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Research Article

Cost analysis of insulation materials used to increase energy performance in buildings with Net Present Value method

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ABSTRACT

Today, producing solutions for the effective and efficient use of energy resources is among the priority areas in almost every sector. In terms of energy consumption, each solution developed in the building sector significantly reduces total energy consumption. In this study, different types of insulation materials used in walls and roofs were investigated in terms of cost-effectiveness to improve the energy performance of a building located in the 1st-degree day zone in Türkiye. Four commonly preferred insulation materials for walls and roofs were tested at specific thicknesses. The Design-Builder simulation program simulated scenarios for the specified thicknesses, and energy consumption values were determined. The initial investment costs of each alternative were calculated, and energy savings were determined. The initial investment costs and energy savings were evaluated according to the Net Present Value method, and each alternative's priority ranking was revealed. According to the results obtained, when the materials used in the study are compared, it is determined that the material with the highest net present value for the roof is glass wool, and the material with the highest net present value for the wall is stone wool.

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1. INTRODUCTION

Many factors, such as rapid population growth, global warming, the oil crisis, and environmental pollution, have made using energy resources efficiently and effectively mandatory. Energy consumption in buildings accounts for 40% of total energy consumption. For this reason, measures should be taken to use energy effectively and efficiently to reduce energy dependency and greenhouse gas emissions in the building sector [1]. In Türkiye, it is known that there is rapid growth in terms of building stock. Consequently, buildings with the highest energy consumption nationwide can potentially create significant energy savings [2].

The most significant part of the energy demand in buildings is heating and ventilation due to heating ventilation air conditioning (HVAC) [3]. Insulation of the building envelope in buildings following climatic conditions can reduce the energy required by the building to a great extent. It is stated in the literature that 76.8% of energy savings can be made in a building with only wall and roof insulation [4]. In this context, building insulation materials are necessary to reduce negative environmental impacts and energy consumption [5]. The correct selection and thickness of the insulation material according to the application area play a vital role in indoor thermal comfort conditions and energy savings [6]. Exterior insulation of the facade affects the total heat loss in a building by 50–60% [7].

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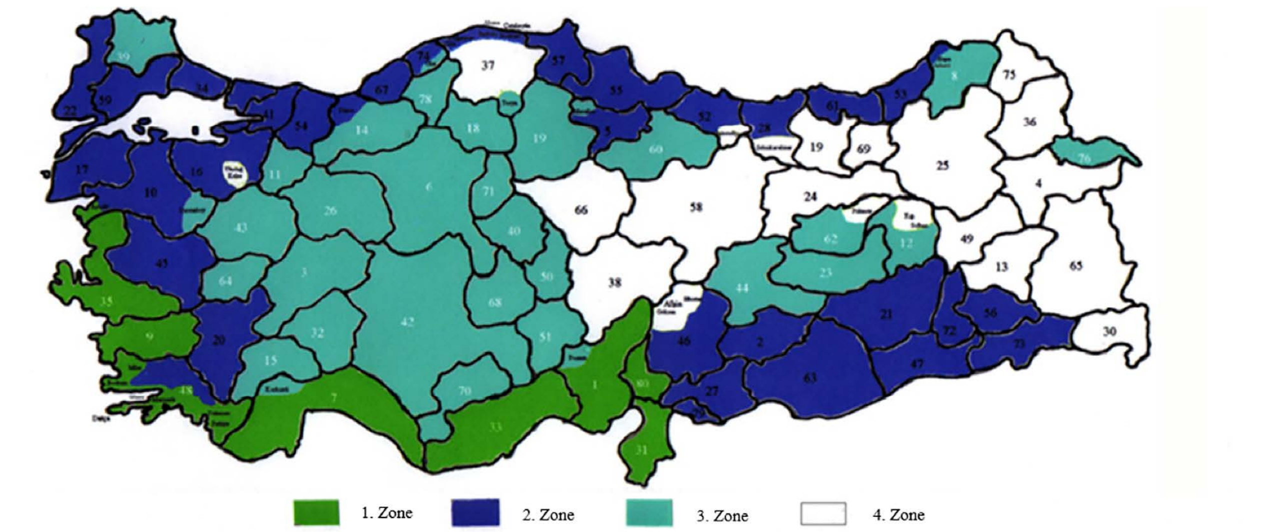

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03- AFYON	12- BİNGÖL	21- DİYARBAKIR	30- HAKKARİ	39- KIRKLARELİ	48- MUĞLA	57- SİNOP	66- YOZGAT	75- ARDAHAN
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08- ARTVİN	17- ÇANAKKALE	26- ESKİŞEHİR	35- İZMİR	44- MALATYA	53- RİZE	62- TUNCELİ	71- KIRIKKALE	80- OSMANİYE
09- AYDIN	18- ÇANKIRI	27- GAZİANTEP	36- KARS	45- MANİSA	54- SAKARYA	63- ŞANLIURFA	72- BATMAN	81- DÜZCE

Figure 1. Degree day zones in Türkiye [9].

In energy-efficient building design, there are many active and passive system solutions such as high insulation, heat bridge-free detail solution, mechanical ventilation, natural lighting, and utilization of renewable energy sources such as solar energy-wind energy. In line with the directives published by the European Union and those published in Türkiye, buildings must be insulated within specific limit values. However, when determining the level of insulation, it should be taken into account that the highest level of insulation is not always the cost-effective choice.

According to the Energy Performance in Buildings Directive (EPBD) 2010/31/EU, a building must be cost-effective throughout its life cycle regarding energy needs and high energy performance. Therefore, according to the directive, buildings and structural elements should be constructed using a cost-effective methodology. When constructing cost-effective high-energy performance buildings, a cost-effective assessment for one-by-one individual building elements or combinations of building elements is required. EPBD 2010 recommends the "net present value" method for cost-effective assessment [1].

It is possible to choose the most appropriate one among different alternatives with the Net Present Value method, which enables a cost-effective choice in selecting material type and thickness while insulating. This study investigates the cost-effectiveness of different insulation materials used on different surfaces at various levels.

2. ENERGY-EFFECTIVE IMPROVEMENT AND INSULATION IN BUILDINGS

With EPBD 2002 and EPBD 2010 published by the European Union, the obligation to construct high-energy performance buildings has been put forward that are insulated within certain limits and where a portion of the energy needed is met from renewable energy sources [1, 8]. In Türkiye, with the 2013 Energy Performance of Buildings Directive, it is mandatory to construct buildings that include appropriate measures for degree day zones as specified in TS 825 [9]. According to TS 825, limit thermal conductivity (U-value) values are determined separately for buildings' walls, roofs, floors, and windows to be built in Türkiye's 4-degree day zone.

Table 1. According to TS 825, U-value requirements for buildings in Türkiye according to degree day zones (1, 2, 3, 4) [9]

	U- value (W/m^{2}K)			
	Degree day zones			
	1	2	3	4
Wall	0.7	0.6	0.5	0.4
Roof	0.45	0.4	0.3	0.25
Floor	0.7	0.6	0.45	0.4
Window	2.4	2.4	2.4	2.4

Determined U-values; are the maximum values required for buildings to have an Energy Performance Certificate (EPC). According to the degree day zones specified in TS 825, the provinces are shown in Figure 1, and the maximum U-values are shown in Table 1. In this study, the maximum U-values specified in TS 825 for the 1st-degree day zone were taken as the limit, and the selected insulation thicknesses were used.

Thermal insulation materials reduce the heat transfer between two environments at different temperatures [10]. It is possible to minimize the heat transfer between the in-

Table 2. Physical properties of the materials used

Material	Conductivity (W/mk)	Spesific heat (J/kgK)	Density (kg/m^3)
Glass wool	0.04	840	12
XPS	0.035	1400	35
Rock wool	0.033	710	100
EPS	0.04	1400	15
Aerated concrete	0.04	1004	550

door and outdoor environment by insulating the building envelope elements such as walls, roof, and floor, which are in contact with the external environment, at the appropriate level with the selection of materials according to the surface used. As a result of proper insulation, indoor comfort conditions continuity can be ensured with high energy performance.

In this study, fibrous and foamed materials were used insulation products commonly used in Türkiye. Thermal insulation materials used in the application phase of the study; glass wool, rock wool, XPS, EPS, and aerated concrete. The features sought according to the application to be used in thermal insulation materials are listed below;

- Conductivity (W/mK)
- Density (kg/m^3)
- Fire class (DIN 4102, BS 476)
- Mechanical strength (kPa)
- Water absorption
- Temperature resistance
- Vapor diffusion resistance
- Dimensional stability [11].

The physical properties of the insulation materials used in the study, such as conductivity, specific heat, and density, are shown in Table 2.

Glass wool is a mineral fiber heat insulation material. Glass wool is produced by melting raw materials such as sand, soda ash, limestone, etc., and turning them into fibers [12]. According to TS EN 13501-1, uncoated glass wool products are in class A1, which are non-combustible materials, and their thermal conductivity value is $0.031 \leq \lambda \leq 0.043$ W/mK [13]. Glass wool is a widely used insulation material in Türkiye, especially in roofs; between rafters, on rafters or slabs. Its thermal properties are similar to rock wool [6].

Stone wool is produced by melting raw materials such as basalt, dolomite, and diabase at high temperatures and turning them into fibers [10]. Stone wool products are in the A1 class, which are non-combustible materials according to TS EN 13501-1, and their thermal conductivity value is $0.033 \leq \lambda \leq 0.040$ W/mK [14]. Stone wool can be used in pitched roofs, flat roofs, ventilated walls, and wall applications.

XPS is produced by extrusion from polystyrene raw material [6]. It is a thermal insulation material in fire class E according to TS EN 13501-1. The thermal conductivity value is $0{,}031 \leq \lambda \leq 0{,}043$ W/mK. It can be used in many application areas, such as flat roofs, pitched roofs, exterior walls, and sandwich panels.

The raw material of EPS, which is widely used in the construction industry, is expandable polystyrene beads [15]. EPS can be produced as plates in different sizes according to the place and purpose of use. Its thermal conductivity value is $0.032 \leq \lambda \leq 0.040$ W/mK, and it is a thermal insulation material in fire class E according to TS EN 13501-1.

Aerated concrete is a mineral-based insulation material manufactured using raw materials such as fly ash, sand, slag, etc. It is a preferred material for its lightweight, high thermal insulation, and energy saving [16]. Thanks to the hollow structure of aerated concrete, its thermal conductivity is up to 20 times lower than regular concrete [17, 18]. According to TS EN 13501-1, the thermal conductivity value of aerated concrete in fire class A is 0.044 W/mK. It can be used as a thermal insulation material on reinforced concrete surfaces and exterior walls.

3. METHODOLOGY

This study investigates the cost-effectiveness of material type and thickness choices in the structural envelope of buildings located in the 1st degree day zone in Türkiye. Insulation materials commonly used in energy-efficient building designs are selected for roofs and walls. For the study, the following path was followed;

1. Different thicknesses of the selected insulation materials were determined according to the applied surface to remain below the limit U-values specified in TS 825 for the 1st-degree day zone. The useful life of the insulation materials was determined.
2. Therm conductivity values were calculated separately in the model created for the study, and the heating-cooling energy requirement was determined for each alternative using the Design Builder simulation program.
3. The initial investment cost per m^2 was calculated using the Construction Unit Price list for all alternatives.
4. With the energy consumption, savings, and initial investment cost data obtained, cost analyses were made using the Net Present Value method.
5. The results obtained were evaluated in terms of net present value.

3.1. Case Study

In order to determine the effect of different thicknesses of different types of materials used in building elements on energy performance in terms of cost, a study was conducted on a building assumed to be located in İzmir/Karşıyaka province in the 1st-degree day zone in Türkiye. The building, modeled using İzmir province climate data, has a floor area of 42.5 m^2. The building is used at all times of the year. There are 3.6 m^2 windows on the east-west facades and 4.6 m^2 on the north and south. The Design-Builder model of the building used in the study is shown in Figure 2.

It belongs to the model created. The material layers of the exterior wall and roof, the physical properties of the materials, and the thermal conductivity values (U-value)

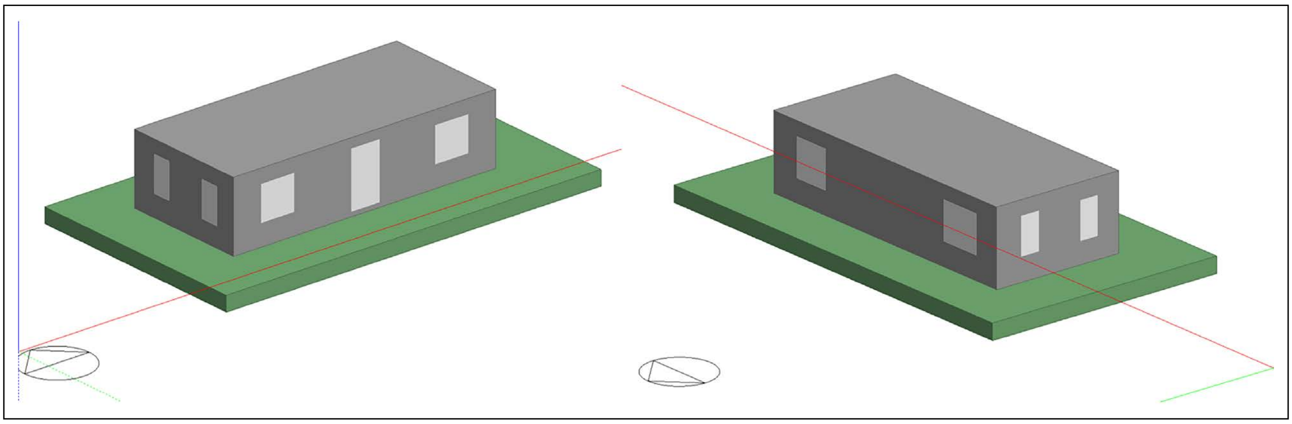

Figure 2. Design builder model of the building used in the study.

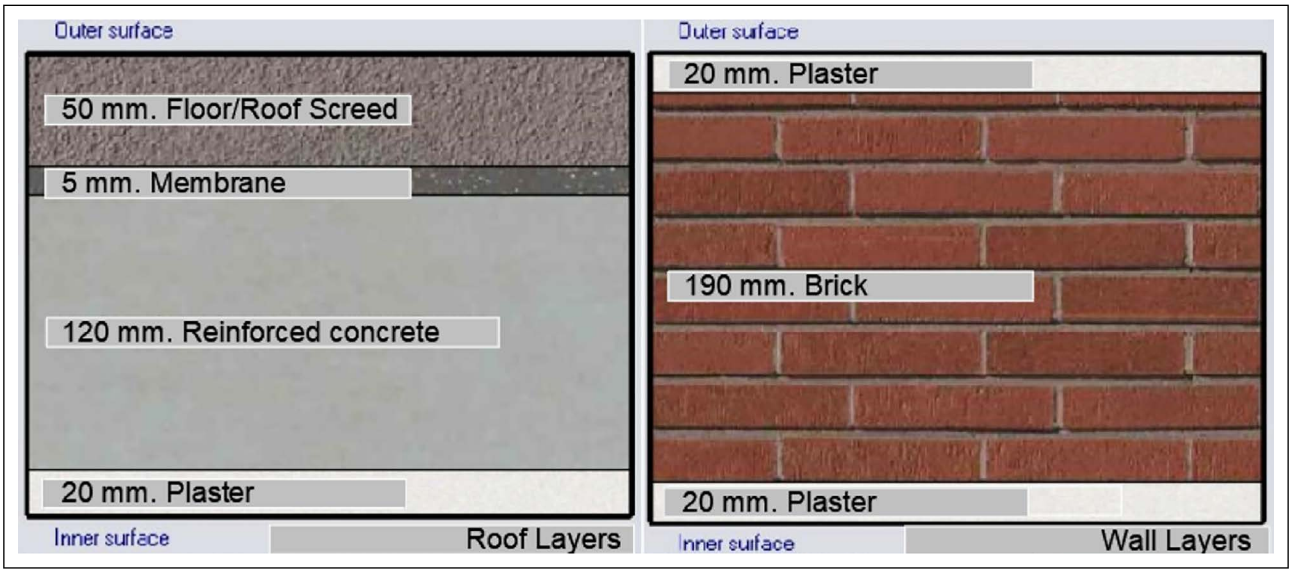

Figure 3. Layers of materials are used in the roof and walls.

obtained for each building element are shown in Table 3. In the current state of the building without insulation, the U-value of the exterior walls is 1.946 W/m²K, and the U-value of the roof is 2.8 W/m²K. Partial sections of the modeled building showing the material layers of the exterior walls and roof are shown in Figure 3.

The thermal conductivity value (U-value) of multilayer building components is calculated using the thicknesses of the individual building elements and the thermal conductivity calculation values of these elements. The formulas used in U-value calculation are shown in equations (1), (2) [9].

$$U = \frac{1}{Ri+R+Re} \quad (1)$$

$$R = \frac{d1}{\lambda h1} + \frac{d2}{\lambda h2} + \cdots + \frac{dn}{\lambda h} \quad (2)$$

U: Total thermal conductivity of the building component (W/m²K)

R: Thermal transmittance resistance (m²K/W)

Ri: Thermal conduction resistance of the inner surface (m²K/W)

Re: Thermal conduction resistance of the outer surface (m²K/W)

λ: Thermal conductivity value (W/mK)

dn: Layer thickness (m.)

3.2. Simulation

The model used in the study was simulated without insulation, and the current situation's heating, cooling and primary energy needs were determined. Since it is aimed to determine the effect of different thicknesses of different insulation materials used in the wall and roof on energy demand and savings, separate insulation scenarios were determined for the wall and roof. The materials used for wall insulation are EPS (0,04 W/mK), rock wool (0,033 W/mK), XPS (0,035 W/mK), and aerated concrete (0,044 W/mK). The materials used in insulation for the roof are glass wool (0,04 W/m²K), XPS (0,035 W/m²K), rock wool (0,033 W/mK), and EPS (0,04 W/mK).

According to TS 825 (Table 1), in buildings located in the 1st-degree day zone, the thermal conductivity value for the wall should be below 0.70 W/m²K, and the thermal conductivity value for the roof should be below 0.45 W/m²K. In this direction, all the insulation alternatives selected for the wall and roof were determined to be below the limit values specified in TS 825. Table 4 shows the type and thickness of the insulation materials used in the

Table 3. Physical properties of the exterior wall, roof, and floor materials

	Material	Width (cm)	Conductivity (W/mk)	Spesific heat (J/kgK)	Density (kg/m³)
Exterior wall	Plaster	2	0.5	1000	1300
	Brick	19	0.72	840	1920
	Plaster	2	0.5	1000	1300
U-value (W/m²K)			1.946		
Flat roof	Floor/Roof screed	5	0.41	840	1200
	Insulation membrane	0.5			
	Concrete, reinforced	12	0.41	840	1200
	Plaster	2	0.5	1000	1300
U-value (W/m²K)			2.8		
Ground floor	Granite	3	2.8	1000	2600
	Floor/Roof screed	3	1.13	1000	2000
	Insulation membrane	0.95			
	Cast concrete	10	1.13	1000	2800
U-value (W/m²K)			2.269		

scenarios for the roof and the energy requirement values obtained. Table 5 shows the type and thickness of the insulation materials used in the scenarios for the wall and the energy requirement values obtained.

3.2. Cost Analysis

For each thickness of the materials used to improve the existing building in an energy-efficient way, initial investment costs were calculated using the Construction Unit Price for 2023 [19]. The exposure numbers of the materials used in the unit price tables are for EPS 10.310.1301, for rock wool 10.310.1101, for XPS 10.310.1501, for aerated concrete 10.330.3301, for glass wool 10.310.1002. Using the initial investment costs and the annual energy savings obtained from the simulation, cost analyses were made with the Net Present Value method.

The net present value method (NPV), which is one of the dynamic methods that take into account the present value of money, is a method that determines the difference between the present value of the cash inflows of the project and the cash outflows and recommends the acceptance of the project if the difference is more significant than zero [20]. With the net present value method, the economic benefit of a project can be measured [21]. Today, the most preferred and advanced economic valuation technique is the NPV approach [22].

Since interest rates in our country do not follow a certain acceleration and show decreases and increases over the years, making precise forecasts for the future is not rational. For this reason, a discount rate for the future was determined by utilizing the discount rates of the past years. Interest rates for the last 10 years were determined for Türkiye by using the interest rate data of the Central Bank of the Republic of Türkiye. For the discount value to be used in the NPV method, the data of the last 10 years were utilized, and the discount value in the study was determined by averaging the data. Interest rates and their averages in Türkiye between 2012 and 2022 are shown in Figure 4.

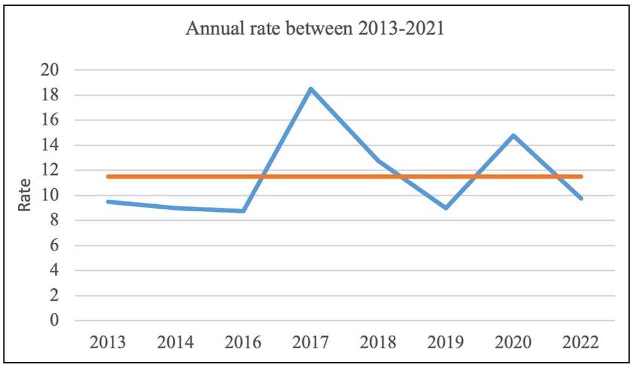

Figure 4. According to data from the Central Bank of the Republic of Türkiye, interest rates and averages for the last 10 years [23].

Based on the average obtained from historical data, the interest rate used in the study is set at 11. NPV can be calculated with the equation (3), (4), (5), (6) [20].

NPV=PV-C (3)

NPV: Net present value
PV: Present value
C: Cost

$$PV = R * \frac{(1+r)^n - 1}{(1+r)^n * r} \quad (4)$$

R: Annual income
r: Rate
n: Time
C: Total cost
ci: Annual investment cost

$$C = \sum_{i=1}^{n} \frac{c_i}{(1+r)^n} \quad (5)$$

$$NPV = R * \frac{(1+r)^n - 1}{(1+r)^n * r} - \sum_{i=1}^{n} \frac{c_i}{(1+r)^n} \quad (6)$$

Table 4. Energy requirement according to simulation results obtained with different insulation materials and thicknesses for the roof

	Roof				
	No	Thickness (cm)	U-value (W/m²k)	Heating-cooling demand (kWh)	Heating-cooling saving (KWH)
	Existing	–	2.800	4092.563	
Glass wool 0.04 W/mK	1	8	0.442	2865.545	1227.018
	2	10	0.362	2827.614	1264.949
	3	12	0.306	2801.310	1291.252
	4	14	0.266	2781.846	1310.717
	5	16	0.235	2766.620	1325.943
	6	18	0.210	2754.912	1337.651
	7	20	0.190	2745.381	1347.182
	8	22	0.173	2737.292	1355.271
XPS 0.035 W/mK	9	7	0.442	2869.038	1223.525
	10	8	0.392	2845.649	1246.914
	11	10	0.32	2812.590	1279.973
	12	12	0.274	2789.659	1302.904
	13	14	0.235	2772.328	1320.235
	14	16	0.207	2759.678	1332.885
	15	18	0.185	2749.405	1343.158
	16	20	0.167	2741.183	1351.380
Rock wool 0.033 W/mK	17	7	0.419	2859.720	1232.843
	18	8	0.372	2837.987	1254.576
	19	10	0.304	2806.963	1285.600
	20	12	0.256	2784.726	1307.837
	21	14	0.222	2768.645	1323.918
	22	16	0.196	2756.697	1335.866
	23	18	0.175	2746.827	1345.736
	24	20	0.158	2738.799	1353.764
EPS 0.04 W/mK	25	8	0.442	2866.648	1225.915
	26	10	0.362	2828.990	1263.573
	27	12	0.306	2802.854	1289.709
	28	14	0.266	2783.704	1308.859
	29	16	0.235	2768.563	1324.000
	30	18	0.210	2757.161	1335.402
	31	20	0.190	2747.839	1344.724
	32	22	0.173	2739.885	1352.678

The insulation material used in this study is considered an investment, and the investment's net present value is determined. In this direction, firstly, the useful lives of the insulation materials used in the study were determined. The literature states the useful life of glass wool, XPS, and rock wool as a building lifetime. The useful life of EPS is stated as 35–50 years [24]. The manufacturer states the useful life of aerated concrete as a building's lifetime.

The useful life of buildings using concrete, masonry, iron, and steel is 50 years, according to the depreciation rates published by the Revenue Administration [25]. In line with this data, the useful life of a building is assumed to be 50 years while performing the cost analysis; calculations are made over 50 years for materials that can be used throughout the life of the building and over 35 years for EPS. The useful lives of the materials used in the study are shown in Table 6.

Net present values were calculated using the energy-saving data and initial investment costs obtained for each scenario resulting from the simulation scenarios. Table 7 shows the net present values obtained with the materials used for roof insulation and different thicknesses within the scope of the study. Table 8 shows the net present values obtained with the materials used for wall insulation and their different thicknesses.

For energy-efficient retrofitting of buildings, the effect of different insulation materials used in walls and

Table 5. Energy requirement according to simulation results obtained with different insulation materials and thicknesses for the wall

	Wall				
	No	Thickness (cm)	U-value (W/m²k)	Heating-cooling demand (kWh)	Heating-cooling saving (KWH)
	Existing	–	1.946	4092.563	
EPS 0.04 W/mK	33	4	0.646	3305.751	786.812
	34	6	0.488	3224.043	868.520
	35	8	0.392	3173.525	919.038
	36	10	0.328	3137.964	954.599
	37	12	0.282	3110.538	982.025
	38	14	0.247	3088.519	1004.044
	39	16	0.22	3070.033	1022.53
	40	18	0.198	3054.515	1038.048
Rock wool 0.033 W/mK	41	3	0.686	3334.056	758.507
	42	5	0.485	3233.944	858.619
	43	7	0.375	3180.662	911.901
	44	9	0.305	3145.863	946.700
	45	11	0.258	3120.545	972.018
	46	13	0.223	3100.249	992.314
	47	15	0.196	3083.075	1009.488
	48	17	0.175	3068.044	1024.519
XPS 0.035 W/mK	49	3	0.712	3344.911	747.652
	50	5	0.506	3240.028	852.535
	51	7	0.392	3183.578	908.985
	52	9	0.321	3146.595	945.968
	53	11	0.271	3119.16	973.403
	54	13	0.235	3098.015	994.548
	55	15	0.207	3080.535	1012.028
	56	17	0.185	3065.308	1027.255
Aerated concrete 0.044 W/mK	57	4	0.686	3378.853	713.710
	58	6	0.523	3309.339	783.224
	59	8	0.423	3260.313	832.25
	60	10	0.355	3220.902	871.661
	61	12	0.305	3188.289	904.274
	62	14	0.268	3163.018	929.545
	63	16	0.239	3142.315	950.248
	64	18	0.216	3124.414	968.149
	65	20	0.196	3127.945	964.618

roofs on energy savings and the net present value of each case was investigated. The graph showing the NPV-U-value relationship for retrofit scenarios with glass wool, XPS, rock wool, and EPS materials used in the roof is shown in Figure 5.

In the scenario alternatives for the roof, when different insulation materials are evaluated in terms of net present value;

- The NPV values of all materials evaluated in roof insulation investments were positive. NPV values vary between 19.562 TL and 6.557 TL.
- Roof insulation with glass wool has the highest NPV value at all levels. The NPV value is 19,562 TL for the roof scenario with 0.042 W/m² K U-value using glass wool and 17,286 TL for the roof scenario with 0.173 W/m² K U-value.

Table 6. Useful lives of the materials used in the case [24]

Material	Service life
Glass wool	Building lifetime
XPS	Building lifetime
Rock wool	Building lifetime
EPS	35–50
Aerated concrete	Building lifetime

Table 7. Insulation materials used for roof and cost analysis according to different thicknesses

	Roof					
	No	U-value (W/m²k)	Heating-cooling saving (TL)	Investment amount (m²/TL)	Investment amount (TL)	NPV
Glass wool 0.04 W/mK	1	0.442	2454.036	53.600	2626.400	19562.993
	2	0.362	2529.898	67.000	3283.000	19592.334
	3	0.306	2582.505	80.400	3939.600	19411.412
	4	0.266	2621.435	93.800	4596.200	19106.813
	5	0.235	2651.886	107.200	5252.800	18725.551
	6	0.210	2675.303	120.600	5909.400	18280.686
	7	0.190	2694.364	134.000	6566.000	17796.441
	8	0.173	2710.543	147.400	7222.600	17286.128
XPS 0.035 W/mK	9	0.442	2447.050	126.000	6174.000	15952.230
	10	0.392	2493.827	144.000	7056.000	15493.187
	11	0.320	2559.946	180.000	8820.000	14327.030
	12	0.274	2605.808	216.000	10584.000	12977.716
	13	0.235	2640.470	252.000	12348.000	11527.131
	14	0.207	2665.771	288.000	14112.000	9991.8978
	15	0.185	2686.316	324.000	15876.000	8413.6711
	16	0.167	2702.759	360.000	17640.000	6798.349
Rock wool 0.033 W/mK	17	0.419	2465.686	128.100	6276.900	16017.834
	18	0.372	2509.151	146.400	7173.600	15514.145
	19	0.304	2571.200	183.000	8967.000	14281.790
	20	0.256	2615.673	219.600	10760.400	12890.517
	21	0.222	2647.835	256.200	12553.800	11387.928
	22	0.196	2671.732	292.800	14347.200	9810.600
	23	0.175	2691.471	329.400	16140.600	8195.682
	24	0.158	2707.528	366.000	17934.000	6547.470
EPS 0.04 W/mK	25	0.442	2451.830	74.800	3665.200	18045.758
	26	0.362	2527.147	93.500	4581.500	17796.385
	27	0.306	2579.417	112.200	5497.800	17342.939
	28	0.266	2617.7188	130.900	6414.100	16765.800
	29	0.235	2648.000	149.600	7330.400	16117.640
	30	0.210	2670.804	168.300	8246.700	15403.268
	31	0.190	2689.447	187.000	9163.000	14652.057
	32	0.173	2705.355	205.700	10079.300	13876.620

- When evaluated in terms of NPV value, glass wool NPV values are followed by EPS. In the EPS scenarios, the highest NPV value is 18,045 TL with a U-value of 0442 W/m² K, while the lowest NPV value is 13,876 TL.
- Regarding NPV in roof insulation, similar values were reached in scenarios using XPS and rock wool. The highest NPV value in the scenarios using XPS and rock wool is 16,017 TL in the roof, where 0.419 W/m² K U-value is reached with rock wool. The lowest NPV is 6547 TL in the roof, where 0.158 W/m² K U-value is reached with rock wool.

The graph showing the NPV-U-value relationship for the retrofit scenarios with XPS, aerated concrete, rock wool, and EPS materials used in the wall is shown in Figure 6.

- The highest NPV value in wall insulation was obtained using rock wool material. It was found that NPV values fell below 0 in some scenarios.
- The scenario with a U value of 0.686 W/m² K in wall insulation made with rock wool has the highest NPV with 10,225 TL. In wall insulation with XPS, the scenario with 0.185 W/m² K U value is the lowest NPV with -10,128 TL.
- Following the rock wool material, the highest NPV values were calculated in the alternatives using aerated concrete.
- In wall insulations made with XPS and EPS, it was observed that the NPV was negative in scenarios with U-values between 0.282–0.185 W/m² K.
- For scenarios with U values below 0.175 W/m² K for rock wool and below 0.196 W/m² K for aerated concrete, the NPV was negative.

Table 8. Insulation materials used for the wall and cost analysis according to different thicknesses

	Wall					
	No	U-value (W/m²k)	Heating-cooling saving (TL)	Investment amount (m²/TL)	Investment amount (TL)	NPV
EPS 0.04 W/mK	33	0.646	1573.624	65.400	5969.189	7965.252
	34	0.488	1737.040	98.100	8953.783	6427.706
	35	0.392	1838.076	130.800	11938.380	4337.785
	36	0.328	1909.198	163.500	14922.970	1982.976
	37	0.282	1964.050	196.200	17907.570	-515.904
	38	0.247	2008.088	228.900	20892.160	-3110.540
	39	0.22	2045.060	261.600	23876.760	-5767.750
	40	0.198	2076.096	294.300	26861.350	-8477.520
Rock wool 0.033 W/mK	41	0.686	1517.014	38.250	3491.154	10225.690
	42	0.485	1717.238	63.750	5818.590	9708.676
	43	0.375	1823.802	89.250	8146.026	8344.792
	44	0.305	1893.400	114.750	10473.460	6646.661
	45	0.258	1944.036	140.250	12800.900	4777.076
	46	0.223	1984.628	165.750	15128.330	2816.672
	47	0.196	2018.976	191.250	17455.770	799.811
	48	0.175	2049.038	216.750	19783.210	-1255.800
XPS 0.035 W/mK	49	0.712	1495.304	55.500	5065.596	8454.943
	50	0.506	1705.070	92.500	8442.660	6974.583
	51	0.392	1817.970	129.500	11819.720	4618.361
	52	0.321	1891.936	166.500	15196.790	1910.097
	53	0.271	1946.806	203.500	18573.850	-970.832
	54	0.235	1989.096	240.500	21950.920	-3965.510
	55	0.207	2024.056	277.500	25327.980	-7026.470
	56	0.185	2054.510	314.500	28705.040	-10128.200
Aerated concrete 0.044 W/mK	57	0.686	1427.420	40.800	3723.898	9182.834
	58	0.523	1566.448	61.200	5585.846	8577.976
	59	0.423	1664.500	81.600	7447.795	7602.614
	60	0.355	1743.322	102.000	9309.744	6453.374
	61	0.305	1808.548	122.400	11171.690	5181.198
	62	0.268	1859.090	142.800	13033.640	3776.250
	63	0.239	1900.496	163.200	14895.590	2288.694
	64	0.216	1936.298	183.600	16757.540	750.467
	65	0.196	1929.236	204.000	18619.490	-1175.340

4. CONCLUSION

High insulation is one of the most widely used solutions for the effective and efficient use of energy in buildings and to improve building energy performance. The Energy Performance of Buildings Directive states that a cost-effective building design is as important as its energy performance. For this reason, this study investigates the cost-effectiveness of a building located in Türkiye's 1-degree-day climate zone depending on the choice of insulation materials.

In this study, to determine the cost-effectiveness of increasing the energy performance of buildings by insulation, different thicknesses of different insulation materials for walls and roofs were applied to a model. The NPV for each alternative was calculated using the energy savings and initial investment cost data obtained. As a result, it can be said that the NPV values of all material alternatives used in the study for the roof are positive. In other words, regarding NPV, roof insulation is positive in all types. It was found that the NPV value was negative at high thicknesses of the materials used for the wall. In both building components, decreasing insulation material thickness increased the NPV value.

In line with the boundaries of this study, the model is in place in the 1st-degree day climate zone. For a building located in the 1st-degree day zone, in terms of the NPV value of the materials used in the study; among the material alternatives used in the study, it was determined that

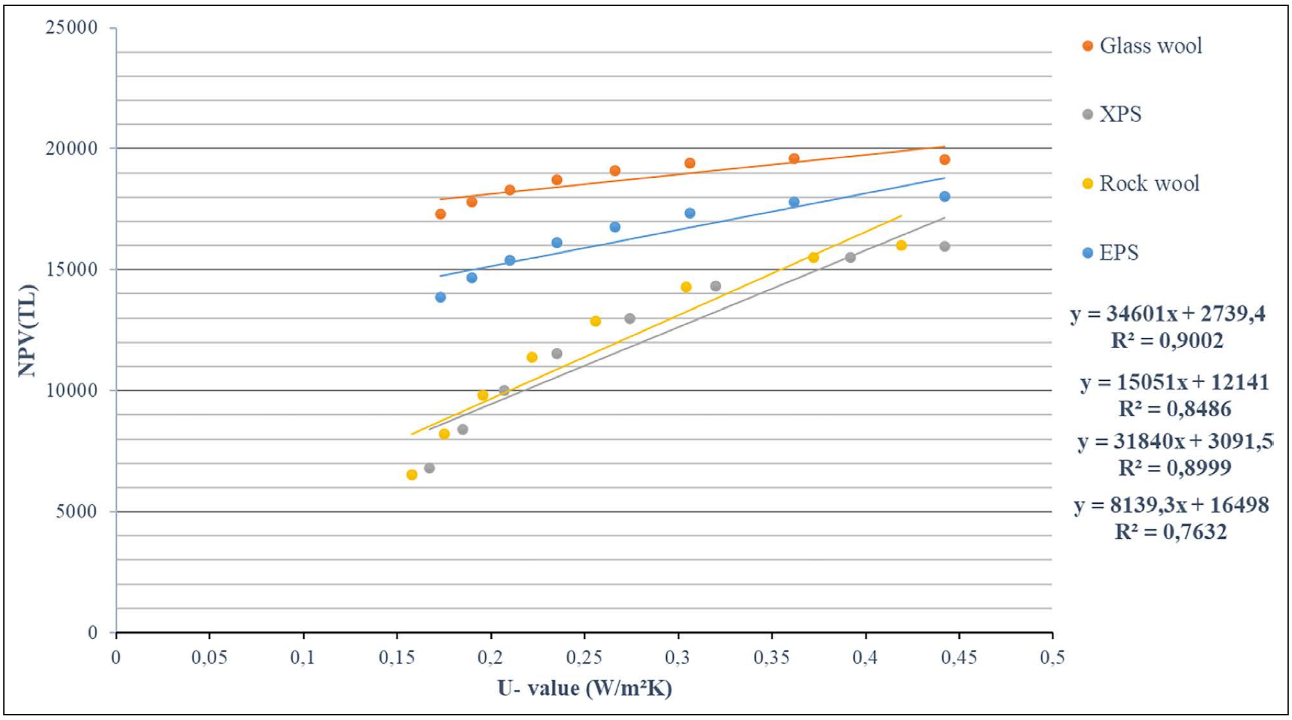

Figure 5. NPV-U-value relationship for insulation thickness scenarios with glass wool, XPS, rock wool, and EPS materials used in the roof.

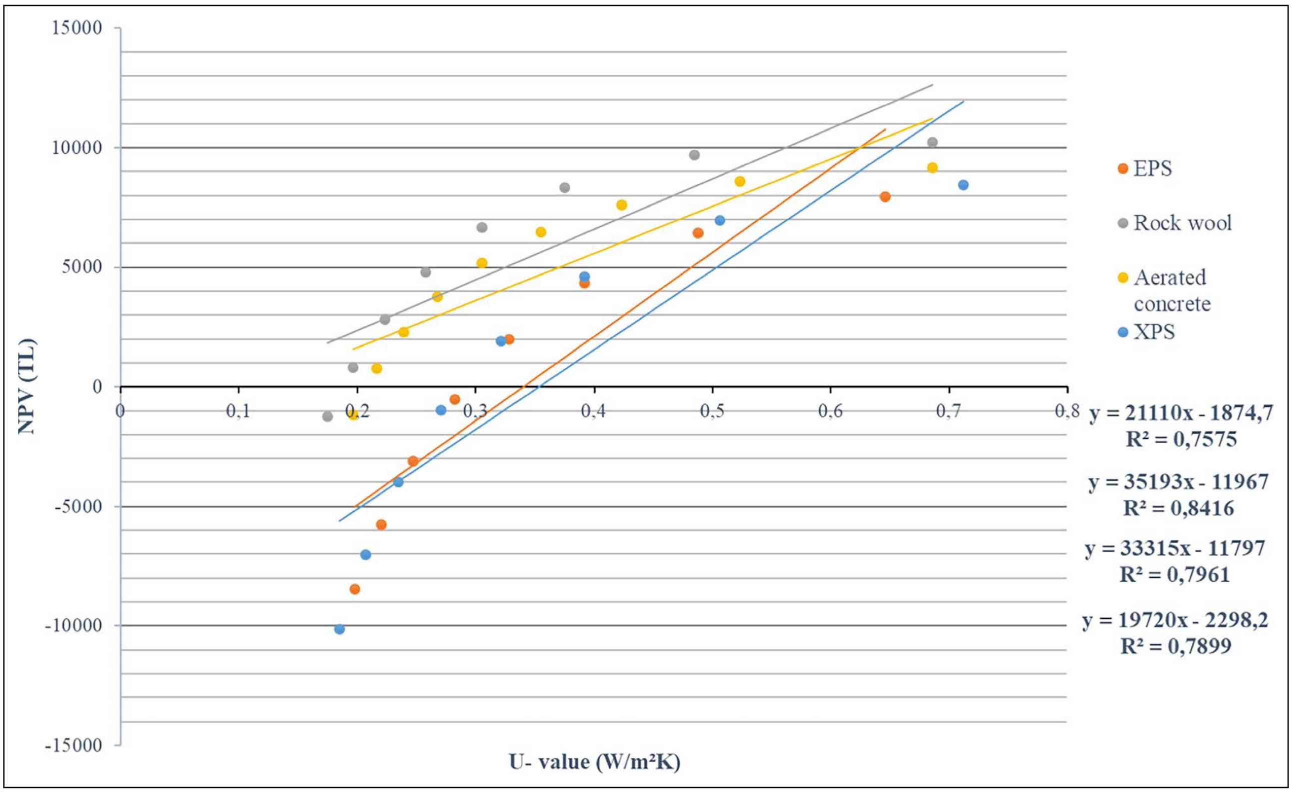

Figure 6. NPV-U-value relationship for insulation thickness scenarios with XPS, aerated concrete, rock wool, and EPS materials used in the wall.

the most efficient material for the roof was glass wool and the most efficient material for the wall was stone wool. When the study is conducted for buildings in different degree day zones, it is possible to reach different NPV values according to the building component. In future studies, it is recommended that this method be applied to buildings located in different degree day zones with different material alternatives.

Based on the results obtained, although the insulation materials used to increase energy performance in buildings are used in thicknesses that will give the same thermal conductivity value, the NPV values of each material are quite different. As stated in the Energy Performance of Buildings published by the European Union, it is as essential to use cost-effective solutions as it is for buildings to have high energy performance. This study emphasizes the importance of investigating cost-effective solutions while achieving similar savings with different materials.

In the study, although in terms of cost-effectiveness, highly insulated alternatives seem to be disadvantageous compared to less insulated alternatives, high levels of insulation can significantly reduce energy demand in the long term. For sustainable architecture, constructing each building as a building that meets its energy from renewable energy sources, with high insulation and low energy needs, will make a tremendous environmental contribution in the long term.

With energy-efficient design or improvement interventions for each building, the total energy consumption of buildings, which have a significant share in the energy sector, can be reduced. In this way, foreign dependence on energy will be reduced in our country, and a significant contribution will be made both nationally and individually economically.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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