Research Article

The Impact of Insulation Material Selection on Energy Efficiency Based on Regional Climate Conditions: An Analysis Using Energy3D Simulations

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Abstract

In recent years, energy conservation and efficiency have gained significant importance globally. Within this scope, increasing the use of renewable energy sources and reducing the energy consumption of buildings, which account for a substantial share of energy use, are among the primary objectives. Insulation applications, in particular, offer a cost-effective and environmentally friendly solution to reduce heating energy demand. Optimal insulation thickness balances insulation and fuel costs, optimizing expenses while reducing the environmental impacts associated with fuel consumption. Consequently, numerous studies in recent years have focused on optimizing insulation thickness. Moreover, in the residential sector, the largest portion of energy consumption is generally attributed to air conditioning systems used for maintaining thermal comfort. In this context, proper insulation applications using energy-saving materials emerge as an effective method to reduce energy costs by minimizing heat loss or gain. This study analyzes the impact of insulation material selection on energy efficiency based on regional climate conditions using Energy3D simulations. The effects of insulation materials applied in different climatic zones and various cities on energy consumption, heating, and cooling loads were examined. The study compares the energy efficiency of insulated and non-insulated buildings under the climatic conditions of different regions in Turkey, including İzmir, Antalya, Istanbul, and Tokat. Simulation results revealed that the use of insulation materials significantly reduces energy consumption and overall costs. Notably, the use of Expanded Polystyrene (EPS) (Dalmaçyalı® Double Carbon Thermal Insulation Board) and Stone Wool (Dalmaçyalı® Stonewool SW035) materials yielded significant improvements in energy efficiency. EPS *material demonstrated the highest energy savings due to its low U-value, while Stone Wool provided additional benefits such as fire safety. Additionally, insulation thickness was found to have a considerable impact on energy efficiency. Insulation applications with a thickness of 10–12 cm emerged as the optimal solution for minimizing energy consumption and costs. The study highlights the critical importance of selecting insulation materials suitable for regional climatic conditions in terms of energy efficiency and cost-effectiveness. The findings provide valuable insights for developing sustainable and efficient building designs.*

Keywords: *Energy saving, Energy conservation, Insulation, U-Value, EPS, Stone wool*

1. Introduction

In last decade, global energy demand has been continuously increasing due to population growth and economic expansion [1]. In the 21st century, we face significant challenges such as climate change, the rise in greenhouse gas emissions, and the growth of global energy demand [2]. According to estimates by the International Energy Agency (IEA), global energy consumption is expected to increase by 53% within the next decade. This surge is a result of intensive industrial and urban activities, as well as the dramatic rise in population growth and the rapid development of countries in recent years [3]. This increase in energy demand is expected to become more critical, especially in developing countries, where the number of new buildings is rapidly growing, and energy efficiency technologies are not sufficiently utilized [4].

As a consequence of this rising energy demand, environmental issues are becoming increasingly apparent. For instance, carbon dioxide (CO_2) is known to be harmful to human health and significantly contributes to the greenhouse effect [5]. This leads to an increase in average global temperatures [6]. If necessary measures to reduce CO2 and other greenhouse gas emissions are not taken, the Earth's surface temperature is projected to rise by approximately 1.1 to 6.4 °C by 2100 [7]. 2 °C increase in global temperature would have irreversible effects on the environment, seriously impact human health, cause substantial damage to natural ecosystems, and endanger the sustainability of global agriculture [8].

The building sector (residential, industrial, and commercial buildings), as a major energy-consuming sector aimed at ensuring thermal comfort, can make a significant contribution to reducing energy consumption through effective insulation strategies. Effective insulation reduces the need for energy to provide cooling in summer and heating in winter by conserving energy [9]. Implementing this energy efficiency technique decreases the use of natural resources (oil and gas reserves) for energy production, slows their depletion rates, and consequently reduces greenhouse gas emissions [8,10].

Research shows that heating, ventilation, and air conditioning (HVAC) systems account for more than 35% of total building energy use [11]. Therefore, there are opportunities to improve the performance of building components and equipment. Studies indicate that approximately 50-60% of the heating load in residential and commercial buildings results from heat transfer through walls, foundations, and roofs [12]. About 28% of energy loss in buildings is caused by leaks. Windows and walls are responsible for more than 45% of heat transfer in residential buildings during cold seasons. During warm seasons, this rate is 23% for leaks and 58% for windows and walls.

Insulation in buildings is a simple yet highly energy-efficient technique applicable in residential, commercial, and industrial sectors. Thermal insulation material consists of a material or composite with high thermal resistance and exhibits the ability to reduce the rate of heat flow [13]. Consequently, building insulation prevents heat flow with the environment, retaining heat or coolness within the home [14]. Commonly used materials for insulation include glass wool, stone wool, PU foam, and other natural resource-based materials.

Another significant advantage of building insulation is cost savings. This is made possible because the energy savings achieved by applying insulation exceed the energy required to produce the insulation material, resulting in a positive net energy balance [15]. Additionally, the use of thermal insulation provides other benefits, such as fire protection, personal comfort, condensation control, and soundproofing. The amount of energy consumed for heating constitutes a significant portion of total energy consumption [16]. Insulation applications in buildings play a crucial role in reducing energy used for heating and recovering this energy. As a result, both energy efficiency is improved, and heating costs are significantly reduced.

Thermal insulation applied at an optimal thickness significantly enhances energy efficiency in both economic and environmental terms. Therefore, the thermal insulation process should not be limited solely to the type of insulation material used but should also integrate various criteria such as economic data, fuel type, and wall structure [17]. In buildings where insulation is inadequate or insufficient, higher energy consumption is required for heating, leading to an increase in fuel emissions as a result. Furthermore, excessively increasing insulation thickness can negatively impact efficiency by merely increasing insulation costs rather than improving energy consumption.

In this context, determining the optimal insulation thickness based on the building's climatic conditions enables effective management of insulation costs, provides economic benefits in terms of energy and fuel consumption, and reduces the emissions and environmental impacts caused by fuel usage [18]. Turkey is divided into four main regions with varying climatic conditions, and energy efficiency calculations for heating and cooling needs are conducted using the concept of "degree days." Degree days measure the extent to which the outdoor temperature of a location deviates from a reference temperature (typically 18°C) over the course of a year, indicating the heating or cooling requirements. This value is used to identify heating and cooling needs and is crucial for achieving energy efficiency targets in buildings [19].

The selection of insulation material, its application process, and determining the insulation thickness are of great importance for energy efficiency. With appropriate insulation thicknesses, energy consumption can be limited, and the targeted savings can be easily achieved. As the thickness of the insulation material increases, heat loss decreases, and energy efficiency improves. However, increased thickness also leads to higher costs, making it undesirable to use excessively thick material. In this context, achieving the optimal insulation thickness is essential [20].

Various methods can be used to calculate optimal thickness, such as the degree-day method and life-cycle cost analysis. In Turkey, the thermal insulation regulations for buildings are divided into four zones based on degree-day numbers in the TS 825 standard. The first zone includes provinces requiring the least energy for heating, while the fourth zone encompasses provinces with the highest energy needs. These data show that the climatic conditions and heating energy requirements of the region where insulation will be applied are critical factors in determining insulation thickness. Thermal insulation applications should be carried out meticulously and with awareness. Low-cost and insufficiently thick insulation materials should be avoided, and the correct materials and application methods should be preferred. The type of insulation material, proper application techniques, and determination of optimal thickness are critical for both energy efficiency and achieving cost savings [21].

Thermal insulation plays a significant role in enhancing energy savings and reducing environmental impacts. Since a large portion of energy consumption in buildings is dedicated to meeting heating and cooling demands, selecting the right insulation materials, determining appropriate thicknesses, and implementing cost-effective applications are critical elements for improving energy efficiency. Various studies in the literature have focused on different climatic regions, insulation materials, and fuel types. These studies provide detailed insights into the effects of insulation applications on energy consumption, savings potential, and environmental impacts, contributing to the determination of optimal solutions. The importance of measures taken during the design phase in reducing a building's energy demand was highlighted in a study by Maduta et al. The thermal performance of the building envelope emerges as a fundamental factor in determining heating and cooling requirements. Key factors influencing thermal performance include building shape, insulation applications, prevention of thermal bridging, and airtightness [22].

A study by Eddib and Lamrani examined the thermal and energy performance of various insulation materials to identify the most suitable insulation material and ideal thickness for Marrakech’s climatic conditions. This study offers a distinct approach by focusing on both building shape and insulation thickness [23].

An investigation into the energy consumption of an energy-independent house, with and without the application of external insulation, was conducted by Paraschiva et al. While this study analyzes the impact of thermal insulation on energy consumption and environmental effects within a specific building design, it does not address the effects of different building designs or orientations on energy efficiency [24].

The effects of insulation thickness on energy consumption in residential buildings of various shapes were examined by Bostancıoğlu. The study demonstrated that increasing insulation thickness generally reduces annual energy costs per square meter, whereas uninsulated buildings face significantly higher energy costs. However, the rate of cost reduction depends on factors such as building shape, insulation thickness, and orientation [25].

Critical parameters for energy-efficient building design in cold climates were analyzed by Feng et al. The study used DEST energy simulation software to evaluate insulation thickness, window heat transfer coefficients, and window-to-wall ratios, revealing that optimizing these parameters can lead to substantial reductions in energy consumption [26].

The effects of different wall construction materials on heat loss were studied by Akgül et al. using an insulated experimental system. The study found that sandwich walls exhibited the lowest heat loss, while firebrick walls had the highest [27].

Yeşildağ and Geliş in Gümüşhane analyzed the total heat transfer coefficient for three insulation materials (XPS, EPS, and rock wool) and four thicknesses (4, 5, 6, and 8 cm). The findings indicated that 8 cm thick XPS provided the best performance [28].

Atmaca and Koçak carried out research comparing completely uninsulated buildings with those applying XPS insulation of various thicknesses. Their study determined that while the thickest XPS insulation increased costs, it reduced heating system requirements by 60% [29].

Özutku and Karakuş demonstrated through simulations that applying 5 cm XPS insulation could reduce a building's annual heating needs by 47% and lower carbon dioxide emissions by 46.7% [30]. An evaluation of the TS 825 standard by Bayer et al. argued that the current division of four degree-day regions is insufficient and should be increased to six. The study emphasized that cooling needs in the first region exceed heating needs, suggesting that insulation calculations should prioritize cooling requirements [21]. Pehlivan (2001) conducted a study identifying that evaporation and condensation durations under TS 825 standards vary across different climatic conditions. The research emphasized the need for regional data to evaluate these durations accurately [31]. Şişman analyzed the economic viability of achieving zero heat loss through insulation. The study demonstrated that optimal insulation thickness is determined by balancing insulation costs with energy savings. A linear relationship was observed between insulation cost and thickness, whereas the relationship between insulation thickness and energy savings was nonlinear [32].

Koçu and Korkmaz investigated the structural damage caused by temperature fluctuations in uninsulated buildings around Konya. Their findings highlighted that such damage shortens building lifespan and leads to high maintenance costs [33].

By the way, Aksoy and Ekici evaluated the suitability of the TS 825 Annex-C table for different climatic regions. The research indicated that the recommended values could result in significant calculation deviations throughout the year [34]. Additionality Bektas et al. explored the impact of insulation thickness on energy efficiency. They noted that increasing thickness reduces heat loss but raises costs, underscoring the necessity of determining optimal insulation thickness [35].

In another study, Özel demonstrated the thermal performance of different wall materials in the 4th climate region, such as Kars. The study showed that with 6 cm thick EPS insulation, reductions in heat flow for stone, brick, concrete, and aerated concrete walls were 83.61%, 80%, 84.8%, and 56%, respectively, with aerated concrete exhibiting the lowest heat loss [36].

Özel and Şengür conducted a study determining the optimum insulation thicknesses with different fuel types and thermal insulation materials in the provinces of Antalya and Kars. The study found that the lowest thicknesses for the combination of rock wool and natural gas were 3.2 cm for Antalya and 6.8 cm for Kars. For the combination of isopor plus and fuel oil, the highest thicknesses were 10.8 cm and 20 cm, respectively, for the two cities [37]. A study comparing insulation materials produced from sunflower stalks and textile waste with XPS was conducted by Binici and colleagues. The study indicated that this panel performed better in terms of heat loss and heating speed compared to XPS but recommended its use only in internal filling walls due to its water absorption properties [38].The properties of insulation material produced from corn cobs and epoxy binder was carried out by Binici and colleagues. The study demonstrated that the material's unit volume weight, water absorption, sound permeability, and thermal conductivity coefficient were within acceptable limits [39]. Gurel and colleagues conducted a study investigating the effects of exterior wall insulation on energy consumption and fossil fuel-related air pollution. The study revealed that the optimum insulation thicknesses ranged from 0.02 m to 0.17 m, energy savings varied between 22% and 79%, and payback periods ranged from 1.3 to 4.5 years [40]. A research comparing insulated and non-insulated buildings was conducted by Çomaklı and colleagues. The study found that insulated buildings exhibited 27% less greenhouse gas emissions and that indoor temperature fluctuations could lead to health issues. It also emphasized that moisture and water corroding the reinforcement bars in reinforced concrete structures could threaten structural safety [41].

Bayraktar and Bayraktar conducted the thermal insulation applications in existing buildings. The study emphasized that a low thermal conductivity coefficient of insulation materials provides higher resistance against heat transfer [42]. Bostancıoğlu carried out impact of wall and roof insulation on building performance in different climate zones. The study found that external insulation was effective in preventing temperature-induced cracking and stress, and provided higher performance compared to other systems [43]. Savaşır and Tuğrul conducted a study comparing EPS-slabbed reinforced concrete structures with autoclaved aerated concrete (AAC) buildings. The study found that EPS panels were more expensive and less commonly used [44].

Hozatlı and Günerhan carried out a research analyzing the life cycle of reinforced concrete and timber frame buildings. The study showed that rock wool could be used in the temperature range of -50°C to +100°C, was suitable for areas with high fire risk, and was effective in sound insulation [45,46]. To addressing the advantages of EPS insulation material in cold storage facilities was conducted by Berber. The study mentioned that EPS is widely used in terraces, pitched roofs, ceiling insulation, and underfloor heating systems [47]. A research by Friess and colleagues analyzed the impact of considering thermal bridges during wall insulation on energy savings through simulations. The study found that thermal bridges were an important factor in insulation decisions and could result in up to 30% energy savings [48]. Passive cooling strategies to reduce energy consumption in residential buildings in the United Arab Emirates was conducted by Taleb. The study indicated that the implementation of these strategies could lead to a reduction in annual energy consumption by up to 23.6% [49]. The study showed that regulations could reduce energy consumption by 31% in villas and 38% in apartments [51].

A study analyzing the thermal modeling of the MUN CSF building was carried out by Liyanage. The study pointed out that due to unaccounted transmission losses, building connections, occupancy, ventilation, and equipment malfunctions, the predictions were lower than actual energy consumption and suggested that transitioning to a heating system could provide energy, financial savings, and reduce greenhouse gas emissions [52]. Simulations were conducted for provinces selected from four different climate zones of Turkey. The first region included İzmir and Antalya, the second region included İstanbul and Tokat, the third region included Ankara and Konya, and the fourth region included Erzurum and Kayseri. For these provinces, the energy consumption and costs of Dalmaçyalı® brand EPS and stonewool insulation materials from Betek Boya ve Kimya Sanayi A.Ş., with different thickness options (3, 5, 7, 10, 12, and 15 cm), were analyzed using the ENERGY 3D simulation software.

As a result of the study, the goal is to achieve energy efficiency specific to each climate zone, reducing direct costs and minimizing environmental impacts. Furthermore, by determining the appropriate insulation material and thickness for each region, optimal energy savings will be achieved, and the most efficient cost structure will be identified. This simulation will not only provide energy savings but also environmental benefits, as lower energy consumption will reduce carbon emissions from fossil fuel sources. Finally, insulation solutions tailored to local conditions will be developed, and industry-specific applications for Betek Boya's products can be implemented.

2. Materials and Methods

In this study, various parameters were analyzed using the Energy3D simulation program to evaluate the energy efficiency of buildings. Simulations were conducted under different scenarios for each climate zone, insulation material, and thickness. Below, the key parameters and scenarios used in the simulations are explained in detail.

Energy3D is a simple, versatile, and user-friendly energy modeling software designed to simulate and analyze the energy performance of buildings and renewable energy systems. It stands out with its ability to create detailed 3D building and landscape models, enabling users to explore and visualize the effects of various design elements on energy efficiency. The software supports a wide range of applications, from assessing renewable energy technologies such as wind turbines and solar panels to modeling the thermal behavior of structures [51].

Thanks to its user-friendly interface, both students and professionals can easily use Energy3D. These features make it a valuable tool for educators, architects, and researchers interested in optimizing energy solutions. The software provides effective support for studies aimed at improving energy efficiency in the built environment.

According to the TS 825 Standard, Turkey is divided into four degree-day regions. The standard aims to determine the annual heating energy requirement by considering the outdoor and indoor temperature values for buildings. In the applied methodology, the annual heating energy requirement is calculated based on monthly average temperatures and the balance between heat losses and heat gains [52].

This study was conducted to examine the effects of insulation material and thickness choices on energy efficiency in cities located within Turkey's four different degree-day regions.

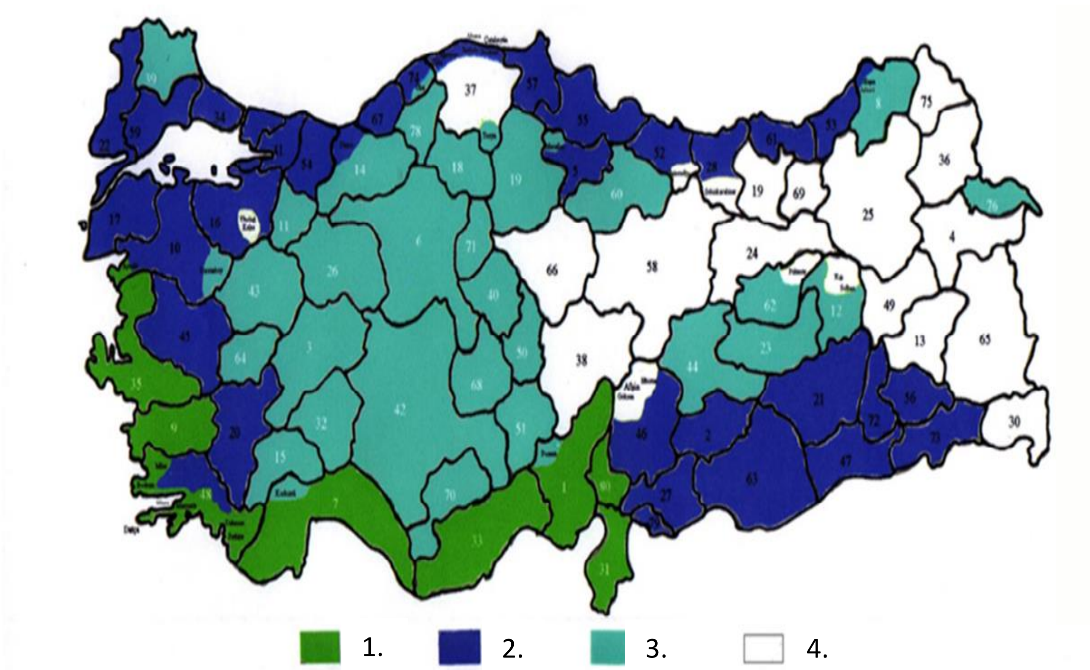


Figure 1: Our provinces according to degree-day regions

The selected cities represent Turkey's climate diversity and are as follows:

1. Zone (Hot-Humid Climate): Izmir and Antalya
2. Zone (Mild-Humid Climate): Istanbul and Tokat
3. Zone (Cold-Dry Climate): Konya and Ankara
4. Zone (Very Cold Climate): Erzurum and Kayseri

The selection of these cities allowed for a comprehensive evaluation of the impact of insulation materials and thicknesses on energy performance under different climate conditions. The climatic characteristics of the cities were determined based on the Turkish Climate Map and data from the General Directorate of Meteorology.

2.1. Insulation Materials and Their Properties

In this study, two different insulation materials from the DALMAÇYALI® and FAWORİ® brands, produced by BETEK BOYA ve KIMYA SANAYI A.Ş., were evaluated.

The insulation product line of Betek Boya ve Kimya Sanayi A.Ş. offers a wide range of high-performance thermal and acoustic insulation solutions. The product portfolio includes 035 White EPS, carbon EPS, and Optimix EPS thermal insulation boards under the Fawori® brand. It also features products tailored to different needs, such as T125, TR7.5, and T150 Stone Wool Roof Boards, as well as T50 Stone Wool Partition Boards.

Additionally, the portfolio contains technologically advanced products like Dalmaçyalı® Thermal Insulation Boards with unique patterns, Stonewool SW035 Stone Wool, CS60 Stone Wool Roof Boards, and the Barrier Fire Barrier. Innovative products like Ideal Carbon and Double Carbon have been developed to maximize efficiency in thermal insulation. This product line provides high-quality solutions aligned with energy savings and sustainability goals.

2.1.1. Expanded Polystyrene (EPS):

The Dalmaçyalı® Double Carbon Thermal Insulation Board, developed by Betek Boya, is a polystyrene-based insulation board featuring advanced carbon technology. The product offers 10% higher thermal insulation performance (λD: 0.032 W/mK), enhancing energy efficiency. Its high water vapor permeability prevents moisture and mold formation while also mitigating cracks caused by wall movement. With its ideal size balance and water-resistant structure, it provides a long-lasting insulation solution.

Compliant with TS EN 13163, TS EN 13499, and ETA (ETAG 004) technical approvals, this board has the following technical specifications [53]:

Thermal Conductivity Coefficient (λD): 0.032 W/mK
Thermal Resistance (R): Ranges from 0.60 $m^2 \cdot K/W$ to 4.80 $m^2 \cdot K/W$
Tensile Strength Perpendicular to Surfaces: ≥100 kPa
Compressive Stress at 10% Deformation: ≥50 kPa
Thickness Tolerance: ±1 mm
Water Vapor Diffusion Resistance: 20–40 μ
Reaction to Fire Class (With System): B-s1,d0
Application Temperature Range: −50°C to +75°C

Produced in 50x100 cm dimensions and available in thicknesses ranging from 2 cm to 15 cm, this product is suitable for various applications such as flat and sloped roofs, external wall insulation, sandwich walls, and floor insulation.

2.1.2. Stone Wool (Mineral Wool):

The Dalmaçyalı® Stonewool SW035 Thermal Insulation Board, developed by Betek Boya, is an inorganic thermal insulation material produced by transforming volcanic rocks into fibrous strands. This product provides high thermal insulation (λD: 0.035 W/mK), along with fire and sound insulation, offering a wide range of applications. Its ideal size allows

for quick and easy installation, while its high water repellency and above-standard mechanical strength ensure a durable insulation solution.
The stone wool board features a smooth surface that does not generate dust and is manufactured in compliance with TS EN 13162, TS EN 13500, and ETA (ETAG 004) technical standards.

Highlighted technical properties of the board are as follows [53]:

Thermal Conductivity Coefficient (λD): 0.035 W/mK
Thermal Resistance (R): Ranges from 0.85 m²·K/W to 4.25 m²·K/W
Tensile Strength Perpendicular to Surfaces: ≥10 kPa
Compressive Stress at 10% Deformation: ≥30 kPa
Water Vapor Diffusion Resistance: 1 μ
Reaction to Fire Class (With System): A1 (Non-combustible)
Application Temperature Range: −50°C to +750°C
Dimensions (Width x Length): 60 cm × 100 cm
Board Thickness: 3 cm ≤ thickness ≤ 15 cm
Both materials were analyzed in thicknesses of 3 cm, 5 cm, 7 cm, 10 cm, 12 cm, and 15 cm to evaluate their energy performance.

2.2. Heat Transfer Coefficient (U-Value) Calculation

The heat loss through building walls and the annual energy requirement can be calculated using the heat loss per unit area of the exterior wall, *Q (W/m^2)* given by Equation (1):

$$Q=U.\ \Delta t \tag{1}$$

The total heat transfer coefficient U (W/m2K) is calculated using Equation (2):

$$U= \frac{1}{Riç\ sıva + Rduvar + Ryalıtım + Rdış\ sıva} \tag{2}$$

Here, R (m2K/W) represents the thermal resistance of each layer.
The annual heat loss per unit area, Q_{annual} *(W/m^2)*, can be calculated using the U-value and the degree-day count (DGS) with Equation (3):

$$Q_{annual}= (86400.\ DGS.\ U) \tag{3}$$

Finally, the annual energy requirement for heating, E_{annual} (W/m^2), is determined by dividing the annual heat loss by the system efficiency (η) using Equation (4):

$$E_{annual} = (86400.DGS.\ U)/\eta \quad (4)$$

2.3. Simulation Program (Energy3D)

In this study, the Energy3D simulation program was used to analyze the impact of insulation materials on energy efficiency. Energy3D is an easy-to-use energy modeling software designed to visualize the energy performance and heat losses of buildings. Through this software, the effects of different insulation materials and thicknesses on the energy consumption of buildings were analyzed in detail.

2.3.1. Simulation Inputs and Parameters

The following parameters were used for modeling each city and material:

1. Climate Data:

Annual temperature, solar radiation, and other meteorological data for Turkey's four climate zones were integrated into Energy3D.

- Climate zones and selected cities:
  Zone 1: İzmir, Antalya
  Zone 2: İstanbul, Tokat
  Zone 3: Konya, Ankara
  Zone 4: Erzurum, Kayseri

2. Building Characteristics:

A standard residential model was created.

- Wall structure, window surface area, and roof pitch were kept constant for all cities.
- The thermal resistance of the existing building structure (R_{wall}) was taken as a fixed value in the simulations.

3. Insulation Materials and Thicknesses:

- EPS (Dalmaçyalı® Double Carbon) and Stonewool (Stonewool SW035) materials were evaluated.
- Six different thicknesses (3 cm, 5 cm, 7 cm, 10 cm, 12 cm, 15 cm) were applied for each material.

4. Objectives:
- Calculating annual heating and cooling energy consumption.
- Comparing different insulation scenarios based on reductions in energy consumption.

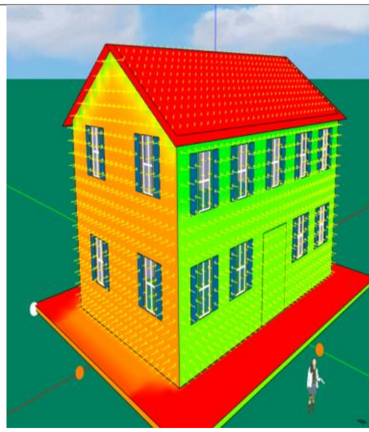
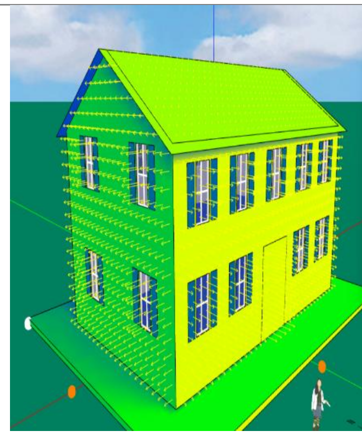
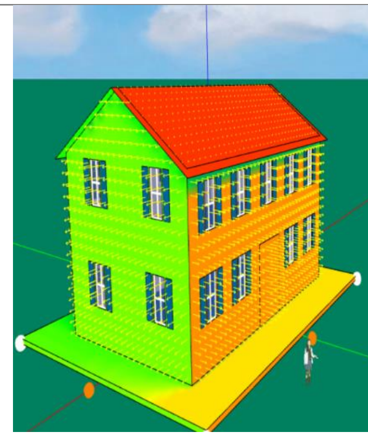
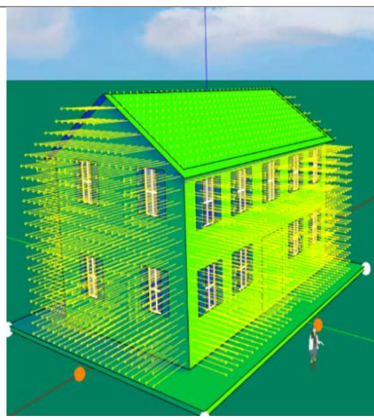
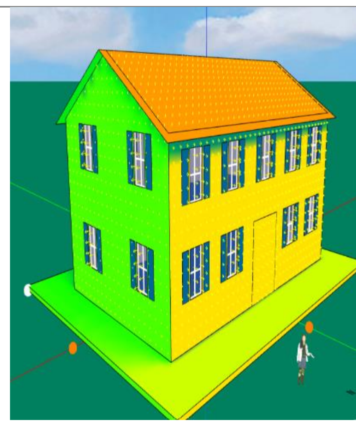
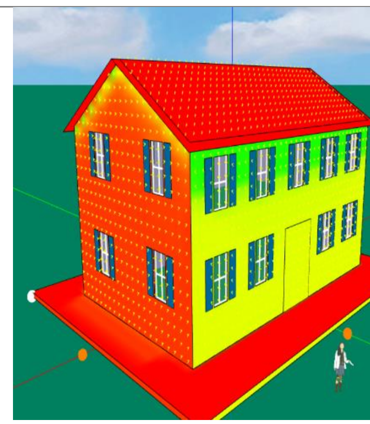
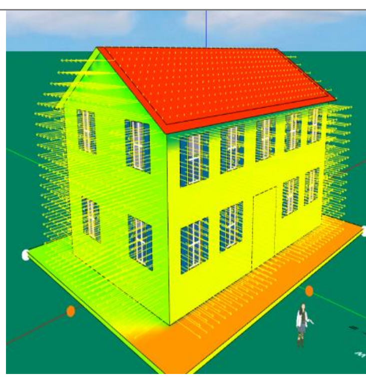
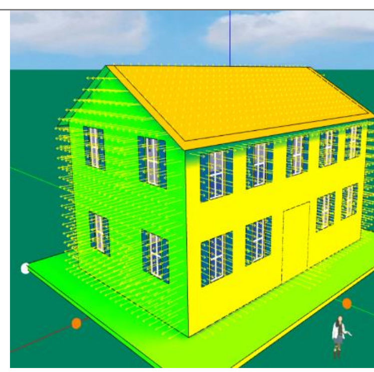
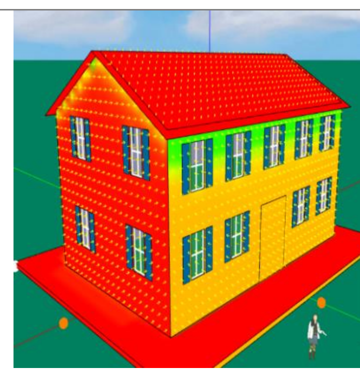
3.2.2. Simulation Scenarios

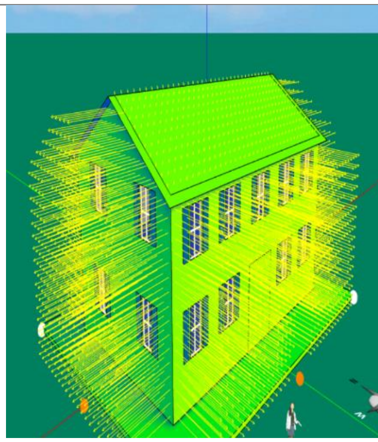
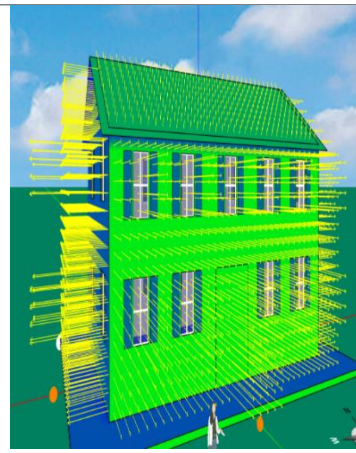
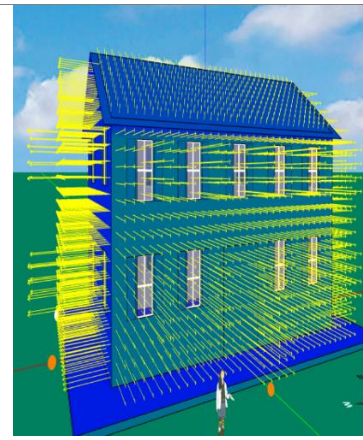
Three different scenarios were analyzed for each city:

1. Uninsulated Case (Control Group):
    - The uninsulated state of the existing building was analyzed to obtain reference values.
2. Insulation with EPS:
    - EPS panels were applied in varying thicknesses, ranging from 3 cm to 15 cm.
    - Energy losses and gains were calculated for each thickness.
3. Insulation with Stonewool:
    - Stonewool panels were applied in varying thicknesses, ranging from 3 cm to 15 cm.
    - Similarly, the energy performance was evaluated for each thickness.

In Table 1, the impacts of insulation materials on energy performance across Turkey's four different climate zones are visualized. Each row represents a climate zone: Zone 1 corresponds to a warm climate (İzmir, Antalya), Zone 2 to a mild climate (İstanbul, Tokat), Zone 3 to a continental climate (Konya, Ankara), and Zone 4 to a cold climate (Erzurum, Kayseri). The columns include three different insulation scenarios: uninsulated, insulated with EPS, and insulated with Stonewool. Table 1 demonstrates that the selection of insulation material and thickness should be optimized according to the climate zone and that both insulation materials effectively enhance energy efficiency.

Table 1: Energy Performance of Insulation Materials Across Different Climate Zones in Turkey

	Uninsulated	EPS	STONEWOOL
1. ZONE			
2. ZONE			
3. ZONE			

4. ZONE			

3.2.3. Simulation Outputs

The Energy3D software produced the following outputs:

1. Energy Consumption:
    - Annual energy consumption (for heating and cooling) for each scenario.
    - Energy savings compared to the uninsulated case.
2. Heat Flow Visualization:
    - Graphical representations of heat losses and gains for both insulated and uninsulated cases of the building.
3. Economic Data:
    - A comparison of energy savings and insulation costs for each material and thickness.
4. Optimal Insulation Thickness:
    - The most suitable insulation thickness for each city, maximizing energy savings while minimizing costs, was determined.

With these detailed parameters, the Energy3D simulations provided a powerful tool for understanding the impact of insulation on energy efficiency under Turkey's diverse climatic conditions and for developing optimal solutions.

3.2.4. Data Analysis

The simulation results were analyzed in detail to compare the effects of insulation materials and thicknesses on energy efficiency. The analysis included the following elements:

- Energy Consumption: The impact of insulation thickness on annual energy consumption was examined.
- Energy Savings: Different materials and thicknesses were compared in terms of energy savings.
- Cost and Efficiency: The relationship between material costs and energy savings was evaluated.

The results were compared both graphically and numerically, and the most suitable insulation material and thickness were recommended for each climate zone.

4. Results

This study provides a comprehensive analysis of the effects of insulation applications on energy consumption, heating and cooling demands, and total costs across different climate zones and cities. The findings highlight the significant energy consumption and economic burden associated with uninsulated buildings, while examining in detail the energy savings and cost advantages achieved through the application of various insulation materials and thicknesses.

The results demonstrate that identifying the most suitable combination of insulation material and thickness based on the specific needs of climate zones and cities is crucial for both economic savings and environmental sustainability.

The analysis conducted using the Energy3D software presents the results for Zone 1 in Table 2.

Table 2: Energy Performance Results for Zone 1 Using Energy3D Software

Zone	City	Insulation Material	Insulation Thickness	U Value (W/ m² °C)	Net Energy Consumption (Kwh)	Heating (Kwh)	Cooling (Kwh)	Building Total Cost ($)	Energy Consumption Reduction (%)
1. ZONE	**İzmir**	**Uninsulated**		3.0	53650	31998,5	21651,5	200997,97	-
		EPS	0,03	1.07	24848	12478,8	12369,2	202399,76	53.7%
			0,05	0.64	18632	8329,4	10302,5	203863,74	65.3%
			0,07	0.46	16147	6692,4	9454,3	205289,23	69.9%
			0,10	0.32	14253	5466,4	8786,9	207506,66	73.5%
			0,12	0.27	13583	5037,5	8545,6	208855,89	74.7%
			0,15	0.21	12782	4525,8	8256,1	211323,05	76.2%
		Stone Wool	0,03	1.167	26275	13437,2	12837,9	202218,65	51.0%
			0,05	0.7	19494	8901,2	10592,4	203551,49	63.7%
			0,07	0.5	16696	7048,8	9647,4	204883,75	68.9%
			0,10	0.35	14650	5726,7	8923,2	206882,16	72.7%
			0,12	0.292	13878	5226	8651,8	208205,3	74.2%
			0,15	0.233	13089	4721,5	8367,1	21027,12	75.7%
	Antalya	**Uninsulated**		3.0	51873	28082,2	23790,6	200997,97	-
		EPS	0,03	1.07	24178	11161,6	13016,1	202239,76	53.3%
			0,05	0.64	18266	7626,1	10639,9	203863,74	64.8%
			0,07	0.46	15907	6184,5	9722,5	205289,23	69.3%
			0,10	0.32	14147	5079,8	9067,2	207506,66	72.7%
			0,12	0.27	13505	4688	8717,1	208855,89	74.0%
			0,15	0.21	12746	4221,6	8524,2	211323,05	75.4%
		Stone Wool	0,03	1.167	25533	11975,8	13557,5	202218,65	50.9%
			0,05	0.7	19044	8112,6	1095,1	203551,75	63.3%
			0,07	0.5	16410	6502,7	9907,4	204883,75	68.4%
			0,10	0.35	14503	5315,2	9187,7	206882,16	72.1%
			0,12	0.292	13799	4860,4	8939	208205,3	73.4%
			0,15	0.233	13051	4399,3	8651,5	21027,12	74.7%

Table 2 presents a detailed analysis of energy efficiency for İzmir and Antalya, which represent Turkey's 1st Climate Zone. The table compares the effects of uninsulated conditions with the application of insulation materials, including EPS (Dalmaçyalı® Double Carbon Thermal Insulation Board) and Stone Wool (Dalmaçyalı® Stonewool SW035), applied at various thicknesses ranging from 3 cm to 15 cm. The impact on energy consumption, costs, and thermal performance has been evaluated. Energy efficiency assessment was conducted based on parameters such as net energy consumption (kWh), U-value (W/m²°C), heating-cooling loads (kWh), and total building cost (USD).

According to the data presented in the table, considering the impact of insulation materials on energy efficiency in İzmir and Antalya, it is evident that insulation applications significantly reduce energy consumption. Compared to the uninsulated scenario, energy consumption has noticeably decreased in both cities. In İzmir, 15 cm thick insulation using Dalmaçyalı® Double Carbon EPS Thermal Insulation Board reduced energy consumption by 76.2%, while the same material achieved a reduction of 75.4% in Antalya. Similarly, the use of Stone Wool also provided energy savings, though its efficiency was slightly lower than that of EPS. A 15 cm Stone Wool insulation reduced energy consumption by 75.7% in İzmir and 74.7% in Antalya. While Stone Wool offers energy efficiency results close to those of EPS, its superior fire resistance and high-temperature durability make it a more suitable option for specific applications.

The effect of increased thickness is also noteworthy. For both insulation materials, as the thickness increases, energy efficiency improves and energy costs decrease. However, beyond 12 cm, the contribution of additional thickness to energy savings diminishes, providing lower returns in terms of cost-effectiveness. This highlights the importance of marginal benefit analyses.

Studies conducted in İzmir and Antalya clearly demonstrate the impact of insulation materials on energy efficiency. Compared to non-insulated buildings, insulation applications have been shown to reduce energy consumption by 74-76% in both cities. EPS (Dalmaçyalı® Double Carbon Thermal Insulation Board) provides the highest energy savings due to its low U-value, while Stone Wool (Dalmaçyalı® Stonewool SW035) stands out with advantages such as fire safety and durability. According to the TS 825 standard, cities located in Zone 1 should have a U-value of less than 0.70 W/m²°C. Considering cost-effectiveness and energy savings, the optimal insulation thickness is determined to be between 7 and 10 cm.

The results obtained for the 2nd Climate Zone through analyses conducted using Energy 3D software are presented in Table 3.

Table 3. Energy Performance Results for Zone 2 Using Energy3D Software

Zone	City	Insulation Material	Insulation Thickness (m)	U Value (W/ m² °C)	Net Energy Consumption	Heating (Kwh)	Cooling (Kwh)	Building Total Cost ($)	Energy Consumption Reduction (%)
2. ZONE	İstanbul	Uninsulated		3.0	61893	52399,5	9493,9	200997,97	-
		EPS	0,03	1.07	26981	21001,8	5978,8	202399,76	56,4
			0,05	0.64	19333	14101,9	5230,9	203863,74	68,7
			0,07	0.46	16273	11270,9	5002,5	205289,23	73,7
			0,10	0.32	13896	9092,7	4803,1	207506,66	77,5
			0,12	0.27	13033	8320,3	4713,2	208855,89	78,9
			0,15	0.21	12044	7411,2	4632,5	211323,05	80,5
		Stone Wool	0,03	1.167	28721	22565,5	6155,5	202218,65	53,6
			0,05	0.7	20397	15057,4	5340,1	203551,49	67,0
			0,07	0.5	16971	11896,6	5074,8	204883,75	72,5
			0,10	0.35	14415	9557,8	4857,1	206882,16	76,7
			0,12	0.292	13412	8659,3	4752,8	208205,3	78,3
			0,15	0.233	12432	7758,1	4673,7	210227,12	80,0
	Tokat	Uninsulated		3.0	78605	68878,4	9726,6	200997,97	-
		EPS	0,03	1.07	33946	27884,8	6061,1	202399,76	56,8
			0,05	0.64	24141	18892,5	5248,3	203863,74	69,3
			0,07	0.46	20098	15170,4	4927,1	205289,23	74,4
			0,10	0.32	16955	12295,5	4659,3	207506,68	78,4
			0,12	0.27	15847	11283,4	4563,7	208855,89	79,9
			0,15	0.21	14574	10081,7	4492,5	211323,05	81,4
		Stone Wool	0,03	1.167	36179	29931,9	6247	202218,65	53,9
			0,05	0.7	25501	20138,2	5363,2	203551,49	67,5
			0,07	0.5	20999	15995,6	5003,6	204883,75	73,3
			0,10	0.35	17627	12910,1	4716,7	206882,16	77,6
			0,12	0.292	16332	11726,1	4605,8	208205,3	79,2
			0,15	0.233	15034	10541,4	4492,9	210227,12	80,8

Table 3 provides a detailed analysis of the impact of different insulation materials and thicknesses on energy efficiency in İstanbul and Tokat, representing Turkey's 2nd Climate Zone. The table compares the effects of uninsulated buildings with the application of Dalmaçyalı® Double Carbon EPS and Dalmaçyalı® Stonewool SW035 insulation materials in thicknesses ranging from 3 cm to 15 cm. The analysis focuses on parameters such as U-value (W/m²°C), net energy consumption (kWh), heating and cooling loads (kWh), and total building cost (USD).

In İstanbul, the annual U-value for an uninsulated building was calculated as 3.0 W/m²°C, with an energy consumption of 61,895 kWh. This energy consumption includes 52,399.5 kWh for heating and 9,493.9 kWh for cooling loads. Consequently, the total building cost was determined to be $200,997.97. Similarly, an uninsulated building in Tokat consumes 78,605 kWh of energy, with heating and cooling loads of 68,878.4 kWh and 9,726.6 kWh, respectively, and a total building cost of $200,997.97. The significant energy consumption associated with uninsulated scenarios is clearly evident.

Applications of insulation materials have significantly reduced energy consumption and costs. In İstanbul, a 15 cm insulation application using Dalmaçyalı® Double Carbon EPS reduced the U-value to 0.21 W/m²°C and energy consumption to 12,044 kWh, with the total cost decreasing to $211,323.05. Similarly, in Tokat, the same insulation material and thickness lowered energy consumption to 14,574 kWh and reduced the total cost to $211,323.05. The low U-value achieved by EPS material highlights its notable advantage in energy efficiency.

Applications using Dalmaçyalı® Stonewool SW035 also resulted in comparable energy savings, though the U-values were slightly higher compared to EPS. In İstanbul, a 15 cm Stonewool application reduced the U-value to 0.233 W/m²°C, energy consumption to 13,089 kWh, and total cost to $210,217.12. In Tokat, the same insulation lowered energy consumption to 16,332 kWh and the total cost to $210,217.12. While Stonewool is slightly less effective than EPS in terms of energy efficiency, it offers additional advantages such as fire safety and durability, making it a suitable option for specific applications.

In both cities, it is clearly observed that as the thickness of the insulation material increases, the U-value decreases, and energy savings improve. However, beyond 12 cm, the contribution of increased thickness to energy savings diminishes, reaching a threshold in terms of cost-effectiveness analysis. This underscores the importance of selecting the optimal insulation thickness.

Studies conducted in Istanbul and Tokat clearly demonstrate the impact of insulation materials on energy efficiency. Compared to non-insulated buildings, insulation applications have reduced energy consumption by 80% in both cities. This highlights the significant energy waste associated with non-insulated structures. According to the TS 825 standard, cities in Zone 2 should have a U-value of less than 0.60 W/m²°C. In this context, the optimal insulation thickness, considering both cost-effectiveness and energy savings, is determined to be between 7 and 10 cm.

The results obtained for the 3rd Climate Zone through analyses conducted using Energy 3D software are presented in Table 4.

Table 4: Energy Performance Results for Zone 3 Using Energy3D Software

Zone	City	Insulation Material	Insulation Thickness (m)	U Value (W/ m² °C)	Net Energy Consumption (Kwh)	Heating (Kwh)	Cooling (Kwh)	Building Total Cost ($)	Energy Consumption Reduction (%)
3. ZONE	Ankara	Uninsulated		3.0	84422	74236,9	10184,7	200997,97	-
		EPS	0,03	1.07	36412	30051,9	6360,3	202399,76	56,9
			0,05	0.64	25939	20330,7	5608,6	203863,74	69,3
			0,07	0.46	21652	16331	5321	205289,23	74,4
			0,10	0.32	18321	13247,1	5073,9	207506,66	78,3
			0,12	0.27	17155	12152,2	5002,4	208855,89	79,7
			0,15	0.21	15748	10863,3	4885,1	211323,05	81,3
		Stone Wool	0,03	1.167	38807	32254,6	6552,5	202218,65	54,0
			0,05	0.7	27353	21676,5	5676,5	203551,49	67,5
			0,07	0.5	25589	17216	5372,6	204883,75	69,7
			0,10	0.35	19039	13906,1	5132,6	206882,16	77,5
			0,12	0.292	17652	12632,6	5019	208205,3	79,1
			0,15	0.233	16286	11355,4	4930,1	210227,12	80,6
	Konya	Uninsulated		3.0	86268	76009,2	10258,6	200997,97	-
		EPS	0,03	1.07	37148	30561,1	6586,5	202399,76	57,0
			0,05	0.64	26409	20611,6	5797,2	203863,74	69,5
			0,07	0.46	21995	16507,5	5487,1	205289,23	74,5
			0,10	0.32	18636	13394	5242	207506,66	78,4
			0,12	0.27	17454	12294,5	5159,3	208855,89	79,8
			0,15	0.21	16025	10982,4	5042,4	211323,05	81,4
		Stone Wool	0,03	1.167	39603	32825,6	6776,9	202218,65	54,2
			0,05	0.7	27876	21987,4	5888,6	203551,49	67,7
			0,07	0.5	22980	17414,5	5565,3	204883,75	73,3
			0,10	0.35	19329	14057,1	5272,3	206882,16	77,6
			0,12	0.292	17979	12776,8	5202,1	208205,3	79,2
			0,15	0.233	16572	11484,6	5087,2	210227,12	80,8

Table 4 examines the energy efficiency and cost impacts of uninsulated and various insulation materials under the climatic conditions of Turkey's 3rd Climate Zone, focusing on the cities of Ankara and Konya. In Ankara, the annual energy consumption for an uninsulated building was calculated as 84,422 kWh, with a total building cost of $200,997.97. When Dalmaçyalı® Double Carbon Thermal Insulation Board was used, a significant reduction in energy consumption was observed with increasing insulation thickness. For instance, at 0.10 m insulation thickness, energy consumption decreased to 18,321 kWh, achieving a 78.3% savings. At the maximum thickness of 0.15 m, energy consumption further decreased to 15,748 kWh, achieving an 81.3% savings. However, increasing insulation thickness also led to higher total building costs.

Similarly, with Dalmaçyalı® Stonewool SW035 Thermal Insulation Board, energy savings improved as insulation thickness increased. At 0.15 m thickness, energy consumption decreased by 80.6%, dropping to 16,286 kWh. However, the energy savings achieved with Stonewool were generally slightly lower compared to the Double Carbon board.

In Konya, the annual energy consumption for an uninsulated building was calculated as 86,268 kWh. Using Dalmaçyalı® Double Carbon Thermal Insulation Board at 0.10 m thickness reduced energy consumption to 18,636 kWh, achieving a 78.4% savings. At the maximum thickness of 0.15 m, energy consumption decreased further to 16,025 kWh, achieving an 81.4% savings. Total costs increased as insulation thickness was increased. Dalmaçyalı® Stonewool SW035 Thermal Insulation Board achieved 80.8% energy savings at the maximum thickness of 0.15 m, reducing energy consumption to 16,572 kWh. However, its performance in terms of energy savings was slightly lower compared to the Double Carbon board.

In both Ankara and Konya, the impact of insulation on energy efficiency is clearly evident. Dalmaçyalı® Double Carbon Thermal Insulation Board provided higher energy savings in both cities. While increasing insulation thickness significantly reduced energy consumption, it also led to higher total building costs. The optimal insulation thickness should be determined based on the balance between energy savings and cost. According to Table 4, a 0.10 m insulation thickness appears to be suitable for both Ankara and Konya, offering energy savings of 77–80% while maintaining a reasonable cost balance.

The results obtained for the 4th Climate Zone through analyses conducted using Energy 3D software are presented in Table 5.

Table 5: Energy Performance Results for Zone 4 Using Energy3D Software

Zone	City	Insulation Material	Insulation Thickness (m)	U Value (W/ m² °C)	Net Energy Consumption (Kwh)	Heating (Kwh)	Cooling (Kwh)	Building Total Cost ($)	Energy Consumption Reduction (%)
4. ZONE	Kayseri	Uninsulated		3.0	98925	89035,7	9889,1	200997,97	-
		EPS	0,03	1.07	42483	36212,4	6270,5	202399,76	57,0
			0,05	0.64	30065	24583,8	5481,4	203863,74	69,6
			0,07	0.46	24940	19781,8	5158	205289,23	74,8
			0,10	0.32	21013	16075	4938,4	207506,66	78,7
			0,12	0.27	19599	14757,6	4841,9	208855,89	80,1
			0,15	0.21	17921	13182,6	4738,8	211323,095	81,9
		Stone Wool	0,03	1.167	45283	38848,1	6434,4	202218,65	54,2
			0,05	0.7	31791	26192,8	5597,8	203551,49	67,8
			0,07	0.5	26081	20845,6	5235,5	204883,75	73,7
			0,10	0.35	21812	16867	4945	206882,16	77,0
			0,12	0.292	20221	15336,8	4884,4	208205,3	79,5
			0,15	0.233	18556	13785,4	4770,5	210227,12	81,2
	Erzurum	Uninsulated		3.0	156536	154274,6	2261,2	200297,97	-
		EPS	0,03	1.07	65146	63389,7	1776,6	202399,76	58,4
			0,05	0.64	44958	43291,1	1667,3	203863,74	71,3
			0,07	0.46	36580	34941,3	1638,7	205289,23	76,7
			0,10	0.32	30128	28476,4	1651,7	207506,66	80,7
			0,12	0.27	27812	26174,5	1637,8	208855,89	82,2
			0,15	0.21	25066	23416,2	1650	211323,05	84,0
		Stone Wool	0,03	1.167	69729	67945,6	1783,4	202216,65	55,5
			0,05	0.7	47767	46082,9	1683,7	203551,49	69,5
			0,07	0.5	38443	36793,1	1649,6	204883,75	75,5
			0,10	0.35	51519	29859,4	1659,2	206882,16	67,0
			0,12	0.292	28830	27189,8	1643,7	208205,3	81,6
			0,15	0.233	26101	24472,8	1627,9	210227,12	83,3

This comparison table for the 4th Climate Zone, including cities such as Kayseri and Erzurum, provides a detailed examination of the impact of insulation materials and thicknesses on energy savings. Table 5 illustrates how insulation optimizes both heating and cooling requirements and the reduction in energy consumption achieved.

In Kayseri, the annual energy consumption for an uninsulated building was 98,925 kWh, with a total building cost of $200,997.97. When Dalmaçyalı® Double Carbon Thermal Insulation Board was used, energy consumption significantly decreased with increasing insulation thickness, achieving energy savings ranging from 57% to 81.9%. For example, with a 0.10 m insulation thickness, energy consumption dropped to 21,013 kWh, resulting in a 78.7% savings.

However, the total building cost increased as the insulation thickness grew. A similar trend was observed with Dalmaçyalı® Stonewool SW035 Thermal Insulation Board. At 0.15 m thickness, energy consumption decreased by 81.2%, reaching 18,556 kWh. However, the energy savings achieved with this material were generally slightly lower compared to the Double Carbon board. In Erzurum, the energy consumption for an uninsulated building was quite high at 156,536 kWh. Using Dalmaçyalı® Double Carbon Thermal Insulation Board with a 0.15 m thickness resulted in an 84% energy savings, reducing energy consumption to 25,066 kWh. As insulation thickness increased, the reduction in energy consumption became more significant.

When Dalmaçyalı® Stonewool SW035 Thermal Insulation Board was used, the energy savings reached 83.3% at 0.15 m thickness, reducing energy consumption to 26,101 kWh. However, total costs showed a similar increase for both materials and thicknesses.

In both Kayseri and Erzurum, the impact of insulation on energy efficiency is clearly evident. Dalmaçyalı® Double Carbon Thermal Insulation Board generally provides a higher energy savings rate, while Dalmaçyalı® Stonewool SW035 Thermal Insulation Board also presents an effective solution. Increasing the insulation thickness enhances energy savings but also leads to an increase in building costs. Therefore, the optimal insulation thickness should be determined in a way that balances energy savings and costs. For both Kayseri and Erzurum, a 0.10 m insulation thickness is the most suitable option, offering energy savings (78–80%) and a balance between cost and efficiency.

5. Discussion and Conclusion

This study comprehensively analyzes the impact of insulation applications on energy consumption, heating and cooling requirements, and total costs in various climate zones and cities across Turkey. The study clearly demonstrates that uninsulated buildings result in high energy consumption and economic burdens, and it examines in detail the energy savings and cost advantages achieved through the application of various insulation materials and thicknesses. The results highlight the significant importance of determining the optimal combination of insulation material and thickness according to the climate zone and the specific needs of cities, as it has a major impact on both economic savings and environmental sustainability.

While uninsulated buildings lead to high energy consumption and costs, it has been found that applications with insulation materials such as Dalmaçyalı® Double Carbon EPS and Dalmaçyalı® Stonewool SW035 significantly reduce energy consumption and total costs. EPS material offers high energy efficiency with its low U-value, while Stonewool material provides additional benefits such as fire resistance and longevity. Furthermore, increasing the thickness of the insulation results in higher energy savings, but it has been determined that beyond a certain point, the benefits of increasing thickness diminish and the balance between cost-effectiveness becomes important. In all regions, the optimal insulation thickness range of 10-12 cm was found to provide the best solution in terms of energy efficiency and cost-effectiveness.

In conclusion, it is once again emphasized that insulation applications play a critical role in both energy savings and environmental sustainability. Decisions should be made in building designs considering regional climate characteristics, material types, and insulation thickness, which will provide both economic and environmental benefits. Future research could focus on the long-term performance and maintenance requirements of different materials, enabling the development of more sustainable insulation strategies. Additionally, the environmental impact of insulation and its role in carbon emissions will also be an important topic for future studies.

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