessed November 2020. [Online]. Available: https://www.gaisma.com/en/location/diyarbakir.html.

[82] Phase change solutions, *Biopcm q27 data sheet*, Accessed April 2021. [Online]. Available: https://phasechange.com/wp-content/uploads/2020/08/BioPCM-Data-Sheet-Q27.pdf.

[83] DesignBuilder, *Designbuilder software ltd - previous versions*, Accessed June 2021. [Online]. Available: https://designbuilder.co.uk/download/previous-versions.

PUBLICATIONS FROM THE THESIS

Conference Papers

1. H. T. Cengiz, G. Zorer Gedik and E. Korkmaz, "FDM Uygulamasının İstanbul'daki İyileştirme Projelerinde Enerji Verimliliği Açısından Değerlendirilmesi", in *II. Mimarlık ve Şehircilik Lisansüstü Sempozyumu, Istanbul*, 16-20 November, 2020.