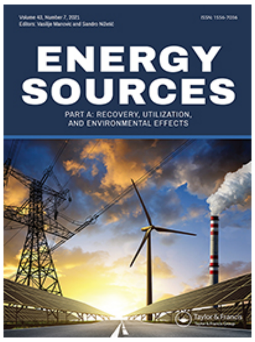

Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ueso20

Determining economic and environmental impact of insulation by thermoeconomic and life cycle assessment analysis for different climate regions of Turkey

Mehmet Kadri Akyüz

To cite this article: Mehmet Kadri Akyüz (2021) Determining economic and environmental impact of insulation by thermoeconomic and life cycle assessment analysis for different climate regions of Turkey, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 43:7, 829-851, DOI: 10.1080/15567036.2020.1813223

To link to this article: https://doi.org/10.1080/15567036.2020.1813223

Published online: 04 Sep 2020.

ENERGY SOURCES, PART A: RECOVERY, UTILIZATION, AND ENVIRONMENTAL EFFECTS
2021, VOL. 43, NO. 7, 829–851
https://doi.org/10.1080/15567036.2020.1813223

Taylor & Francis
Taylor & Francis Group

Check for updates

Determining economic and environmental impact of insulation by thermoeconomic and life cycle assessment analysis for different climate regions of Turkey

Mehmet Kadri Akyüz

Department of Airframe and Power Plant Maintenance, School of Civil Aviation, Dicle University, Diyarbakır, Turkey

ABSTRACT

In this study, economic and environmental impact of thermal insulation have been determined for building wall in the cities of İzmir, İstanbul, Ankara, and Erzurum, located in different climates of Turkey. Three different realistic scenarios have been determined and the analysis have been carried out through these scenarios. The calculations have been made considering four different insulation materials, expanded polystyrene (EPS), glass wool (GW) rock wool (RW) and extruded polystyrene (XPS). Environmental assessments have been carried out by the life cycle assessment (LCA) method for all scenarios. Environmental analysis were carried out by combining 17 environmental effects with the ReCiPe method. The novelty of this study is the determination of environmental payback periods by combining 17 environmental effects using the ReCiPe method. As a result, economic payback times for all scenarios have the lowest value for RW. While the lowest environmental payback period was found as EPS, the highest environmental payback period was found as XPS for all scenarios. The highest economic payback time was assessed at XPS for all scenarios. The thermal insulation material with the highest economic payback period was found as XPS for all scenarios. It has been observed that thermal insulation is more effective in colder climates in terms of economic and annual avoided environmental impact. In all scenarios, environmental payback period was found to be considerably lower than economic payback period.

ARTICLE HISTORY
Received 17 June 2020
Revised 26 July 2020
Accepted 16 August 2020

KEYWORDS
Thermal insulation; energy saving; environmental impact; lca analysis; recipe

Introduction

Designing the buildings envelope to have minimum heat loss and gain is one of the most effective methods of reducing energy consumption for air conditioning. Residental and the service buildings are responsible for 34% of total energy consumption in Turkey (Açıkkalp and Kandemir 2019; National Energy Conservation Center 2006). Determination of the optimum insulation thickness is critical for environmental and economic aspects. Thermal insulation is simple but very important method that can be applied in all residential, commercial, and industrial areas. Insulators have high thermal resistance to decrease the heat flow (Al-Homoud 2005; Ustaoglu et al. 2020).

Global warming and climate change are the most important topic for countries in recent years. Nowadays, fossil fuel-based greenhouse gas emission has become one of the most critical problems. Building and construction sector causes about 45% of global CO_2 emissions. Therefore, methods should be developed to reduce the economic and environmental impacts of the building sector (Dylewski 2019). Most of the global energy demands are met by fossil fuels, which will cause serious environmental problems. Two degrees of global temperature rise cause irreversible environmental problems (Gopalakrishnan et al. 2014; World Wildlife Fund 2020). For this reason, the amount of

CONTACT Mehmet Kadri Akyüz mkadri.akyuz@dicle.edu.tr Dicle University, 21280 Diyarbakır, Turkey

energy used for heating in the residential buildings without compromising comfort conditions is economically and environmentally critical. Thermal insulation in Turkey is determined by the TS 825 "Thermal Insulation Requirements for Buildings" standard. TS 825 defines four climate zone depending on outdoor temperature in Turkey. The minimum heat transfer coefficient (U) for the building envelope is determined in this standard (TS 825, 2008).

There are numerous studies in the open literature about optimum insulation thickness based on economic analysis. In these studies, the optimum insulation thickness (OIT) was calculated using the Life Cycle Cost (LCC) method. In calculations carried out with this method, heating degree day (HDD) and cooling degree day (CDD) values, which are the parameters affecting the optimum insulation thickness, were used. In literature, studies on optimum insulation thickness have been generally investigated for pipes and exterior surfaces of buildings. OIT calculations were performed on pipes with different thermal insulation materials and diameters. Pipes with larger diameters have been found to save more energy. In addition, the two most important parameters that determine OIT are lifetime and unit cost of insulation material (Ertürk 2016). In the analysis performed by economic and environmental cost, the OIT calculated with the environmental approach is higher. (Açıkkalp and Yerel Kandemir 2018). In OIT calculations for pipes of different sizes, the effect of the air gap was examined. It is concluded that the air gap in small diameter pipes is effective in energy saving. It was found that the insulation thickness plays an important role in energy saving for large diameter pipes (Daşdemir et al. 2017a). Economic and exergy approach was combined in pipe insulation to determine the effect of thermal insulation. The OIT value determined by the exergoeconomic method was found to be higher. (Yin et al. 2018). Economic analyses were carried out for various fuel and insulation materials in pipes for different material types. It is concluded that the most effective fuel in terms of energy-saving is fuel oil and insulation material is rockwool (Daşdemir et al. 2017b).

On the other hand, there are many OIT studies in the literature for exterior walls in buildings. Bollutürk (Bolattürk 2006) calculated optimum insulation thickness for 16 cities in Turkey with five different fuel types. In the study, also economic payback time (PBT) determined. Kaynaklı (Kaynakli 2008) determined the optimum insulation thickness for the city of Bursa in Turkey with different fuel types and insulation materials. Bollutürk (Bolattürk 2008) calculated optimum insulation thickness, energy savings, and the economic payback times for Turkey's warmest zone. Uçar and Balo (Ucar and Balo 2010) calculate the optimum insulation thickness for the four cities located in different climate regions in Turkey. Besides, the economic payback period for the five different energy types and four different insulation materials applied externally on walls also determined. Özel (Ozel 2011) determined the optimum insulation thickness for various structures and insulation materials. Energy saving and economic payback periods were also calculated in this study. Daouas (Daouas 2011) determined optimum insulation thickness energy saving and payback period based on cooling and heating loads. Ekici et al. (Ekici, Gulten, and Aksoy 2012) calculated optimum insulation thickness and its effect on energy saving and bayback period for various types of external walls with different insulation materials, fuels and climate zones. Kürekçi (Kurekci 2016) calculated the optimum insulation thickness for the all Turkey's provincial centers. In this study effect of different insulation materials and fuels are considered on economic payback time and energy saving. Dombaycı et al. (Dombayci et al. 2017) determined the OIT of exterior wall for four climate zone. The OIT calculation performed with termoeconomic method for two differnt (polystyrene and polyurethane) insulation material. Huang et al. (Huang et al. 2020) determined the OIT for two different heat source and three different concrete structure. In this study, EPS has been chosen as insulation material for its enviromental impact. Ziapour et al. (Ziapour, Rahimi, and Yousefi 2020) determined the OIT for a new composite prefabricated wall block with respect to differnt insuation materials. Rosti et. al (Rosti, Omidvar, and Monghasemi 2020) determined the optimum insulation thickness of various walls in different climate regions. They carried out energy-saving and economic analysis of the optimum insulation thickness for different wall structures.

Some studies have examined the effect of optimum insulation thickness on reducing greenhouse gas emissions. In these studies, greenhouse gas emissions to be saved annually with the application of OIT to the structures were determined by combustion equations. In the analysis made for Denizl province, it was concluded that with the application of OIT to the external walls, energy consumption and emissions (CO_2 and SO_2) will decrease by 46.6% and 41.53% respectively (Dombaycı 2007). In the study for cold climates, it was concluded that CO_2 emissions will decrease by 27% with application of OIT on the external walls (Çomaklı and Yüksel 2004). The economic and environmental consequences of OIT have been evaluated for various fuels in different climate regions. It was concluded that applying thermal insulation in cold regions will save more CO_2 (Küçüktopcu and Cemek 2018). It was found that the air gap on the outer walls of the building reduced OIT and insulation costs. The air gap and thermal insulation provide savings in CO_2 and SO_2 emissions compared to the uninsulated building (ERTÜRK 2016). OIT values were calculated for the external walls and the effect of the air gap was examined economically and environmentally. It is concluded that the air gap between 2 and 6 cm with OIT reduces energy consumption and emissions between 65 and 77% (Mahlia and Iqbal 2010). OIT calculations were performed for different climate regions, wall structures, and insulation materials. It has been found that the use of sandwich walls provides higher savings in fuel consumption and CO_2 emissions (Gülten 2020).

In the literature, some studies have focused on the economic and environmental effects of OIT. In these studies, OIT calculations have been focused on saving environmental impacts, taking into account the global warming potentials (GWP) of heat sources (Axaopoulos et al. 2019; Ramin et al. 2019). Başoğlu et al. (Başoğul, Demircan, and Keçebaş 2016) calculated the optimum insulation thicknesses with LCC and LCA method and analyzed the decrease in environmental impact with LCA method. In the evaluations for different fuels and insulation materials, it was observed that the optimum insulation thickness calculated by the LCA method was much larger than that calculated by the LCC method. Akyuz et al. (Akyüz et al., 2017) calculated the optimum insulation thickness for an old airport terminal building wall and roof. After the optimum insulation thickness is applied, economic and environmental benefit analyzes have been carried out. In the study, they calculated both economic payback period and environmental payback period. The results showed that environmental payback period shorter than economic payback period. Tingley et al. (Tingley, Hathway, and Davison 2015) determined the environmental effects of EPS, phenolic foam and mineral wool insulation used on exterior wall insulation with LCA method. As a result of the study, it was seen that the environmentally best option is the use of EPS. Gonzalo et al. (Braulio-Gonzalo and Bovea 2017) evaluated the use of different insulation materials economically and environmentally. LCA and LCC methods have been combined to optimize insulation thickness. Valancius et al. (Valančius, Vilutienė, and Rogoža 2018) examined the application of different thermal insulation materials to the building exterior surfaces in terms of energy saving and environmental aspects. LCA and LCC methods were combined and the effect of thermal insulation on energy class in buildings was evaluated. Environmental calculations were performed considering the CO_2 emissions. In addition, economic and environmental payback period of the different thermal insulation materials were calculated.

In the literature, there are studies in which OIT for thermal insulation is calculated by LCC method and its environmental effects are evaluated by LCA. When all these studies are considered, the economic payback period has been calculated, but it has been observed that a large gap in the environmental payback period for insulation. The aim of this study is to investigate the economic and environmental effects of thermal insulation with different scenarios. Natural gas was chosen as the heat source since the main source for heating is natural gas in the selected regions. In this study, EPS, XPS, glass wool (GW) and rock wool (RW) have been chosen as thermal insulation materials and economic and environmental analyzes have been made for the following three scenarios.

- Application of optimum insulation thickness
- Application of the minimum insulation thickness that meets the TS 825 standard
- Application of equal insulation thicknesses

All of these scenarios have been examined for four different climate zones in Turkey identified in TS 825 standard. The novelty of this study is the determination of environmental payback period as well as economic payback period for different thermal insulation materials and climate zones. In addition, in this study, 17 environmental effects were combined, and its effects were examined. This study provides researchers with an economically and environmentally innovative perspective on the use of thermal insulation materials in real life.

Methodology

In this study, economic and environmental analyses of heat loss from the walls were carried out. The wall structure considered in the study can be seen in Figure 1. In addition, the physical properties of the components of the wall are specified in Table 1 (Kallioğlu et al. 2020; Kurekci 2016).

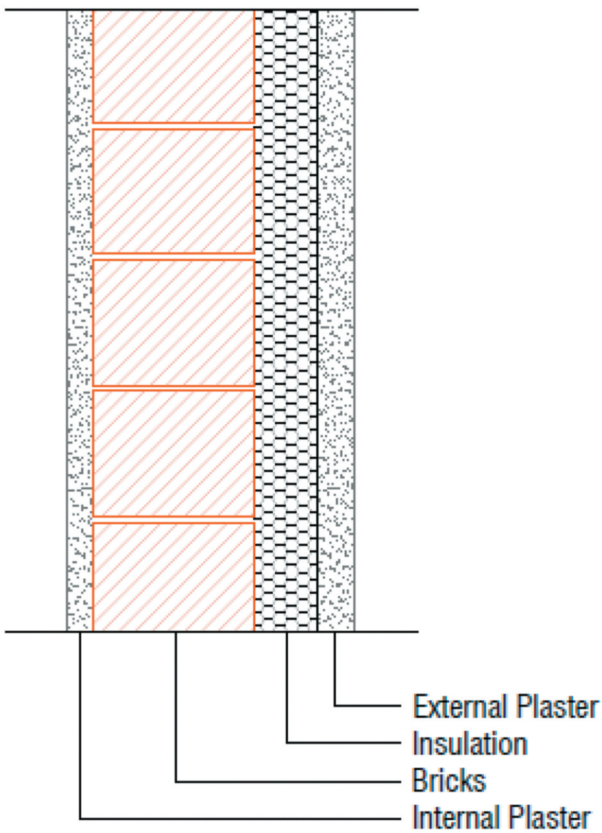

Figure 1. External wall strucre.

Table 1. Wall construction used in the study.

Wall Structure	Thickness (m)	*k* (W/mK)	*R* (m^2 K/W)
Internal plaster	0.02	0.87	0.023
Bricks	0.13	0.45	0.289
External plaster	0.03	1.4	0.021
R_i			0.13
R_0			0.04
$R_{w,t}$			0.503

Scenario 1. Application of optimum insulation thickness

Heat loss occurs in buildings from walls, roofs, floors, and windows and due to air infiltration. One of the most frequently used methods for determining the amount of energy required for heating is the heating degree day (HDD) method. The number of HDD can be calculated by Equation (1) by determining an equilibrium temperature. The equilibrium temperature is a temperature value that does not need heating. In this study, the equilibrium temperature was chosen as 18 °C (BULUT, BÜYÜKALACA, and Yılmaz 2007; Kurekci 2016).

$$HDD = \sum_{day} (T_b - T_0)^+ \tag{1}$$

T_b is equilibrium temperature and, T_0 is mean outdoor temperature

The annual heat losses for the unit surface area can be calculated with the heat transfer coefficient (U) and degree – day values as in Equation (2).

$$q_{,H} = \frac{86400 \times HDD \times U}{\eta} \tag{2}$$

ﬁﬁ represents the efficiency of the heating system, The U value including the insulation can be calculated with Equation (3). (Ertürk 2017).

$$U = \frac{1}{R_{\mathrm{i}} + R_w + R_{ins} + R_0} \tag{3}$$

R_i and R_0 are the thermal resistances of the air film inside and out side. R_w is the thermal resistance of the non-insulated surface and R_{ins} represents the thermal resistance of the insulation;

$$R_{ins} = \frac{x}{k} \tag{4}$$

k and x are the thermal conductivity coefficient and thickness of the thermal insulation material, respectively. $R_{w,t}$ expresses the total thermal resistance of the non-insulated surface and can be calculated by Equation (5).

$$R_{w,t} = R_i + R_w + R_0 \tag{5}$$

The total heat transfer coefficient of the insulated surface is calculated by Equation (6).

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

Annual energy need for heating ($E_{yera,H}$) is determined by Equation (7) (Kurekci 2016).

$$E_{yearl_H} = \frac{86400 \times HDD}{\left(R_{w,t} + R_{ins}\right) \times \eta} \tag{7}$$

Optimum Insulation Thickness

Cost analysis should be done to calculate the optimum insulation thickness. Annual heating cost for unit surface area can be calculated by Equation (8) (Bolattürk 2006; KAYNAKLI and KAYNAKLI 2016).

$$C_{A_H} = \frac{86400 \times HDD \times C_{fuel}}{\left(R_{w,t} + R_{ins}\right) H \times \eta} \tag{8}$$

C_{AH} is the annual heating cost for the unit area, C_{fuel} is the unit price of the fuel, H is the lower heating value of the fuel. The present worth factor (PWF), is calculated by Equation (9) with interest and inflation rates (Kurekci 2016).

İf $i > g$

$$r = \frac{i - g}{1 + g} \tag{9}$$

İf g > i

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

$$PWF = \frac{(1 + r)^{LT} - 1}{r \times (1 + r)^{LT}} \tag{11}$$

If $i = g$

$$PWF = \frac{LT}{1 + i} \tag{12}$$

i, g and LT represent interest rate, inflation rate and lifetime, respectively.

In this study, similar to the studies in the literature, LT is chosen for 10 years. The cost of the thermal insulation material is calculated by Equation (13).

$$C_{ins} = C_y \times x \tag{13}$$

$$C_{t_H} = C_{A_H} \times PWF + C_y \times x \tag{14}$$

C_{tH}, is the cost of heating calculated on an insulated surface using LCC analysis.

The optimum insulation thickness is calculated by minimizing heating costs. The optimum insulation thickness can be found by taking the derivatives of equation (14) according to x and equating it to zero. The optimum insulation thickness for heating is calculated by Equation (15)

$$x_{opt,H} = 293.94 \times \left(\frac{HDD \times C_{fuel} \times PWF \times k}{H \times C_y \times \eta}\right)^{1/2} - k \times R_{w,t} \tag{15}$$

Payback Time

Total savings in annual heating costs are calculated by Equation (16) C_H is the pre insulation of heating cost. $A_{year,H}$ represents the difference of annual total heating cost (\$/m^{2}year).

$$A_{year} = C_H - C_{t_H} \tag{16}$$

Payback time (PBT) for heating is determined by Equation (17). Parameters use in calculation are shown in Table 2.

$$\mathrm{PBTH} = \frac{C_{ins}}{A_{year_H}} \tag{17}$$

The properties of the insulation material are summarized in Table 3.

Table 2. Parameter used in the calculation.

Parameter	Value
i	12
g	11.8
LT	10 year
PWF	9.92
H	344,850,00 J/m3
η	0.9
C_{fuel}	0.33 $\$/m^3$

Table 3. Properties and cost of the insulation materials (EPSA 2020; Evin and Ucar 2019; Kurekci 2016; Ozel 2012).

	EPS	XPS	Glass Wool	Rock Wool
K (W/mK)	0.039	0.031	0.038	0.04
C_y ($\$/m^3$)	120	180	85	80
d (kg/m^3)	16	28	24	40

Application of the minimum insulation thickness that meets the TS 825 standard

Acoording to TS 825 the minimum U value of the external wall are shown in Table 4.

In this study, İzmir, Istanbul, Ankara and Erzurum were selected from different climate regions as shown in Figure 2.

Minimum insulation thicknesses to be applied to the wall type determined by Figure 1 are calculated with Equations (3–6). The purpose of this scenario is that the insulation thickness to be applied to the specified wall structure is at the minimum value that will ensure the TS 825 standard. In other words, applying different thermal insulation materials and to obtain the wall structure with the same thermal resistance.

Table 4. Minimum U values of the walls according to TS 825.

Regions	U_W (W/m^2K)
Region 1	0.70
Region 2	0.60
Region 3	0.50
Region 4	0.40

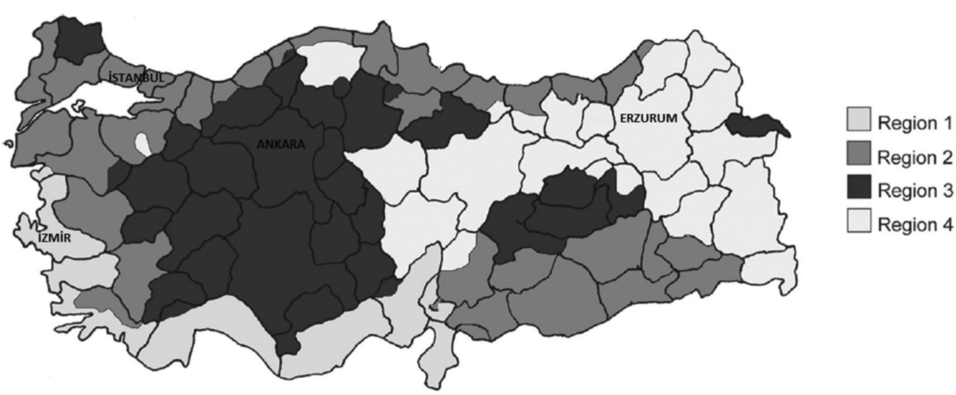

Figure 2. Climate zones of cities in the study (TS 825, 2008).

Application of equal insulation thicknesses

In the third scenario, the economic and environmental effects of applying equal insulation thicknesses were examined. The insulation thicknesses, which provide the TS 825 standard for the determined wall structure, are calculated in the second scenario for EPS, XPS, rock wool, and glass wool. In this scenario, the highest insulation thickness determined in the second scenario was examined economically and environmentally for all thermal insulation materials. The aim is that the selected equal insulation thickness value meets the TS 825 standard for all insulation materials and clamate regions.

Life Cycle Assessment

In this study, LCA method was used to examine the environmental impacts of thermal insulation materials. LCA is a method, that the environmental impacts of a product or process can be examined from the cradle to the grave. LCA is a frequently used method in the construction industry to evaluate the environmental impacts of building materials (Audenaert, De Cleyn, and Buyle 2012). According to ISO standards, an LCA study should include four stages to compare with different studies. These stages are; goal and scope, life cycle inventory, life cycle impact assessment (LCIA) and interpretation (International Organization for Standardization 2006).

Goal and Scope Definition

It is known that using thermal insulation in buildings will save energy for heating purposes. For this reason, the environmental impact saving of using different thermal insulation materials in different climate zones has been investigated. The goal and scope of this study is to compare the effects caused by the process of thermal insulation materials from production to the use. Another goal is to determine the environmental savings provided by using different thermal insulation materials on the external walls. Determining the best environmental choice for different climate regions is the main purpose of this study.

Functional Unit

The functional unit is a reference parameter that enables the basic function of a product or service to be characterized. In this study, functional unit is chosen as 1 m^2 surface area. All of the economic and environmental calculations carried out on 1 m^2 wall area.

System Description and Life Cycle Inventory

The system boundaries of the LCA study are shown in Figure 3. All effects identified in Figure 3 were included in the LCA study. It is assumed that the thermal insulation materials are produced in the cities designated for the study and carried 50 km by lorry. The data used in the model is grouped into two categories as foreground and background data. The foreground data are boiler efficiency, the quantity of adhesive mortar and density of insulation material have been obtained from the literature and technical reports. Background data regarding manfacture and packaging insulation (EPS, XPS, Glas wool, and rock wool), transportation, construction of power plants and production of 1 kWh heat from natural gas was gathered from the ecoinvent 3 databases which is embodied in SimaPro 8.3.0.0 software.

Life Cycle Impact Assessment and Interpretation

LCA analysis was performed by Sima Pro 8.3.0.0 based on the ReCiPe Endpoint (H) V1.13/Europe ReCiPe H/A. ReCiPe is an advanced version of Eco-indicator 99 and CML 2002. With the ReCiPe

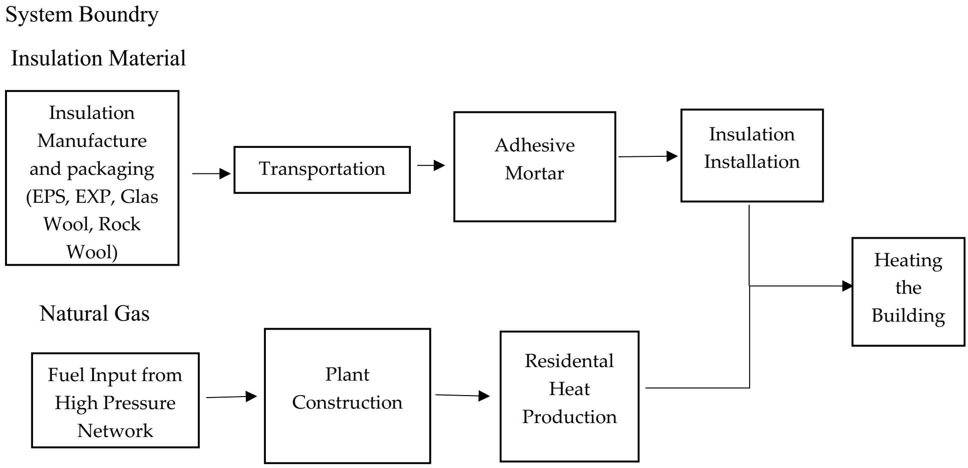

Figure 3. System boundaries of the LCA study.

Table 5. ReCiPe midpoint and endpoint indicator.

Human Health	Ecosystems	Resources
Climate change Human Health	Climate change Ecosystems	Metal depletion
Ozone depletion	Terrestrial acidification	Fossil depletion
Human toxicity	Freshwater eutrophication	
Photochemical oxidant formation	Terrestrial ecotoxicity	
Particulate matter formation	Freshwater ecotoxicity	
Ionizing radiation	Marine ecotoxicity	
	Agricultural land occupation	
	Urban land occupation	
	Natural land transformation	

method, the 17 environmental effects seen in Table 5 can be determined. With this method, the effects of Damage to Human Health (HH), Damage to Ecosystem (ED) and Damage to Resource Availability (RA) of a product or process can be determined. The 17 midpoint effects shown in Table 5 can be converted to these 3 endpoint effects (Goedkoop et al. 2009).

These 17 impacts, which can be determined with ReCiPe, are expressed in milipoint (mPt). All of the impacts that can be determined with ReCiPe are expressed in milipoint (mPt), which is the total endpoint score. One of the main objectives of the study is to calculate the environmental payback times of thermal insulation materials. Therefore, the ReCiPe payback time (RPBT), in which the following equation calculates all these effects. The life cycle impact of energy saving is the annual avoided impact due to natural gas.

$$RPBT = \frac{Life\ Cycle\ Impact\ of\ Insulation}{Life\ Cycyle\ Impact\ of\ Energy\ Saving}(year) \tag{18}$$

Results and discussion

Scenario 1

In this study, economic and environmental analysis of the use of different thermal insulation materials (EPS, XPS, GW and RW) for four different climate regions in Turkey (Izmir, Istanbul and Erzurum) was performed. The analyses performed for three different scenarios, economic payback times (EPBT) and ReCiPe payback times (RPBT) were determined. This study focused on determining the most

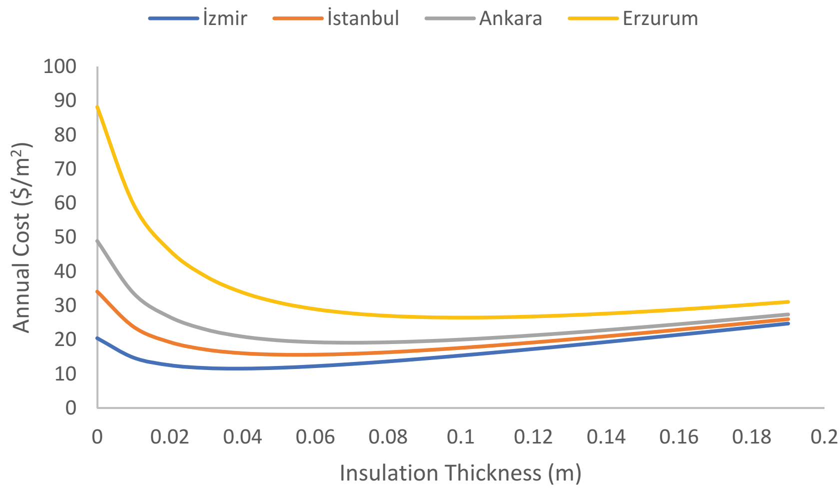

Figure 4. The annual cost of heating versus insulation thickness (EPS).

economical and environmentally friendly options during the use of thermal insulation materials. In scenario 1, OIT is calculated for different climate regions by LCC method and the results are presented in terms of energy saving, economical, and environmental aspects. As seen in Figure 4, OIT (for EPS) for İzmir, Istanbul, Ankara, and Erzurum was found as 0.038 m, 0.05 m, 0.069 m and 0.1 m, respectively. EBPT was calculated as 3.83, 2.62, 2.18, and 1.63 years, respectively, for the same cities.

In the evaluation performed with GW, OIT for İzmir, Istanbul, Ankara, and Erzurum was found 0.048 , 0.068, 0.085, and 0.12 m, respectively, as seen in Figure 5. EPBT was calculated as 2.81, 2.66, 1.83, and 1.36 years, respectively.

For different climate zones (İzmir, Istanbul, Ankara, and Erzurum), OIT was calculated for RW as 0.051, 0.072, 0.09, and 0.128 m, respectively, as seen in Figure 6. EPBT was calculated as 2.8, 2.16, 1.8, and 1.34 years, respectively.

Finally, OIT calculations were performed for XPS and were found to be 0.026 m, 0.038 m, 0.05 m and 0.071 m for İzmir, Istanbul, Ankara and Erzurum, respectively. The results are also seen in Figure 7. EPBT was calculated as 3.69, 2.86, 2.16, 2.38, and 1.78 years, respectively.

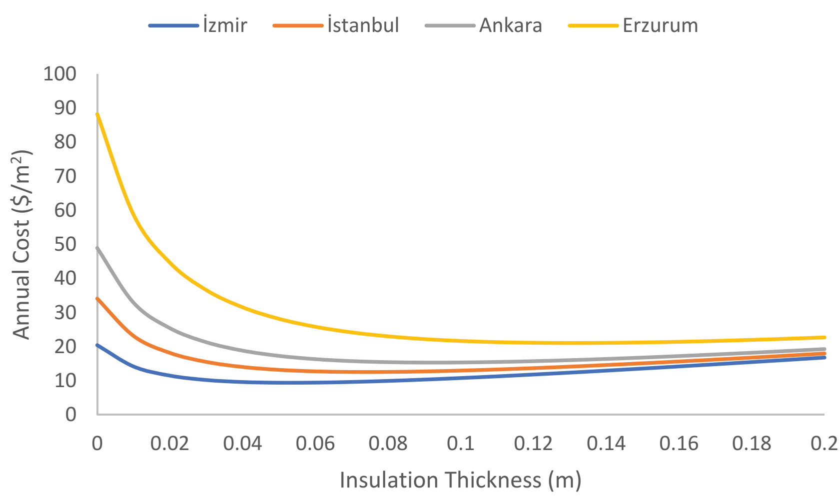

Figure 5. The annual cost of heating versus insulation thickness (GW).

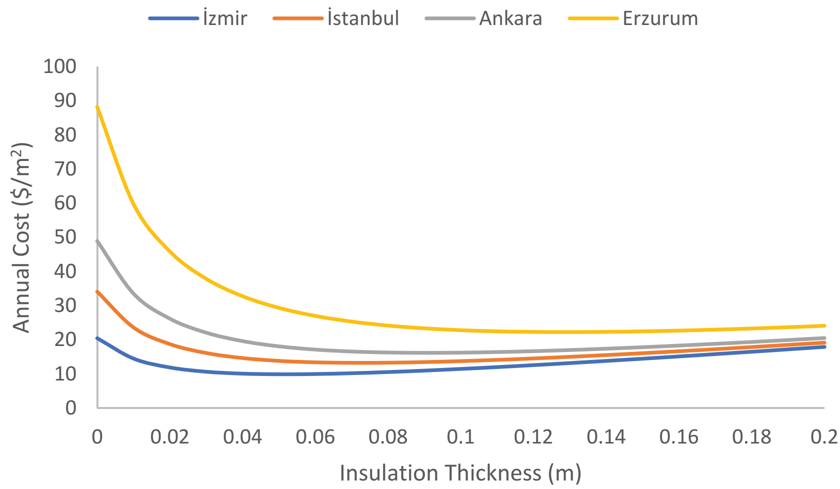

Figure 6. The annual cost of heating versus insulation thickness (RW).

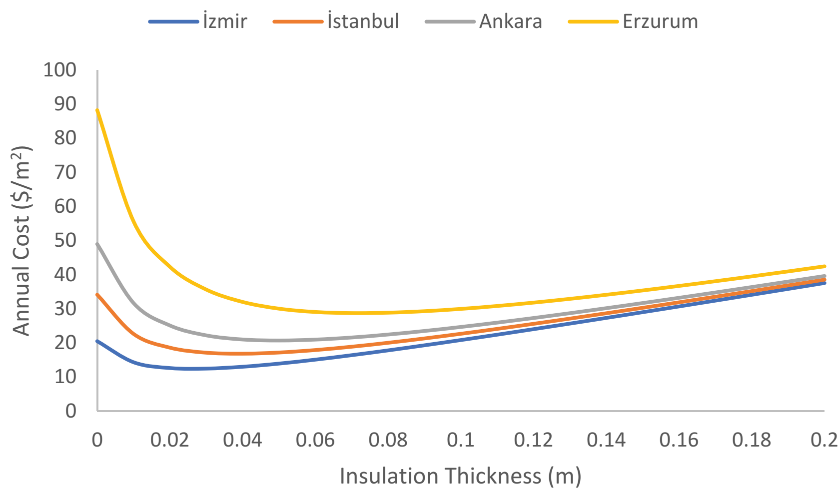

Figure 7. The annual cost of heating versus insulation thickness (XPS).

The results of economic calculations for OIT are summarized in Table 6. It is seen that from Table 6 OIT increased as HDD increased but EPBT decreased for all climate zones. When the results were interpreted for all climate zones, the OIT value was found to be the highest for RW and the lowest for XPS. For EPBT, it is concluded that the most economical option (EPBT is the lowest) is RW. EPBT's highest thermal insulation material was found as XPS for all climate regions.

In addition to its economic results, environmental results were obtained with the LCA method. For the system boundaries seen in Figure 3, all the impacts in Table 5 were evaluated for a single unit, mPt. The aim is to select the most economical option in each climate region as well as the most environmental option. Environmental analysis results for EPS, GW, RW, and XPS (when OIT is applied) for all climate zones are summarized in Table 7. As can be seen from Table 7, avoided environmental impact (AEI) and ReCiPe payback time (RPBT) results are given.

As it is understood from the results (when OIT is applied), as the HDD increases, AEI increases. Besides, as HDD increases, RPBT decreases. Both economic and environmental analyzes for OIT conclude that thermal insulation is a more economical and environmentally friendly option for colder

Table 6. OIT and EPBT for all climate zone.

City	HDD	EPS		GW		RW		XPS	
		OIT (m)	EPBT (year)	OIT (m)	EPBT (year)	OIT (m)	EPBT (year)	OIT (m)	EPBT (year)
İzmir	1118	0.038	3.38	0.048	2.8	0.051	2.79	0.026	3.69
İstanbul	1865	0.055	2.62	0.068	2.17	0.072	2.16	0.038	2.86
Ankara	2677	0.069	2.18	0.085	1.83	0.09	1.81	0.05	2.38
Erzurum	4827	0.1	1.62	0.12	1.36	0.128	1.34	0.071	1.78

Table 7. AIE and RPBT for all climate zone.

		EPS		GW		RW		XPS	
City	HDD	AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)
İzmir	1118	780	1.75	849	0.37	850	1.70	743	2.03
İstanbul	1865	1454	0.99	1542	0.27	1544	1	1406	1.18
Ankara	2677	2211	0.69	2316	0.24	2319	0.71	2153	0.84
Erzurum	4827	4274	0.39	4416	0.18	4419	0.42	4197	0.49

climates. As can be seen from Table 7, AEI increases as HDD increases. This value varies between 743 mPt and 850 mPt for İzmir. However, for Erzurum, AEI varies between 4197 mPt and 4419 mPt. The following results were obtained for scenario 1 (application of IOT) for different climate zones and different insulation materials:

- AEI is higher in colder climates
- RPBT is lower for colder climate regions.
- The AEI value is the highest for GW and RW in all climate regions.
- RPBT has the lowest value for EPS and highest value for XPS in all climate zones
- Compared with other insulation materials, EPS balances its environmental effects in a shorter time.

Environmental payback times were found to be much smaller than economic payback times.

In Figure 8, the relationship between the insulation thickness and the heat losses on the wall surface can be seen. In Figure 9, the relationship between insulation thickness and AEI is presented.

Figure 10 shows the variation of RPBT based on insulation thickness. As the insulation thickness increases, RPBT decreases to a certain value and then increases.

Scenario 2

In the second scenario, economical, and environmental analyses were carried out for the smallest insulation thicknesses meeting the TS 825 standard. Taking into account the wall structure shown in Figure 1, the minimum insulation thicknesses (MIT) that meet the TS 825 standard for each climate zone and insulation material were calculated. Minimum insulation thicknesses to be applied to the wall type are calculated using Equations (3–6). The purpose of this scenario is to achieve equal U value by applying different thermal insulation materials with different insulation thickness. The minimum thickness that meets the TS 825 standard with different thermal insulation materials was determined and economic and environmental results were interpreted. MIT values that must be applied to meet the standard are given in Table 8.

As can be seen from Table 8, the MIT value increases as the HDD increases. With the increase of HDD, EPBT decreases. As in Scenario 1, EPBT has the smallest value for RW and the highest for XPS.

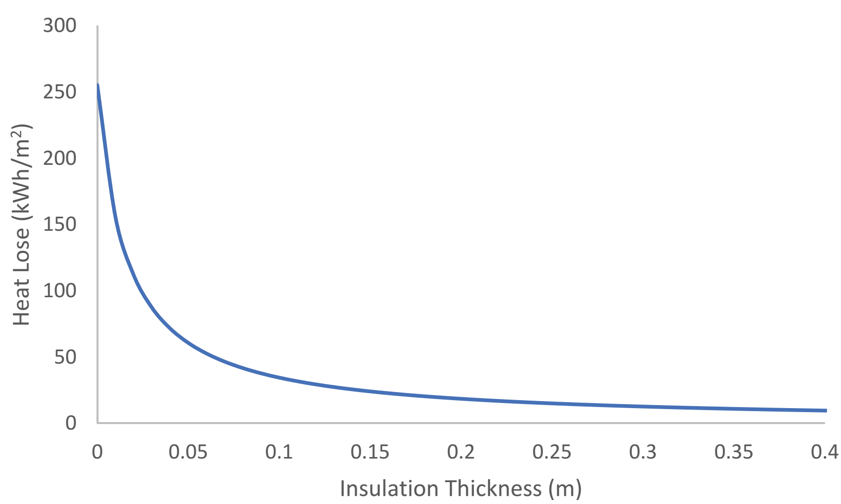

Figure 8. Heat loss versus insulation thickness.

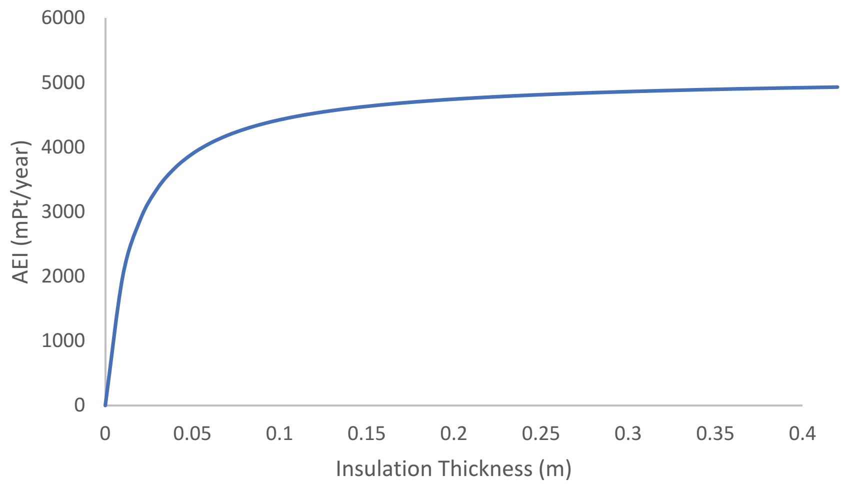

Figure 9. AEI versus insulation thickness.

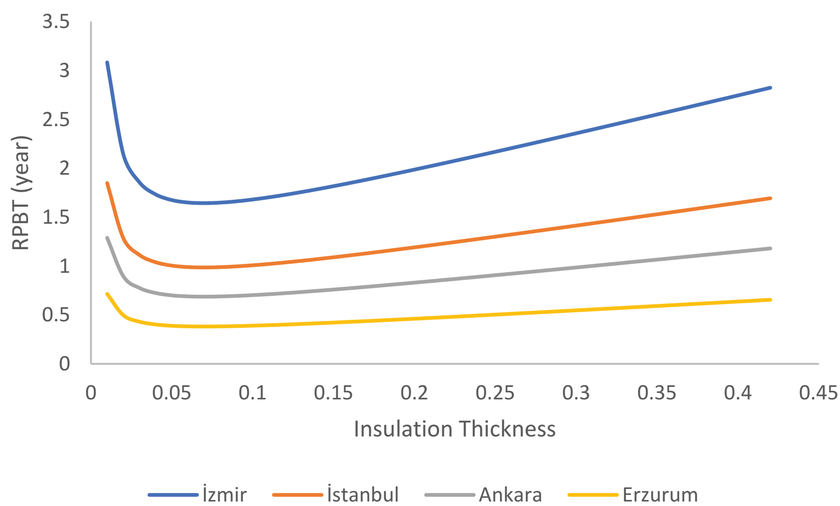

Figure 10. RPBT versus insulation thickness.

For RW, EPBT is found between 2.19 and 0.89 years and it can be concluded that it is the best economic choice. On the other hand, in environmental evaluations, the U values of the insulated wall are equal for the cities in the same climate zone, so the heat losses and therefore the AEI values are equal. AEI for İzmir, İstanbu, Ankara, and Erzurum foun as to be 759 mPt, 1369 mPt, 2212 mPt, and 4072 mPt, respectively. The results obtained for RPBT are presented in Figure 11 and are similar to scenario 1.

As can be seen from the results, RPBT vary from 0.38 to 1.78 years in all climate zones for EPS. RPBT has the highest value for XPS in all climate zones and vary between 0.48 and 2.02 years. When evaluated in terms of RPBT, it is concluded that the most environmentally friendly insulation material is EPS. In scenario 2, EPBT was found to be much higher than RPBT as in scenario 1.

Table 8. MIT and EPBT for different climate regions and insulation materials.

City	HDD	EPS		GW		RW		XPS	
		MIT (m)	EPBT (year)	MIT (m)	EPBT (year)	MIT (m)	EPBT (year)	MIT (m)	EPBT (year)
İzmir	1118	0.035	3.21	0.034	2.22	0.036	2.19	0.028	3.83
İstanbul	1865	0.044	2.25	0.043	1.55	0.045	1.54	0.035	2.67
Ankara	2677	0.057	1.89	0.056	1.30	0.059	1.29	0.045	2.25
Erzurum	4827	0.077	1.31	0.075	0.91	0.079	0.89	0.061	1.56

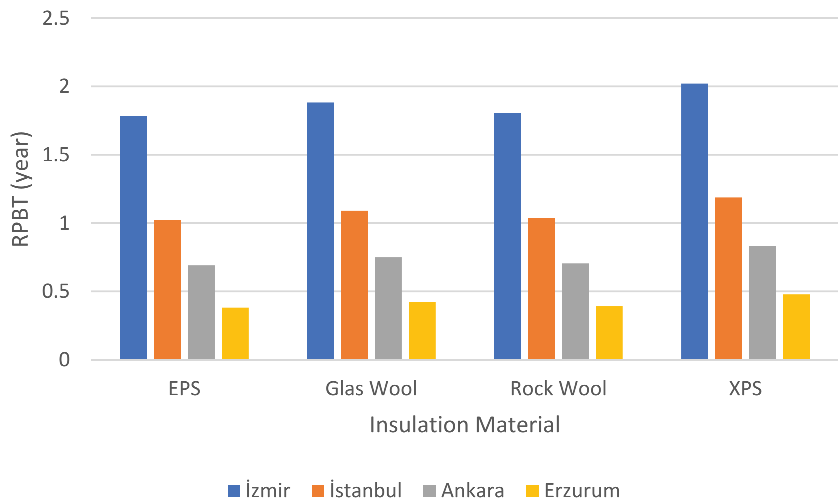

Figure 11. RPBT for MIT.

Scenario 3

In the third and final scenario, economic and environmental evaluations were carried out for equal insulation thicknesses (EIT). Insulation thicknesses were selected by considering MIT values calculated for all climate zones. MIT values meeting the TS 825 standard for each climate zone were calculated in scenario 2 and presented in Table 8. For EPS, GW, RW and XPS, the maximum insulation thickness calculated for different climate zones is selected as EIT. The aim is that the selected EIT value meets the TS 825 standard for all insulation materials. As can be seen from Table 8, the maximum insulation thicknesses that meet the standard for the different climate zones are 0.036 m, 0.045 m, 0.059 m and 0.079 m, respectively. EIT values for climate zones 1, 2, 3 and 4 were selected as 0.036 m, 0.045 m, 0.059 m and 0.079 m, respectively. The application of these insulation thicknesses to each climate zone guarantees the requirements of the TS 825 standard. Economic results of EIT application to different climatic zones are presented in Table 9.

According to economic calculations, when EIT is applied, EPBT has the smallest value for RW as in other scenarios. It is observed that the EPBT value decreases as the HDD increases, and it is concluded that thermal insulation is more important in energy and economic saving for cold climates. On the other hand, environmental results of EIT are given in Table 10 and the results are similar to other scenarios.

When Table 10 is analyzed, it is seen that the RPBT value for all climate zones is the smallest for EPS. However, as HDD increases, RPBT decreases and annual AEI increases. The RPBT value is the smallest for EPS. The insulation material that balances the environmental effects in the longest time was found as XPS. In addition, it has been observed that thermal insulation balances both economic and environmental effects in a shorter period in cold climatic regions. However, as in other scenarios, the fact that RPBT is smaller than EPBT emphasizes the importance of thermal insulation for environmental protection.

Conclusions

This study focused on determining the economic and environmental impact of the most common thermal insulation materials in different climate regions. For this purpose, three realistic scenarios have been determined and the analyses have been carried out through these scenarios. The life cycle assessment (LCA) method was used for environmental analyses. EPS, glass wool (GW), rock wool

Table 9. EIT and EPBT for all climate zone.

City	HDD	EPS		GW		RW		XPS	
		MIT (m)	EPBT (year)	MIT (m)	EPBT (year)	MIT (m)	EPBT (year)	MIT (m)	EPBT (year)
İzmir	1118	0.036	3.26	0.036	2.29	0.036	2.19	0.036	4.54
İstanbul	1865	0.045	2.29	0.045	1.61	0.045	1.54	0.045	3.22
Ankara	2677	0.059	1.92	0.059	1.35	0.059	1.29	0.059	2.73
Erzurum	4827	0.079	1.34	0.079	0.94	0.079	0.89	0.079	1.92

Table 10. Enviromental result for scenario 3

City	HDD	EPS		GW		RW		XPS	
		AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)	AEI (mPt)	RPBT (year)
İzmir	1118	766	1.77	773	1.86	759	1.80	826	1.98
İstanbul	1865	1380	1.02	1391	1.08	1369	1.038	1471	1.19
Ankara	2677	2126	0.69	2140	0.75	2112	0.70	2241	0.86
Erzurum	4827	4093	0.38	4114	0.42	4073	0.39	4268	0.51

(RW) and XPS selected as the thermal insulation material and their effects on four different climate zones in Turkey is assessed. The determined scenarios are; application of optimum insulation thickness (OIT), minimum insulation thickness (MIT) and equal insulation thickness (EIT). The results from all three scenarios are listed below.

RW has the highest value in all climate zones in optimum insulation thickness calculations. The economic payback time (EPBT) for these calculated OITs was found to be the smallest for RW in all scenarios. Environmental impacts determined by using LCA were interpreted by ReCiPe method. In addition, it was observed that the avoide environmental impact (AEI) has the highest value for GW and RW in all scenarios. It is concluded that the most economical option is RW with the lowest EPBT in all scenarios.

Since environmental analyses are performed with ReCiPe, payback times are evaluated as ReCiPe payback time (RPBT). In all scenarios, RPBT was found to have the smallest value for EPS. Compared with other insulation materials, EPS balances its environmental effects in a shorter time. XPS was found to have the highest EPBT and RPBT in all scenarios. In addition, AEI has the lowest value for XPS in all scenarios. Therefore, it was seen that the worst option both economically and environmentally is the use of XPS.

It was found that AEI is high in cold climates and RPBT is low. It has been found that using thermal insulation in cold climates is more important in terms of economic and environmental savings. In all scenarios, RPBT was found to be considerably lower than EPBT, and it was concluded that the use of thermal insulation is more environmentally beneficial. When determining the insulation thicknesses, economic evaluations should be supported by the LCA method to determine environmental impacts. This study provides researchers with an economically and environmentally innovative perspective on the use of thermal insulation materials in real life.

Nomenclature

$A_{year,H}$	Difference of annual total heating cost ($/m^{2}year)
HDD	Heating degree-day
CDD	Cooling degree-day
PWF	Present Worth Factor
Annual energy need for heating (J/m^{2}year)	
LT	Lifetime
U	Total heat transfer coefficient (W/m^{2}K)
AEI	Avoided environmental impact
RPBT	ReCiPe payback time
EPBT	Economic payback time
x_{opt}	Optimum insulation thickness (m)
η	Efficiency of the combustion system
LCC	Life Cycle Cost
LCA	Life Cycle Assessment
C_{fuel}	Cost of the fuel ($/m^3)
$C_{ins.}$	Cost of the insulation ($/m^2)
$C_{t,H}$	Total heating cost of the insulated building($/m^{2}year)
H	Low heat value of the fuel (J/m^3)
i	Interest rate (%)
g	Inflation rate (%)
R	Heat transfer resistance (m^{2}K/W)
T	T Temperature (K)
k	Thermal conductivity of insulation (W/mK)
q	Annual heat loss (W/m^2)
r	Actual interest rate

Notes on contributor

Mehmet Kadri Akyüz completed his Bachelor degree in Airframe and Powerplant Maintenance of Kocaeli University in 2012. He received his Ph. D. degrees in the Graduate School of Sciences at Anadolu University. Dr. Mehmet Kadri Akyüz is Asst. Prof. Dr. at Dicle University.

ORCID

Mehmet Kadri Akyüz http://orcid.org/0000-0003-0229-2943

References

Açıkkalp, E., and S. Y. Kandemir. 2019. A method for determining optimum insulation thickness: Combined economic and environmental method. *Thermal Science and Engineering Progress* 11:249–53. doi:10.1016/j.tsep.2019.04.004.

Açıkkalp, E., and S. Yerel Kandemir. 2018. Optimum insulation thickness of the piping system with combined economic and environmental method. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 40 (23):2876–85. doi:10.1080/15567036.2018.1512683.

Akyüz, M. K., Ö. Altuntaş, and M. Z. Söğüt. 2017. Economic and environmental optimization of an airport terminal building's wall and roof insulation. *Sustainability* 9 (10):1849. doi:10.3390/su9101849.

Al-Homoud, D. M. S. 2005. Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment* 40 (3):353–66. doi:10.1016/j.buildenv.2004.05.013.

Audenaert, A., S. H. De Cleyn, and M. Buyle. 2012. LCA of low-energy flats using the Eco-indicator 99 method: Impact of insulation materials. *Energy and Buildings* 47:68–73. doi:10.1016/j.enbuild.2011.11.028.

Axaopoulos, I., P. Axaopoulos, J. Gelegenis, and E. D. Fylladitakis. 2019. Optimum external wall insulation thickness considering the annual CO 2 emissions. *Journal of Building Physics* 42 (4):527–44. doi:10.1177/1744259118774711.

Başoğul, Y., C. Demircan, and A. Keçebaş. 2016. Determination of optimum insulation thickness for environmental impact reduction of pipe insulation. *Applied Thermal Engineering* 101:121–30. doi:10.1016/j.applthermaleng.2016.03.010.

Bolattürk, A. 2006. Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. *Applied Thermal Engineering* 26 (11–12):1301–09. doi:10.1016/j.applthermaleng.2005.10.019.

Bolattürk, A. 2008. Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Building and Environment* 43 (6):1055–64. doi:10.1016/j.buildenv.2007.02.014.

Braulio-Gonzalo, M., and M. D. Bovea. 2017. Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation. *Energy and Buildings* 150:527–45. doi:10.1016/j.enbuild.2017.06.005.

BULUT, H., O. BÜYÜKALACA, and T. Yılmaz (2007). Türkiye için isitma ve soğutma derece-gün bölgeleri. In *16. National heat science and technique congress*, Kayseri-Türkiye.

Çomaklı, K., and B. Yüksel. 2004. Environmental impact of thermal insulation thickness in buildings. *Applied Thermal Engineering* 24 (5–6):933–40. doi:10.1016/j.applthermaleng.2003.10.020.

Daouas, N. 2011. A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads. *Applied Energy* 88 (1):156–64. doi:10.1016/j.apenergy.2010.07.030.

Daşdemir, A., M. Ertürk, A. Keçebaş, and C. Demircan. 2017a. Effects of air gap on insulation thickness and life cycle costs for different pipe diameters in pipeline. *Energy* 122:492–504. doi:10.1016/j.energy.2017.01.125.

Daşdemir, A., T. Ural, M. Ertürk, and A. Keçebaş. 2017b. Optimal economic thickness of pipe insulation considering different pipe materials for HVAC pipe applications. *Applied Thermal Engineering* 121:242–54. doi:10.1016/j.applthermaleng.2017.04.001.

Dombaycı, Ö. A. 2007. The environmental impact of optimum insulation thickness for external walls of buildings. *Building and Environment* 42 (11):3855–59. doi:10.1016/j.buildenv.2006.10.054.

Dombayci, Ö. A., Ö. Atalay, Ş. G. Acar, E. Y. Ulu, and H. K. Ozturk. 2017. Thermoeconomic method for determination of optimum insulation thickness of external walls for the houses: Case study for Turkey. *Sustainable Energy Technologies and Assessments* 22:1–8. doi:10.1016/j.seta.2017.05.005.

Dylewski, D. 2019. Optimal Thermal Insulation Thicknesses of External Walls Based on Economic and Ecological Heating Cost. *Energies* 12 (18):3415. doi:10.3390/en12183415.

Ekici, B. B., A. A. Gulten, and U. T. Aksoy. 2012. A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey. *Applied Energy* 92:211–17. doi:10.1016/j.apenergy.2011.10.008.

EPSA (2020). https://epsa.com.tr/resimler/2/dokumanlar/yal%C4%B1t%C4%B1m_rehberi.pdf

Ertürk, M. 2016. Optimum insulation thicknesses of pipes with respect to different insulation materials, fuels and climate zones in Turkey. *Energy* 113:991–1003. doi:10.1016/j.energy.2016.07.115.
Ertürk, M. 2017. A new model for exergetic optimum insulation thickness. *International Journal of Exergy* 22 (4):309–30. doi:10.1504/IJEX.2017.083945.
ERTÜRK, M. 2016. BİNA DIŞ DUVARLARINDA FARKLI YALITIM MALZEMESİ VE HAVA BOŞLUĞU KULANIMININ, BİRİM ALANDAKİ ENERJİ TASARRUFU VE KİŞİ BAŞI EMİSYON HESAPLAMALARINDA YENİ BİR YAKLAŞIM. *Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi* 31 (2):2. doi:10.17341/gummfd.11046.
Evin, D., and A. Ucar. 2019. Energy impact and eco-efficiency of the envelope insulation in residential buildings in Turkey. *Applied Thermal Engineering* 154:573–84. doi:10.1016/j.applthermaleng.2019.03.102.
Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. 2009. "ReCiPe 2008." A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 1:1–126. http://www.lcia-recipe.net
Gopalakrishnan, B., K. Ramamoorthy, E. Crowe, S. Chaudhari, and H. Latif. 2014. A structured approach for facilitating the implementation of ISO 50001 standard in the manufacturing sector. *Sustainable Energy Technologies and Assessments* 7:154–65. doi:10.1016/j.seta.2014.04.006.
Gülten, A. 2020. Determination of optimum insulation thickness using the entransy based thermoeconomic and environmental analysis: A case study for Turkey. Energy Sources. *Part A: Recovery, Utilization, and Environmental Effects* 42 (2):219–32.
Huang, J., H. Lv, W. Feng, P. Qu, and Z. Huang. 2020. Determination of economical thermal insulation thickness for a building wall with two parallel structures. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 42 (4):399–409. doi:10.1080/15567036.2019.1587086.
International Organization for Standardization. Environmental Management—Life Cycle Assessment—Principles and Framework; International Standard ISO 14040; ISO: Geneva, Switzerland, 2006.
Kallioğlu, M. A., U. Ercan, A. S. Avcı, C. Fidan, and H. Karakaya. 2020. Empirical modeling between degree days and optimum insulation thickness for external wall. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 42 (11):1314–34. doi:10.1080/15567036.2019.1651797.
Kaynakli, O. 2008. A study on residential heating energy requirement and optimum insulation thickness. *Renewable Energy* 33 (6):1164–72. doi:10.1016/j.renene.2007.07.001.
KAYNAKLI, Ö., and F. KAYNAKLI. 2016. Determination Of Optimum Thermal Insulation Thicknesses For External Walls Considering The Heating, Cooling And Annual Energy Requirements. *Uludağ University Journal of the Faculty of Engineering* 21 (1):229–42. doi:10.17482/uujfe.27323.
Küçüktopcu, E., and B. Cemek. 2018. A study on environmental impact of insulation thickness of poultry building walls. *Energy* 150:583–90. doi:10.1016/j.energy.2018.02.153.
Kurekci, N. A. 2016. Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers. *Energy and Buildings* 118:197–213. doi:10.1016/j.enbuild.2016.03.004.
Mahlia, T. M. I., and A. Iqbal. 2010. Cost benefits analysis and emission reductions of optimum thickness and air gaps for selected insulation materials for building walls in Maldives. *Energy* 35 (5):2242–50. doi:10.1016/j.energy.2010.02.011.
National Energy Conservation Center. 2006. *The Principles of Energy Management in Industry,* Ankara: National Energy Conservation Center.
Ozel, M. 2011. Thermal performance and optimum insulation thickness of building walls with different structure materials. *Applied Thermal Engineering* 31 (17–18):3854–63. doi:10.1016/j.applthermaleng.2011.07.033.
Ozel, M. 2012. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. *Energy and Buildings* 49:552–59. doi:10.1016/j.enbuild.2012.03.002.
Ramin, H., P. Hanafizadeh, T. Ehterami, and M. A. AkhavanBehabadi. 2019. Life cycle-based multi-objective optimization of wall structures in climate of Tehran. *Advances in Building Energy Research* 13 (1):18–31. doi:10.1080/17512549.2017.1344137.
Rosti, B., A. Omidvar, and N. Monghasemi. 2020. Optimal insulation thickness of common classic and modern exterior walls in different climate zones of Iran. *Journal of Building Engineering* 27:100954. doi:10.1016/j.jobe.2019.100954.
Tingley, D. D., A. Hathway, and B. Davison. 2015. An environmental impact comparison of external wall insulation types. *Building and Environment* 85:182–89. doi:10.1016/j.buildenv.2014.11.021.
TS 825, Binalarda Isı Yalıtım Kuralları. 2008. Ankara:Turkish Standards Institute.
Ucar, A., and F. Balo. 2010. Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls. *Renewable Energy* 35 (1):88–94. doi:10.1016/j.renene.2009.07.009.
Ustaoglu, A., K. Kurtoglu, O. Gencel, and F. Kocyigit. 2020. Impact of a low thermal conductive lightweight concrete in building: Energy and fuel performance evaluation for different climate region. *Journal of Environmental Management* 268:110732. doi:10.1016/j.jenvman.2020.110732.
Valančius, K., T. Vilutienė, and A. Rogoža. 2018. Analysis of the payback of primary energy and CO_2 emissions in relation to the increase of thermal resistance of a building. *Energy and Buildings* 179:39–48. doi:10.1016/j.enbuild.2018.08.037.

World Wildlife Fund. 2 °C is Too Much. Available online: http://www.worldwildlife.org/climate/Publications/ (accessed on 30 May 2020)

Yin, H., H. Guo, Z. Lin, W. Xiao, and Z. Duan. 2018. Determining optimum insulation thickness by thermoeconomic analysis for a pipeline system in a subway central cooling system. *Applied Thermal Engineering* 136:454–61. doi:10.1016/j.applthermaleng.2018.02.078.

Ziapour, B. M., M. Rahimi, and M. Yousefi. 2020. Thermoeconomic analysis for determining optimal insulation thickness for new composite prefabricated wall block as an external wall member in buildings. *Journal of Building Engineering* 31:101354. doi:10.1016/j.jobe.2020.101354.