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Energy analysis of the provinces in the Southeastern Anatolia Region: An evaluation using artificial and natural insulation materials with the degree-day method

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Abstract
Increased energy efficiency is critically important for both achieving environmental sustainability and realizing economic savings. Specifically, insulation materials used in buildings play a key role by minimizing heat losses, which in turn reduces energy consumption. Furthermore, reduced energy usage leads to lower carbon emissions, mitigating adverse environmental impacts. This study focuses on improving building energy performance in Türkiye's Southeastern Anatolia Region through a comprehensive energy analysis. Two distinct insulation materials (artificial polyurethane and natural glass wool) and two fuel types (fuel oil and LPG) were investigated. The degree-day method was employed to calculate the optimal insulation thicknesses for eight provinces within the region. Subsequently, the annual net savings and payback periods resulting from these optimized insulation applications were determined. The study culminates in a comparison of the annual energy requirements of insulated versus uninsulated buildings, providing a detailed examination of the potential for energy savings. This research aims to contribute to informed decision-making regarding building energy performance enhancements and offers valuable insights to shape future sustainable energy policies.

1. Introduction

Energy is a fundamental building block of economic and social development in modern societies and is critical for sustainable growth. However, the inadequacy of domestic energy resources and the high level of dependence on foreign sources in Türkiye pose a significant threat to energy security. This situation is exacerbated by the continuously increasing energy demand, making it increasingly urgent to reduce external dependence and utilize domestic energy resources effectively. In this context, innovative strategies in energy production and consumption play a crucial role, not only economically but also in terms of environmental sustainability. Türkiye's energy sector faces a growing demand, driven by both population growth and industrialization. This increase presents several challenges, including reliance on foreign energy sources, inefficiencies in energy production, and the environmental impacts of fossil fuels. The high proportion of energy imports, in particular, poses a potential constraint on economic growth and can negatively affect foreign exchange reserves. Therefore, integrating renewable energy sources and accelerating energy efficiency efforts will significantly contribute to reducing external dependence and ensuring environmental sustainability. Türkiye's energy future can be shaped not only by utilizing existing resources in the most efficient way but also by developing innovative and environmentally friendly solutions.

Therefore, prioritizing energy efficiency and investments in renewable energy will contribute to Türkiye's energy independence and support a growth model aligned with global environmental goals.

Energy efficiency is critically important for economic and environmental sustainability in the modern world. This study investigates the effects of different energy sources (fuel oil and LPG) and building insulation conditions on energy consumption in various provinces of Türkiye. Furthermore, analyses focusing on optimizing these energy sources and building characteristics have yielded results aimed at enhancing energy efficiency. The study examines the effects of insulation and the chosen energy sources by comparing energy consumption data across parameters such as x_{opt}, A_{year}, pp, and $E_{year,H}$.

The gradual depletion of fossil fuel reserves necessitates a more efficient and conscious use of energy resources. As the economic value of remaining fossil fuels continues to rise, their efficient utilization is of paramount importance, both for reducing energy costs and minimizing environmental impacts. Simultaneously, the environmental pollution and global warming caused by fossil fuel consumption make the implementation of sustainable energy policies imperative [1, 2].

Approximately 33% of total energy consumption in Türkiye is used for heating buildings. However, a significant portion of this energy is wasted due to insufficient or improperly applied insulation. A considerable number of existing buildings lack insulation entirely, while many insulation applications utilize low-density and low-cost materials. In contrast, selecting the correct materials and determining the optimum insulation thickness offers a substantial advantage in terms of both reducing fuel consumption and lowering energy costs [3].

Energy consumption occurs across four primary sectors: industry, buildings, transportation, and agriculture. Among these sectors, the building sector exhibits the second-highest energy consumption after industry. A large portion of the energy used in Türkiye is dedicated to heating and cooling buildings. The building sector's share of total energy consumption, around 30-35%, coupled with its high potential for savings, underscores the importance of energy efficiency efforts in this area. Implementing effective insulation strategies in buildings promotes energy savings, thereby offering significant contributions to both economic and environmental sustainability [4].

The thickness of insulation applied to exterior building walls is a significant factor. While increasing insulation thickness reduces heat loss, it also increases costs. Therefore, determining the optimum insulation thickness is necessary for both energy savings and cost-effectiveness. This approach can reduce both fuel consumption and insulation costs [5].

It is a fact that our country's energy resources are not at a sufficient level. A large part of the energy demand, approximately 60-65%, is imported from abroad. This situation is an important factor threatening energy supply security and reveals the need for strategic steps to be taken to increase the use of domestic energy resources in order for the country to gain energy independence. Energy sources such as fossil fuels and natural gas are especially supplied from abroad, which puts a great burden on the country's foreign exchange reserves [6,7].

Furthermore, energy demand is increasing steadily every year. In recent years, this growth rate has been around 4.4%. This constantly increasing energy need continues in parallel with both economic growth and population growth [8]. This situation necessitates the development of more sustainable solutions in energy production and consumption. In this context, increasing investments in renewable energy sources and ensuring energy efficiency are critically important to meet the country's energy needs [9].

To overcome these challenges, Türkiye's energy sector must develop and implement innovative technologies and strategies. Increased energy efficiency and the effective use of domestic resources are key to reducing import dependence, minimizing environmental impacts, and achieving a more sustainable energy future. Unlike previous studies, this study determines the optimum insulation thicknesses for heating in buildings using degree-day values for the year 2024 in the provinces of Adıyaman, Batman, Diyarbakır, Gaziantep, Kilis, Mardin, Siirt, and Şanlıurfa in the Southeastern Anatolia Region. Two different wall types are considered, with glass wool as the natural insulation material and polyurethane as the artificial insulation material. Fuel Oil and LPG were chosen as heating fuels.

2. Material and Method

This study performed energy and cost analyses for seven provinces in Türkiye's Southeastern Anatolia Region, considering two insulation materials (one natural, one artificial) and two fuel types.

2.1. Wall Type

The wall models used in this study were selected as brick walls (TYPE 1) and block pumice walls (TYPE 2). The layers of the wall models, from exterior to interior are: cement exterior plaster, wall, insulation material, and lime interior plaster. Their configurations are shown in Figure 1 and Figure 2.

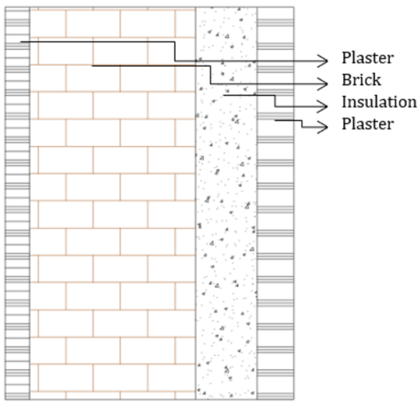

Figure 1. Horizontal hole brick wall (TYPE 1).

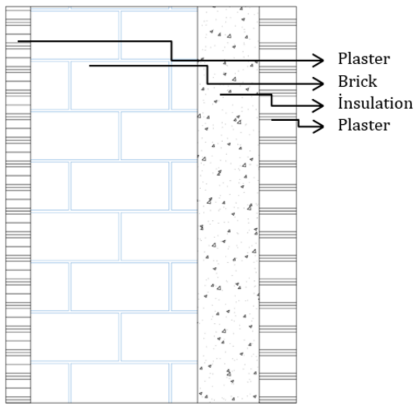

Figure 2. Pumice block wall (TYPE 2).

Table 1 presents the thermal resistance values for the wall structures used in this study.

Table 1. Thermal resistance calculations of the wall model.

Wall Type	Wall Structure	Thickness (m)	Thermal Conductivity (k) (W/mK)	Thermal Resistance (R) (m^2K/W)
Brick Wall (TYPE 1)	R_i	-	-	0.1300
	Lime Interior Plaster	0.02	0.80	0.0250
	Horizontal Hole Brick	0.135	0.72	0.1875
	Cement Exterior Plaster	0.03	0.87	0.0345
	R_0	-	-	0.0400
	$R_{w,t}$	-	-	0.4170
Pumice Block Wall (TYPE 2)	R_i	-	-	0.1300
	Lime Interior Plaster	0.02	0.80	0.0250
	Pumice Brick	0.135	0.27	0.5000
	Cement Exterior Plaster	0.03	0.87	0.0345
	R_0	-	-	0.0400
	$R_{w,t}$	-	-	0.7295

2.2 Calculating Heating Energy Needs

The greatest heat transfer in buildings (heat loss in winter, heat gain in summer) occurs through the building envelope and varies based on several factors. Proper thermal insulation improves building energy efficiency by reducing fuel consumption. This study used glass wool (as natural insulation material) and polyurethane (as synthetic insulation material). Table 2 presents the properties of these insulation materials.

Table 2. Properties of thermal insulation materials.

Insulation Material	Thermal Conductivity (k) (W/mK)	Insulation Cost ($C_{ins,cost}$) ($\$/m^2$)
Glass Wool	0.040	34.48
Polyurethane	0.020	56.20

Table 3 lists the fuel types used in the calculations, along with their key properties relevant to energy and cost analysis. These properties, such as heating value and price, are crucial for determining the overall energy consumption and cost associated with each fuel.

Table 3. Fuel types and properties.

Fuel	Fuel Cost ($C_{fuel,cost}$) ($/kg)	Lower Heat Value (H_u) (J/kg)	Efficiency (η)
Fuel – Oil	0.865	40,546,000	0.80
LPG	0.741	45,980,000	0.88

To calculate using the Degree-Day method, a life cycle cost analysis must be conducted. This analysis employs the parameters outlined in Table 4 to provide the data necessary for the calculation process.

Table 4. Parameters.

Parameter	Value
Lifetime, N	10 year
Interest Rate, i	%48.58
Inflation Rate, g	%50
PWF	9.494

Table 5 presents the heating degree-day data for eight provinces located in the Southeastern Anatolia Region of Türkiye. Heating degree-days (HDD) are a measure of how much (in degrees) and for how long (in days) the outdoor temperature was below a specific base temperature, typically the temperature below which buildings need to be heated. This data is essential for estimating the heating energy demand of buildings in the region.

Table 5. HDD

Province	Heating Degrees Days (HDD)
Adıyaman	1387
Batman	1734
Diyarbakır	1821
Gaziantep	1576
Kilis	1154
Mardin	1668
Siirt	1696
Şanlıurfa	1122

The heat loss occurring through a unit area of an exterior wall per year (q_{year}) can be calculated using the Equation (1) [10].

$$q_{year} = HDD86400U \tag{1}$$

where 86400 is the conversion factor from days to seconds, HDD represents the annual Heating Degree-Days for the location, and U is the overall heat transfer coefficient (U-value) of the wall. The HDD is a climatic parameter reflecting the cumulative difference between the outdoor temperature and a predefined base temperature (often 18°C) over the heating season. A higher HDD value indicates a colder climate. The U-value quantifies the rate of heat transfer through the wall per unit area and per degree of temperature difference between the inside and outside. A lower U-value indicates better thermal insulation.

The overall heat transfer coefficient (U) is the reciprocal of the total thermal resistance (R_{total}). The total thermal resistance of a wall is determined by summing the individual thermal resistances of its components [11]. For a simple wall without insulation, the total thermal resistance ($R_{w,t}$) can be calculated as Equation (2), and the thermal resistances of the uninsulated wall layer and the insulation material are calculated using Equation (3)[10]:

$$R_{w,t} = R_i + R_{wall} + R_o \tag{2}$$

$$R_{ins} = \frac{x}{k} \tag{3}$$

where $R_{w,t}$ is the total thermal resistance of the uninsulated wall, R_i is the thermal resistance of the inside surface film, R_{wall} is the thermal resistance of the wall material itself, R_o is the thermal resistance of the outside surface film, R_{ins} is the thermal resistance of the insulation layer, x is the thickness of the insulation layer, and k is the thermal conductivity of the insulation material. All thermal resistance values are expressed in m^2K/W, thickness in meters (m), and thermal conductivity in W/mK.

The overall heat transfer coefficient of the uninsulated wall (U) is calculated using Equation (4), and the overall heat transfer coefficients of the insulated wall are calculated using Equation (5) and Equation (6) [10]:

$$U = \frac{1}{R_i + R_{wall} + R_o} \tag{4}$$

$$U = \frac{1}{R_i + R_{wall} + R_{ins} + R_o} \tag{5}$$

$$U = \frac{1}{R_{w,t} + R_{ins}} \tag{6}$$

where, the overall heat transfer coefficient (U-value) of a wall, expressed in W/m^2K, is calculated using the thermal resistances of the individual wall components. The annual energy required for heating is calculated using Equation (7) for the uninsulated wall and Equation (8) for the insulated wall [10]:

$$E_{year} = \frac{86400HDD}{R_{w,t}\eta} \tag{7}$$

$$E_{year} = \frac{86400HDD}{(R_{w,t} + R_{ins})\eta} \tag{8}$$

where η represents the efficiency of the fuel type. The annual energy cost of heating per unit area (C_{year}) is calculated using Equation (9)[10]:

$$C_{year} = \frac{86400UHDDc_{fuel}}{H_u\eta} \tag{9}$$

where c_{fuel} represents the unit cost of the fuel, determining the financial expenditure per unit of energy consumed, Hu denotes the lower heating value (LHV) of the fuel, indicating the amount of useful energy that can be extracted from combustion. These parameters play a crucial role in evaluating the economic and energetic efficiency of the heating system, directly impacting overall fuel consumption and operational costs. In life cycle cost (LCC) analysis, the real discount rate (r) is determined based on the relationship between the nominal interest rate (i) and the inflation rate (g). The following cases are considered [10]:

When ***i> g***; r can be calculated with Equation (10):

$$r = \frac{i - g}{1 + i} \tag{10}$$

When **g> i**; r can be calculated with Equation (11):

$$r = \frac{g - i}{1 + g} \tag{11}$$

Once the discount rate, r, has been determined, the present worth factor (PWF) is calculated using Equation (12):

$$PWF = \frac{(1 + r)^N - 1}{r(1 + r)^N} \tag{12}$$

The annual heating cost per unit area is calculated using Equation (13) for the uninsulated wall, Equation (14) for insulation material cost, and Equation (15) for the insulated wall [10]:

$$c_{total} = \frac{86400HDDc_{fuel,cost}PWF}{R_{w,t}H_u\eta} \tag{13}$$

$$c_{ins} = c_{ins,cost}x \tag{14}$$

$$c_{ins,t} = \frac{86400HDDc_{fuel,cost}PWF}{(R_{w,t} + R_{ins})H_u\eta} + c_{ins,cost}x \tag{15}$$

where, c_{total} represents the total annual heating cost per unit area for the uninsulated wall, and $c_{ins,t}$ represents the total annual heating cost per unit area for the insulated wall, both expressed in units of currency per area and c_{ins} represents the cost of insulation material per unit area. The remaining parameters are defined as follows: $c_{fuel,cost}$ is the unit cost of the fuel, with units consistent with those of the fuel's heating value (Hu); Hu represents the heating value of the fuel; x is the thickness of the insulation layer (m); $c_{ins,cost}$ is the unit cost of insulation material per unit thickness [10]. The optimum insulation thickness (x_{opt}) is calculated using Equation (16):

$$x_{opt} = 293{,}94\sqrt{\frac{HDDc_{fuel,cost}PWFk}{Huc_{ins,cost}\eta}} - kR_{w,t} \tag{16}$$

The net annual savings (A_{year}) is calculated using Equation (17):

$$A_{year} = c_{total} - c_{ins,total} \tag{17}$$

The payback period (pp) is calculated using Equation (18):

$$pp = \frac{C_{ins}}{C_{year}^{1} - C_{year}^{2}} \tag{18}$$

where, C_{year}^{1} represents the cost per unit area for the insulated wall, and C_{year}^{2} represents the cost per unit area for the uninsulated wall.

3. Results

For provinces in the Southeastern Anatolia Region of Türkiye, calculations were performed to determine the following: optimum insulation thickness (x_{opt}); annual net savings (A_{year}) resulting from insulation; payback period (pp) for the insulation investment; and annual energy costs ($E_{year,H}$) for heating both uninsulated and insulated walls. The results of these calculations are presented in the relevant tables and figures.

3.1. Optimum Insulation Thickness

Heat losses in buildings generally occur through various building components, including exterior walls, windows, and roofs. In this study, to calculate the optimum insulation thickness, only heat losses through the exterior walls were considered. Table 6 presents the calculated optimum insulation thicknesses for the Type 1 wall model (Brick Wall) in eight provinces of the Southeastern Anatolia Region of Türkiye. These calculations are based on the thermal resistance values of the wall components and the degree-day data for each province.

Table 6. Optimum thickness (x_{opt}) analysis for TYPE 1 brick wall.

Glass Wool			
Province	**HDD**	**(x_{opt}) (m)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	0.171	0.139
Batman	1734	0.193	0.157
Diyarbakır	1821	0.198	0.161
Gaziantep	1576	0.183	0.149
Kilis	1154	0.154	0.125
Mardin	1668	0.189	0.154
Siirt	1696	0.191	0.155
Şanlıurfa	1122	0.152	0.123
Polyurethane			
Province	**HDD**	**(x_{opt}) (m)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	0.096	0.078
Batman	1734	0.108	0.088
Diyarbakır	1821	0.111	0.090
Gaziantep	1576	0.102	0.083
Kilis	1154	0.086	0.070
Mardin	1668	0.106	0.086
Siirt	1696	0.107	0.087
Şanlıurfa	1122	0.085	0.069

Table 7 presents the calculated optimum insulation thicknesses for the Type 2 wall model (block pumice wall) across the same eight provinces in the Southeastern Anatolia Region. As with the Type 1 wall calculations, these results are based on the thermal resistance values of the wall components and the degree-day data for each province, focusing solely on heat losses through the exterior walls.

Table 7. Optimum thickness (x_{opt}) analysis for TYPE 2 pumice block wall.

Glass Wool			
Province	**HDD**	**(x_{opt}) (m)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	0.158	0.126
Batman	1734	0.181	0.145
Diyarbakır	1821	0.186	0.149
Gaziantep	1576	0.171	0.137
Kilis	1154	0.142	0.113
Mardin	1668	0.177	0.141
Siirt	1696	0.178	0.143
Şanlıurfa	1122	0.140	0.111
Polyurethane			
Province	**HDD**	**(x_{opt}) (m)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	0.089	0.072
Batman	1734	0.102	0.082
Diyarbakır	1821	0.104	0.084
Gaziantep	1576	0.096	0.077
Kilis	1154	0.080	0.064
Mardin	1668	0.099	0.080
Siirt	1696	0.100	0.081
Şanlıurfa	1122	0.079	0.063

The results of the optimum insulation thickness calculations are presented graphically in Figure 3 and Figure 4.

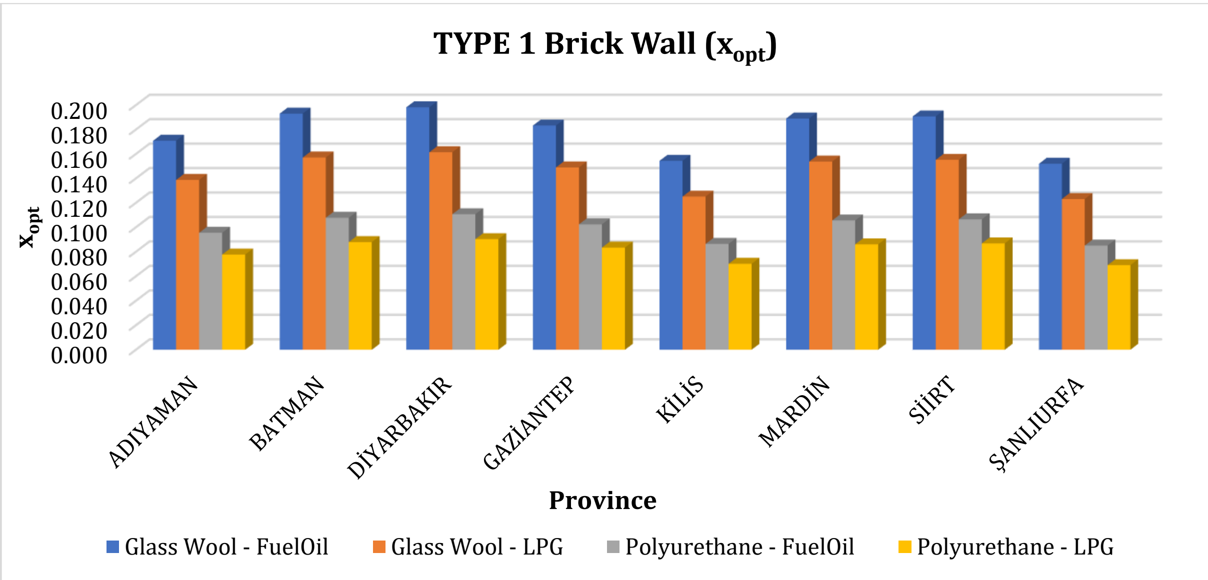

Figure 3. Optimum thickness (x_{opt}) for TYPE 1 brick wall.

Figure 3 illustrates the calculated optimum insulation thicknesses (x_{opt}) for each province, considering the TYPE 1 wall model (brick wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the

TYPE 1 wall revealed that the combination of polyurethane insulation and LPG fuel consistently yielded the lowest required insulation thickness. Notably, the most favorable result was observed for Şanlıurfa, which exhibited an optimum insulation thickness (x_{opt}) of 0.063 m.

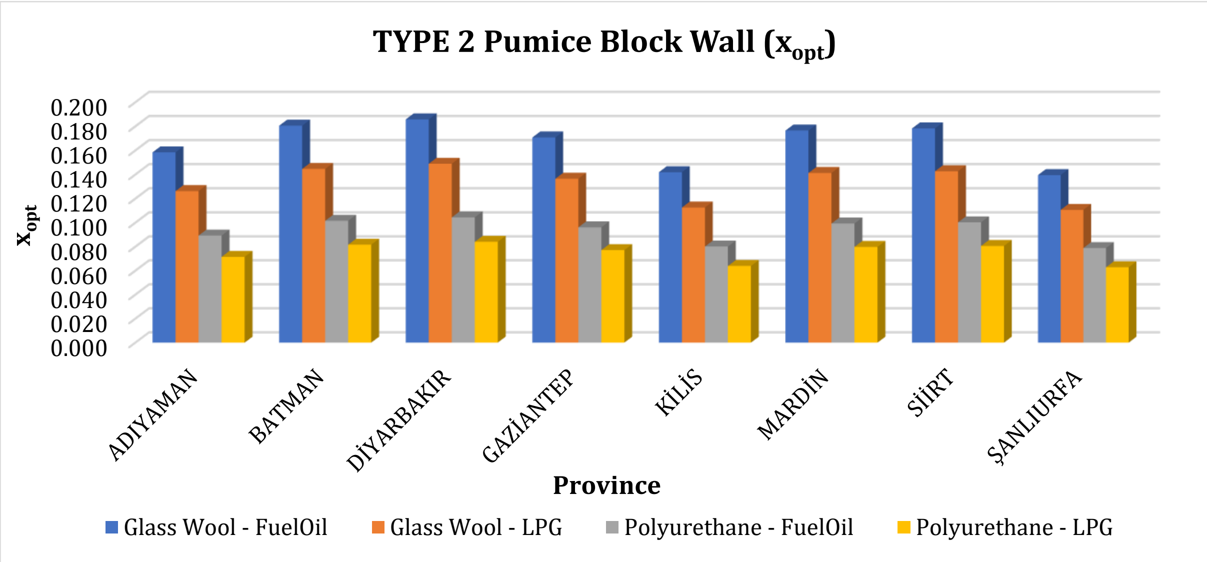

Figure 4. Optimum thickness (x_{opt}) for TYPE 2 pumice block wall.

Figure 4 illustrates the calculated optimum insulation thicknesses (x_{opt}) for each province, considering the TYPE 2 wall model (block pumice wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the TYPE 2 wall revealed that the combination of polyurethane insulation and LPG fuel consistently yielded the lowest required insulation thickness. Notably, the most favorable result was observed for Şanlıurfa, which exhibited an optimum insulation thickness (x_{opt}) of 0.123 m. Figure 5 compares the optimum insulation thickness (x_{opt}) results for the TYPE 1 (brick wall) and TYPE 2 (block pumice wall) wall models. The TYPE 2 wall model consistently yielded lower x_{opt} values, indicating that less insulation is required to achieve optimal thermal performance with this wall type.

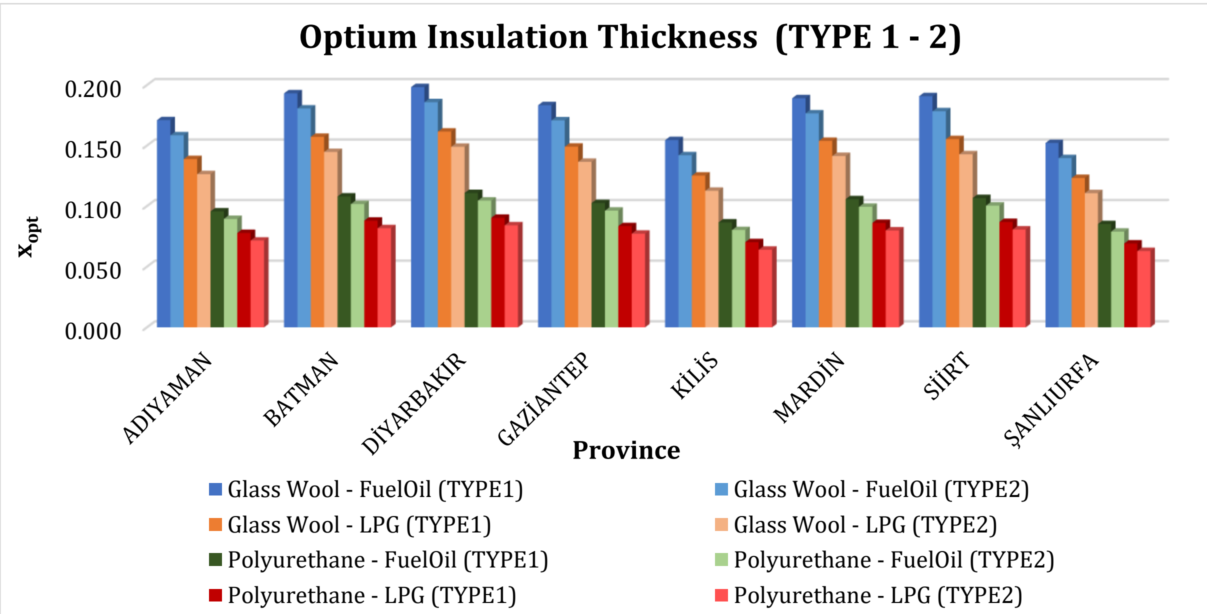

Figure 5. Comparision fo optimum thickness (x_{opt}) for TYPE 2 pumice block wall.

3.2. Net Savings Amount

Energy efficiency is key to both environmental sustainability and economic savings. Quantifying potential energy savings through detailed calculations highlights the benefits of efficiency measures. Table 8 shows the net annual savings (A_{year}) for the TYPE 1 (Brick Wall) model across provinces with various insulation materials and fuel types, while Table 9 presents the same for the TYPE 2 (Block Pumice Wall) model.

Table 8. Annual Energy Save (A_{year}) for TYPE 1 Brick wall.

Province	HDD	(A_{year}) ($/m²) Fuel - Oil	(A_{year}) ($/m²) LPG
Glass Wool			
Adıyaman	1387	60.4	39.8
Batman	1734	77.1	51.1
Diyarbakır	1821	81.3	53.9
Gaziantep	1576	69.5	45.9
Kilis	1154	49.3	32.4
Mardin	1668	73.9	48.9
Siirt	1696	75.2	49.8
Şanlıurfa	1122	47.8	31.4
Polyurethane			
Adıyaman	1387	61.5	40.8
Batman	1734	78.4	52.1
Diyarbakır	1821	82.6	55.0
Gaziantep	1576	70.7	46.9
Kilis	1154	50.4	33.2
Mardin	1668	75.2	49.9
Siirt	1696	76.5	50.9
Şanlıurfa	1122	48.8	32.2

Table 9. Annual energy save (A_{year}) for TYPE 2 pumice block wall.

Province	HDD	(A_{year}) ($/m²) Fuel - Oil	(A_{year}) ($/m²) LPG
Glass Wool			
Adıyaman	1387	29.7	18.8
Batman	1734	38.5	24.7
Diyarbakır	1821	40.8	26.2
Gaziantep	1576	34.5	22.0
Kilis	1154	23.8	15.0
Mardin	1668	36.8	23.6
Siirt	1696	37.6	24.1
Şanlıurfa	1122	23.0	14.5
Polyurethane			
Adıyaman	1387	30.7	19.7
Batman	1734	39.8	25.7
Diyarbakır	1821	42.0	27.2
Gaziantep	1576	35.6	23.0
Kilis	1154	24.8	15.8
Mardin	1668	38.0	24.6
Siirt	1696	38.8	25.0
Şanlıurfa	1122	24.0	15.2

The results of the net annual savings (A_{year}) calculations are presented graphically in Figure 6 and Figure 7. Figure 6 illustrates the calculated net annual savings (A_{year}) for each province, considering the TYPE 1 wall model (Brick Wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the TYPE 1 wall revealed that the combination of polyurethane insulation and LPG fuel consistently yielded the highest annual savings. Notably, the most favorable result was observed for Şanlıurfa, which exhibited net annual savings (A_{year}) of 31.35 $/m².

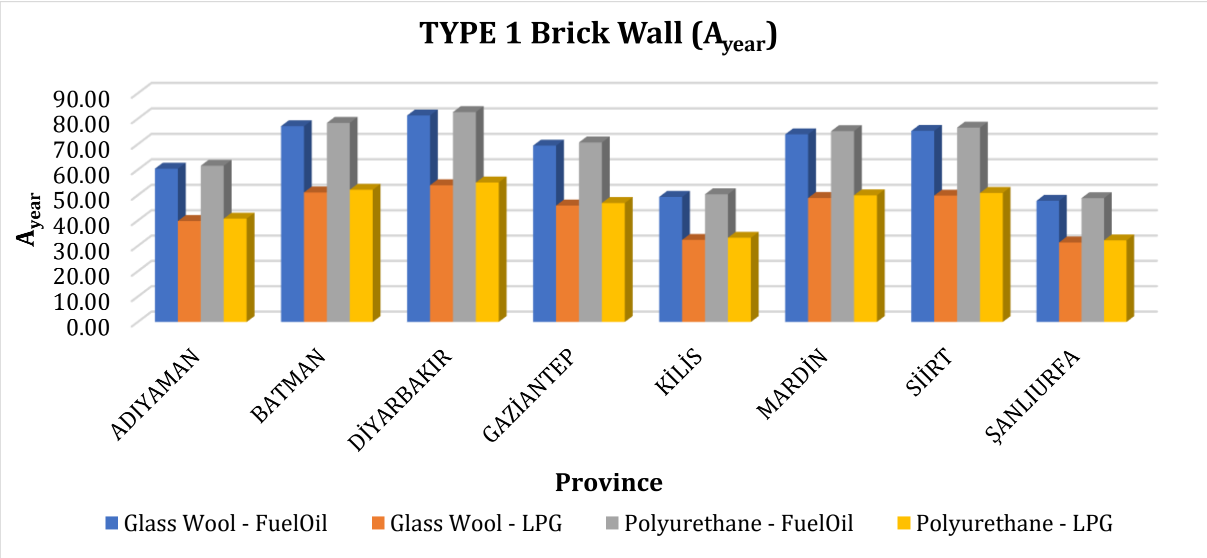

Figure 6. Annual Energy Save (A_{year}) for TYPE 1 Brick wall.

Figure 7 illustrates the calculated net annual savings (A_{year}) for each province, considering the TYPE 2 wall model (block pumice wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the TYPE 2 wall revealed that the combination of polyurethane insulation and LPG fuel consistently yielded the highest annual savings. Notably, the most favorable result was observed for Şanlıurfa, which exhibited net yearly savings (A_{year}) of 14.47 $/m².

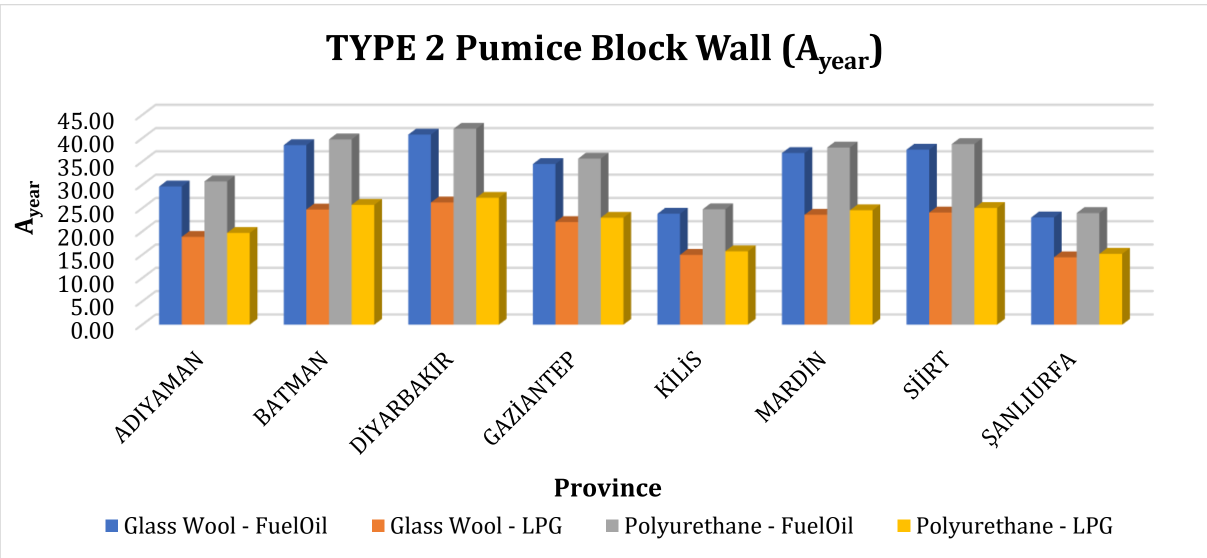

Figure 7. Annual Energy Save (A_{year}) for TYPE 2 pumice block wall.

Figure 8 presents a comparative analysis of the net annual savings (A_{year}) achieved with the TYPE 1 (brick wall) and TYPE 2 (block pumice wall) wall models, building upon the optimum insulation thickness calculations presented earlier. The results unequivocally demonstrate that the TYPE 1 wall model consistently provides higher net annual savings than the TYPE 2 model across all provinces and insulation/fuel combinations. This superior economic performance of the TYPE 1 wall can likely be attributed to a combination of factors, including differences in the base wall's thermal resistance and the resulting differences in optimal insulation thickness. This suggests that, from a purely economic perspective based on heating costs, the TYPE 1 (Brick Wall) configuration offers a more advantageous starting point for insulation improvements in this region.

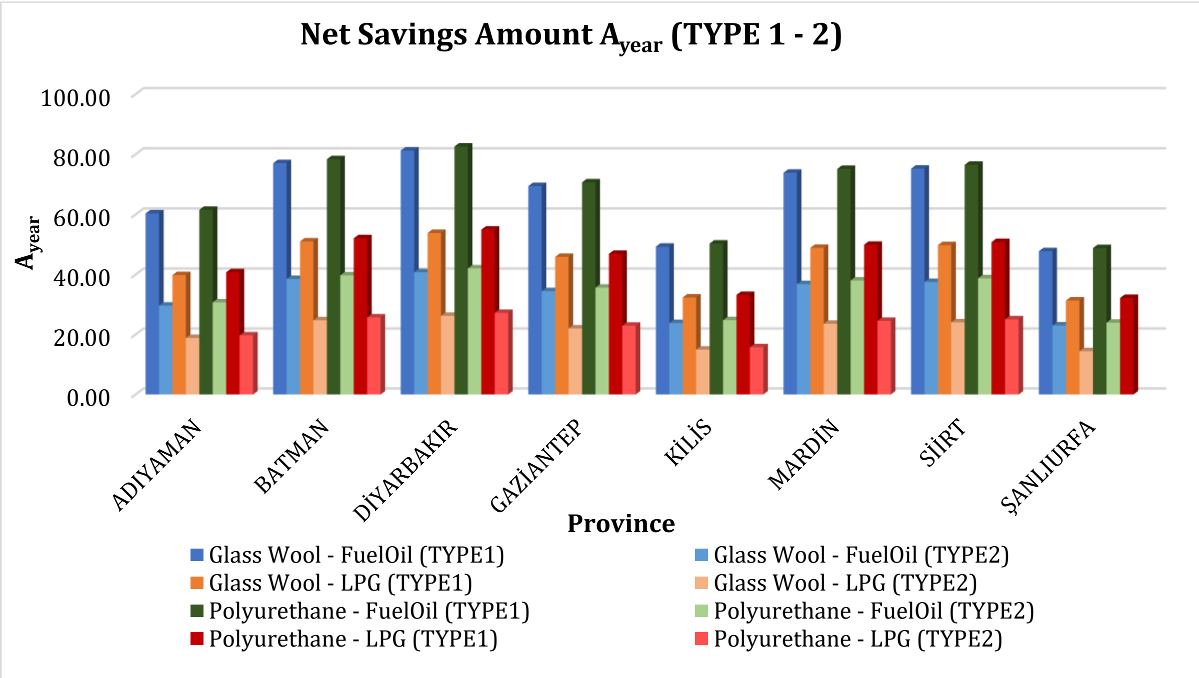

Figure 8. Comparison of TYPE 1 and TYPE 2 Walls in Terms of Annual Energy Savings (A_{year}).

3.3. Payback Period

To evaluate the economic feasibility of insulation investments, we calculated the payback periods for each scenario. Table 10 shows the payback periods (in years) for the TYPE 1 wall model (Brick Wall), taking into account different provinces, insulation materials (glass wool and polyurethane), and fuel types (fuel oil and LPG). These values indicate the time required for the cumulative energy cost savings to recover the initial investment in insulation.

Similarly, Table 11 presents the calculated payback periods (pp, in years) for the TYPE 2 wall model (block pumice wall) across the same provinces and for the same combinations of insulation materials and fuel types. This allows for a direct comparison of the economic attractiveness of insulation investments between the two wall types.

Table 10. Payback period (pp) Analysis for TYPE 1 Brick wall.

Province	HDD	(pp) (year) Fuel - Oil	(pp) (year) LPG
Glass Wool			
Adıyaman	1387	0.71	0.86
Batman	1734	0.64	0.77
Diyarbakır	1821	0.74	0.89
Gaziantep	1576	0.79	0.96
Kilis	1154	0.93	1.12
Mardin	1668	0.77	0.93
Siirt	1696	0.76	0.92
Şanlıurfa	1122	0.79	0.95
Polyurethane			
Adıyaman	1387	0.65	0.78
Batman	1734	0.58	0.70
Diyarbakır	1821	0.67	0.80
Gaziantep	1576	0.71	0.86
Kilis	1154	0.84	1.01
Mardin	1668	0.69	0.84
Siirt	1696	0.69	0.83
Şanlıurfa	1122	0.72	0.86

Table 11. Payback period (pp) Analysis for TYPE 2 pumice block wall.

Province	HDD	(pp) (year) Fuel - Oil	(pp) (year) LPG
Glass Wool			
Adıyaman	1387	1.34	1.61
Batman	1734	1.20	1.44
Diyarbakır	1821	1.29	1.56
Gaziantep	1576	1.39	1.67
Kilis	1154	1.62	1.95
Mardin	1668	1.35	1.62
Siirt	1696	1.34	1.61
Şanlıurfa	1122	1.48	1.78
Polyurethane			
Adıyaman	1387	1.21	1.45
Batman	1734	1.08	1.30
Diyarbakır	1821	1.16	1.40
Gaziantep	1576	1.25	1.51
Kilis	1154	1.46	1.76
Mardin	1668	1.22	1.47
Siirt	1696	1.21	1.45
Şanlıurfa	1122	1.34	1.61

The graphs obtained from the net savings calculations are shown in Figure 9 and Figure 10. Figure 9 illustrates the calculated payback periods (pp, in years) for each province, considering the TYPE 1 wall model (Brick Wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the TYPE 1 wall revealed that the combination of polyurethane insulation and fuel oil consistently yielded the shortest payback periods, indicating the quickest return on investment. Notably, the most favorable result was observed for Batman, which exhibited a payback period (pp) of 0.58 years.

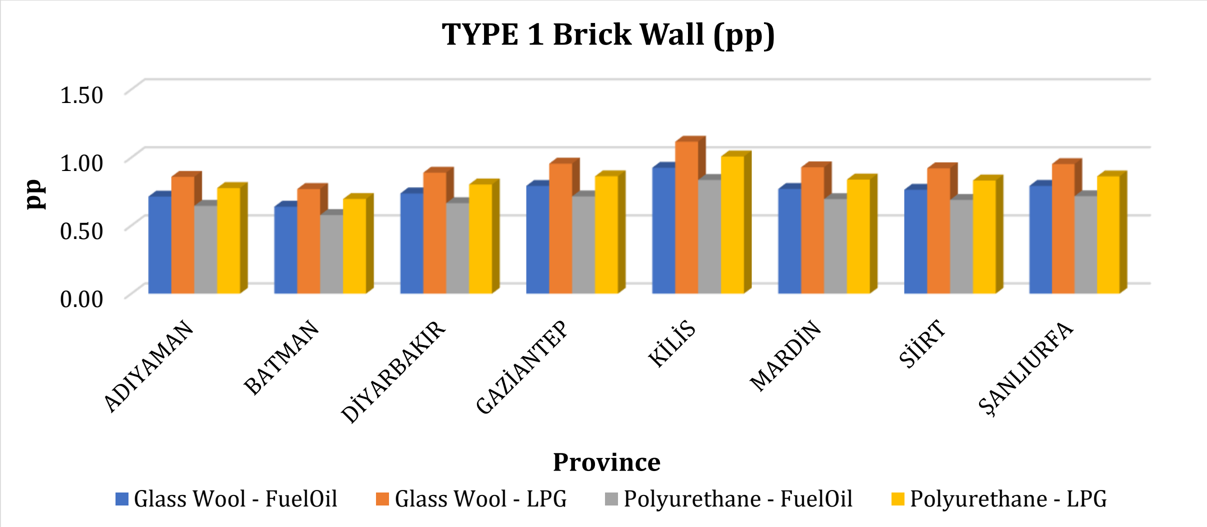

Figure 9. TYPE 1 brick wall: Payback period (pp) analysis (pp).

Figure 10 illustrates the calculated payback periods (pp, in years) for each province, considering the TYPE 2 wall model (block pumice wall) and the following insulation material and fuel type combinations: glass wool with fuel oil, glass wool with LPG, polyurethane with fuel oil, and polyurethane with LPG. Analysis of the results for the TYPE 2 wall revealed that the combination of polyurethane insulation and fuel oil consistently yielded the shortest payback periods, indicating the quickest return on investment. Notably, the most favorable result was observed for Batman, which exhibited a payback period (pp) of 1.08 years.

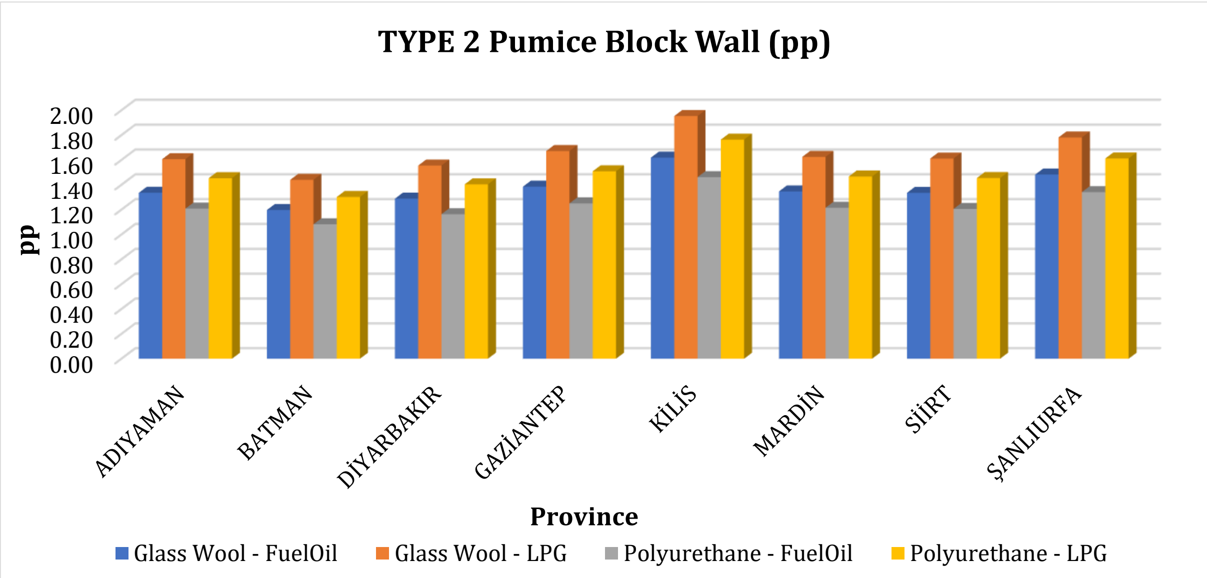

Figure 10. TYPE 2 pumice block wall: Payback period (pp) analysis.

Figure 11 compares the payback periods (pp) achieved with the TYPE 1 (brick wall) and TYPE 2 (block pumice wall) wall models. The results demonstrate that the TYPE 1 wall model consistently provides shorter payback periods, indicating a faster return on investment for insulation in this configuration.

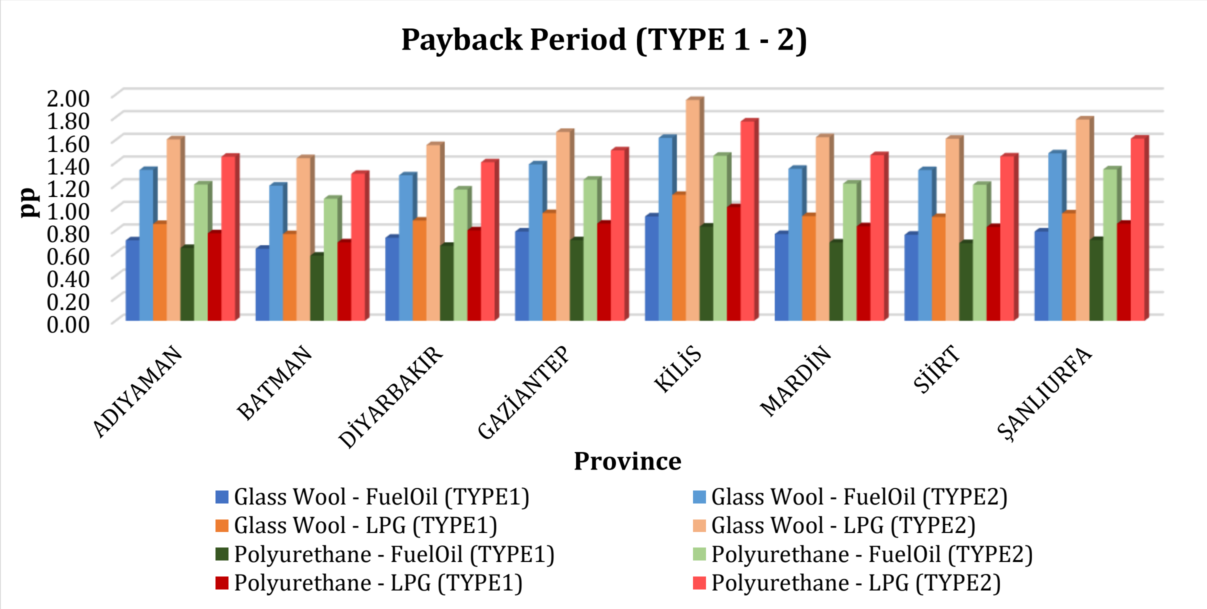

Figure 11. Payback period Comparison of TYPE 1 and TYPE 2 Walls (pp).

3.4. Annual Energy Calculation for Heating

The annual heating energy requirement of a building is the total energy needed to maintain indoor comfort. It varies with insulation, climate, and construction materials. Table 12 presents the calculated heating energy requirements (kJm^2-year) for uninsulated TYPE 1 and TYPE 2 wall models, considering scenario-specific parameters.

Table 12. Annual heat energy for Unninsulated Wall ($E_{year,H}$) ($kJm^2 - year$).

Brick Wall (TYPE 1)			
Province	**HDD**	**($E_{year,H}$) ($kJm^2 - year$)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	359,223	326,566
Batman	1734	449,093	408,266
Diyarbakır	1821	471,625	428,750
Gaziantep	1576	408,172	371,066
Kilis	1154	298,877	271,707
Mardin	1668	432,000	392,727
Siirt	1696	439,251	399,319
Şanlıurfa	1122	290,589	264,172
Pumice Block Wall (TYPE 2)			
Province	**HDD**	**($E_{year,H}$) ($kJm^2 - year$)**	
		Fuel - Oil	**LPG**
Adıyaman	1387	205,341	186,673
Batman	1734	256,713	233,375
Diyarbakır	1821	269,593	245,084
Gaziantep	1576	233,321	212,110
Kilis	1154	170,846	155,314
Mardin	1668	246,942	224,492
Siirt	1696	251,087	228,261
Şanlıurfa	1122	166,108	151,008

Table 13 presents the calculated annual heating energy requirements ($E_{year,H}$, in kJ/m^2·year) for the insulated wall models, combining the results for both the TYPE 1 (brick wall) and TYPE 2 (block pumice wall) configurations.

Critically, the simulation results showed no difference in $E_{year,H}$ values between the two wall types after the application of insulation, given the same insulation material, fuel type, and location. Therefore, the results are presented together in a single table. The table shows the variations across provinces, insulation materials (glass wool and polyurethane), and fuel types (fuel oil and LPG).

Table 13. Annual heat energy for insulated wall models ($E_{year,H}$) ($kJm^2 - year$).

Province	HDD	($E_{year,H}$) ($kJm^2 - year$)	
Glass Wool			
		Fuel - Oil	**LPG**
Adıyaman	1387	31,938	35,036
Batman	1734	35,710	39,174
Diyarbakır	1821	36,595	40,145
Gaziantep	1576	34,044	37,347
Kilis	1154	29,132	31,958
Mardin	1668	35,024	38,422
Siirt	1696	35,317	38,743
Şanlıurfa	1122	28,725	31,512
Polyurethane			
		Fuel - Oil	**LPG**
Adıyaman	1387	28,832	31,629
Batman	1734	32,237	35,365
Diyarbakır	1821	33,036	36,241
Gaziantep	1576	30,734	33,715
Kilis	1154	26,299	28,850
Mardin	1668	31,618	34,685
Siirt	1696	31,882	34,975
Şanlıurfa	1122	25,932	28,447

Analysis of Table 13 reveals several key trends. First, and most significantly, the choice of insulation material has a substantial impact on the annual heating energy requirement. For both fuel types, polyurethane insulation consistently outperforms glass wool, resulting in lower $E_{year,H}$ values across all provinces. This indicates the superior thermal resistance characteristics of polyurethane compared to glass wool at the simulated thicknesses. Second, the choice of fuel also influences the annual heating energy requirement, although to a lesser extent than the insulation material. In most cases, fuel oil resulted in slightly lower $E_{year,H}$ values compared to LPG, suggesting a higher overall energy efficiency for heating with fuel oil under the simulated conditions. This difference is likely attributable to variations in the heating values and/or assumed combustion efficiencies of the two fuels. Third, as expected, significant variations in $E_{year,H}$ are observed across the different provinces, reflecting the differing climatic conditions as quantified by the HDD values. Provinces with higher HDD values, indicating colder climates, exhibit correspondingly higher annual heating energy requirements. Finally, it's important to highlight that within each province, and for a given fuel type, the lowest $E_{year,H}$ values are consistently associated with the use of polyurethane insulation.

Taken together, Table 12, and Table 13 present the annual heating energy requirements ($E_{year,H}$) for all combinations of wall type, insulation material, fuel type, and province, allowing for a comprehensive comparison of the energy performance under different scenarios. As expected, the annual heating energy requirement is significantly higher for uninsulated walls compared to insulated walls. For the TYPE 1 wall model (brick wall), the minimum annual heating energy requirement ($E_{year,H}$) of 25932 kJ/m^2·year was observed in Şanlıurfa with the combination of polyurethane insulation and fuel oil. The TYPE 2 wall model (block pumice wall) also exhibited its minimum annual heating energy requirement ($E_{year,H}$) of 28832 kJ/m^2·year in Şanlıurfa, using the same combination of polyurethane insulation and fuel oil.

Figure 12 provides a detailed comparison of the annual heating energy requirements ($E_{year,H}$) for the uninsulated and insulated configurations of the TYPE 1 wall model (brick wall). This comparison highlights the impact of insulation on energy consumption across the different provinces and fuel types.

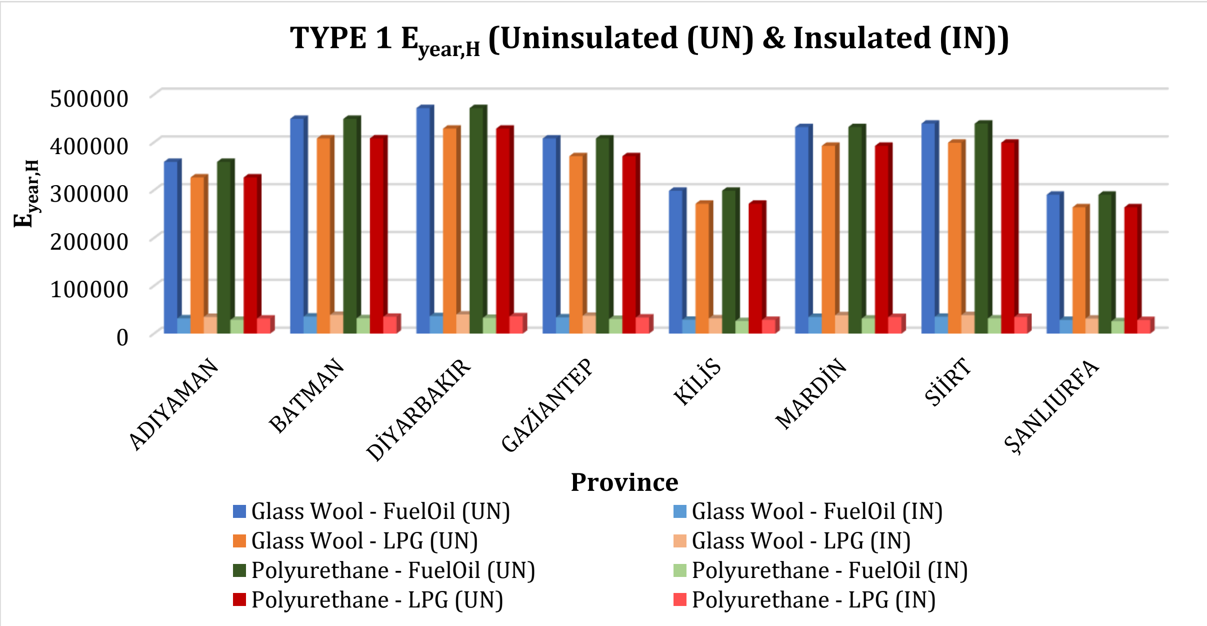

Figure 12. Comparison of Annual Heat Energy $E_{year,H}$ for TYPE 1 Wall (Uninsulated (UN) & Insulated (IN)).

Similarly, Figure 13 presents a detailed comparison of the annual heating energy requirements ($E_{year,H}$) for the uninsulated and insulated configurations of the TYPE 2 wall model (block pumice wall). This Figure 13 allows for an assessment of the energy savings achievable with insulation for this specific wall type, considering the same range of provinces and fuel types.

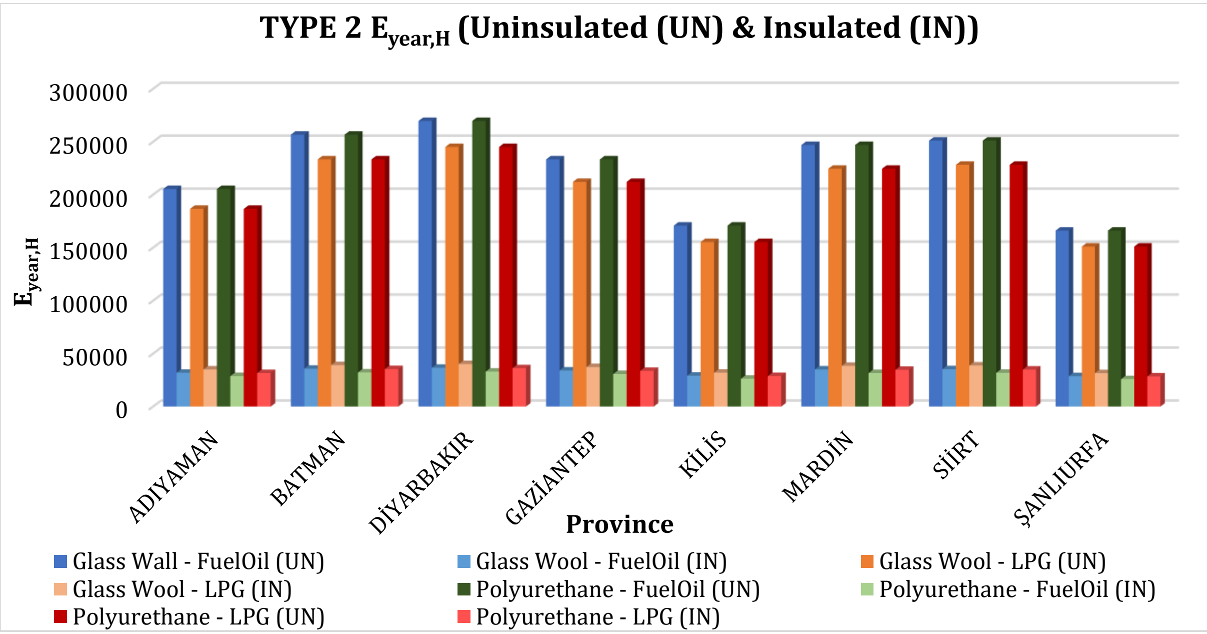

Figure 13. Comparison of Annual Heat Energy $E_{year,H}$ for TYPE 1 Wall (Uninsulated (UN) & Insulated (IN)).

4. Discussion

This study demonstrates the significant impact of insulation on energy consumption. As expected, energy consumption in uninsulated buildings was substantially higher compared to insulated buildings. For instance, in Gaziantep province, the annual heating energy requirement for an uninsulated building using the TYPE 1 (brick wall) and fuel oil was 408.173 kWh/m^2, whereas the corresponding value for an insulated building with glass wool was reduced to 34.044 kWh/m^2. This substantial difference underscores the critical role of insulation in achieving energy efficiency. Insulation minimizes heat loss by maintaining a stable indoor temperature, directly resulting in energy savings.

Observations of energy consumption across different provinces reveal the significant influence of varying geographical and climatic conditions. Distinct differences in energy consumption are evident between provinces such as Diyarbakır and Şanlıurfa. For example, the annual heating energy requirement for uninsulated buildings in Diyarbakır was 471.626 kWh/m^2, compared to 290.590 kWh/m^2 in Şanlıurfa. This disparity highlights the impact of local climatic conditions on energy use and underscores the need for regionally tailored energy efficiency strategies. Therefore, considering local energy infrastructure and weather conditions will play a crucial role in enhancing energy savings.

The impact of fuel type on energy consumption is also evident. A comparison between fuel oil and LPG reveals that fuel oil generally performed as the more energy-efficient option under the simulated conditions. In Gaziantep province, for instance, the annual heating energy requirement with glass wool insulation and LPG was 37.347 kWh/m^2, whereas with fuel oil it was 34.044 kWh/m^2. This difference suggests that fuel oil use led to lower energy consumption in this specific scenario. Therefore, energy efficiency policies should consider the variations in efficiency between different fuel types.

The parameters x_{opt} and A_{year} serve as significant indicators in optimizing energy consumption. In provinces where these parameters are higher, energy consumption has been observed to be more efficient. For instance, in Batman, the Glass Wool-Fuel Oil energy type achieves high efficiency with an x_{opt} value of 0.108 m, leading to lower energy consumption levels. This highlights the importance of implementing effective energy management strategies. Additionally, the A_{year} parameter is a crucial indicator for energy savings, as lower values are associated with higher energy consumption. Optimizing insulation applications and energy type selection can contribute to the improvement of these parameters, ultimately enhancing energy efficiency.

The benefits of insulation extend beyond reducing energy consumption, encompassing significant economic and environmental advantages. As energy consumption decreases in insulated buildings, so do associated costs. For instance, in Adıyaman province, the annual heating energy requirement for an uninsulated building using glass wool and fuel oil was 359.223 kWh/m^2, while this value decreased to 31.938 kWh/m^2 for an insulated building with the same configuration. Such savings not only reduce energy bills but also contribute to minimizing environmental impacts by lowering carbon emissions. Insulation is one of the most effective methods for achieving sustainable energy use and should, therefore, be a central focus of energy policies.

The study results underscore the importance of local conditions in shaping effective energy efficiency strategies. Variations in energy infrastructure and climatic conditions across different regions lead to significant differences in energy consumption patterns. For example, in smaller provinces like Kilis, the annual heating energy requirement for an uninsulated building using glass wool and fuel oil was 298.878 kWh/m^2, while this decreased to 29.132 kWh/m^2 with insulation. These local variations demonstrate the necessity of tailoring energy efficiency strategies to meet specific regional needs. This approach allows for the implementation of targeted efficiency-enhancing projects and more effective management of energy consumption in each region.

5. Conclusion

In Türkiye, insulation is generally applied to buildings to achieve energy savings. Therefore, in this study, the optimum insulation thickness, annual net savings, and payback periods for different insulation materials have been calculated. The analyses conducted in this study demonstrate that insulation plays a crucial role in energy consumption and that optimizing energy source preferences contributes to significant savings. The energy consumption of non-insulated buildings is considerably higher compared to insulated ones. Moreover, regional differences and local climate conditions are key factors influencing energy consumption. Among the energy sources examined, Fuel Oil has emerged as a more efficient option compared to LPG when used with the insulation materials in this study. These findings emphasize the need to tailor energy efficiency policies to local conditions and highlight the importance of expanding insulation applications by considering their economic and environmental benefits.

Conflicts of interest
The author declares no conflicts of interest.

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