

Optimum Insulation Thickness for the Exterior Walls of Buildings in Turkey Based on Different Materials, Energy Sources and Climate Regions

Cenker Aktemur*[‡], Uğur Atikol*

* Department of Mechanical Engineering, Eastern Mediterranean University, via Mersin 10, Famagusta, N.Cyprus

(cenkeraktemur41@hotmail.com, ugur.atikol@emu.edu.tr)

[‡]Corresponding Author; Cenker Aktemur, Department of Mechanical Engineering, Eastern Mediterranean University, via Mersin 10, Famagusta, N.Cyprus, Tel: +90 538 266 0367

cenkeraktemur_41@hotmail.com

Received: 20.04.2017 Accepted: 21.06.2017

Abstract- Thermal insulation improves the strength and longevity of buildings by reducing energy consumption, and as a related result, improved energy use. The selection of insulation material is governed by important parameters, including the average outdoor air temperature, the thermal conductivity of the buildings and the cost of the insulation material. Increases in the thickness of the insulation material will gradually decrease the energy consumption for heating; however, the insulation thickness has an optimum value that minimises the total investment cost, and determination of this optimum value is critical for economic analysis. In this paper, a life-cycle cost analysis is presented to show the optimum insulation thickness, energy savings over a lifetime of 15 years and payback periods for six different fuels and insulation materials for four cities in Turkey selected from climate regions identified by the Turkish Thermal Insulation Standard (TS 825). Muğla (1st region), Kocaeli (2nd region), Ankara (3rd region) and Ardahan (4th region) were selected for analysis of a sandwich-type wall constructed from the following six insulation materials: extruded polystyrene, expanded polystyrene, glass wool, rock wool, polyisocyanurate and polyurethane. The calculations were also made on the basis of six different fuels, such as motorin, natural gas, propane (LPG), electricity, coal (imported), and fuel-oil No. 4. As a consequence, results demonstrated that the optimum insulation thickness varies between 2.8 cm and 45.1 cm, with energy savings between 16.4 $\text{₺}/\text{m}^2$ and 479 $\text{₺}/\text{m}^2$, and payback periods fluctuating between 0.078 and 0.860 years, depending on the city, the insulation material, and the cost of fuel.

Keywords Energy saving, optimum insulation thickness, payback period, climate region, life-cycle cost.

1. Introduction

Energy is a basic resource needed in all areas of human life, and it is consequently a significant component that influences economic and social development. As an energy source, fossil fuels (fuel oil, natural gas, coal, etc.) are preserving their place as primary energy resources and continue to meet a substantial portion of the world's energy requirements [1].

Statistics presented by the Turkish Ministry of Energy and Natural Resources [2] have indicated that Turkey has the potential for significant energy savings of 30% in the building sector, 20% in the industry sector and 15% in the transportation sector. In the building sector, most of the energy

is consumed as heating energy, and one of the most important methods for reducing heating energy consumption is the use of insulation. The application of thermal insulation to buildings reduces the energy requirements for heating and cooling, thereby conserving fuel.

Many countries have developed new building codes and standards since the 1970s, and these standards have undergone constant renewal due to ever-evolving insulation technology. In Turkey, the TS 825 standard, "Thermal Insulation Rules in Buildings", aims to save energy by reducing the amount of energy consumed in the heating of buildings, as this represents a significant share of the energy consumption in the country.

A substantial 25% of this energy is consumed by the residential sector, and a recent study indicates a savings potential in this sector of between 25 and 45%. In the residential sector, the amount of energy used for heating is twice that used for other sources of consumption (cooking, etc.). Notably, the use of insulation material in the residential sector not only saves energy, but it also reduces the harmful emissions caused by the burning of fossil fuels.

Insulation thickness in buildings is a vital parameter in the design of exterior walls [3], as too low an insulation thickness allows heat to pass from the inside to the outside or from the outside to the inside, resulting in a negative effect on thermal comfort and energy savings. Increasing the insulation thickness in the walls reduces heat loss and the subsequent heating load and fuel cost; however, an increase in insulation thickness results in an increase in insulation investment costs.

The total cost, which is the sum of the costs of the fuel consumption of the building and the insulation, decreases to a certain value and then increases beyond that level [4]. For this reason, it is important that in the optimization of insulation thickness the environment in which the building is located, the type of fuel and the choice of insulation material are all taken into account.

2. A review on the Determination of Optimum Insulation Thickness

The previous studies on the efficient use of energy reported in the literature were generally aimed at determining the optimum insulation thickness and a simple payback period. For example, Dombaycı et al. [5] calculated the optimum insulation thickness for Denizli based on the use of two different insulants and five different fuel types. Similarly, Çomaklı and Yüksel [6] calculated the optimum insulation thickness for the three coldest cities in the fourth DD region of Turkey in accordance with the TS Standard no 825. Bolattürk [7] carried out a comparative analysis to determine the optimum insulation thickness on the outside walls of buildings, whereas Kaynaklı [8] determined the optimum insulation thicknesses for different types of fuel, such as natural gas, coal, fuel oil, propane (LPG) and electricity in a prototype building in Bursa. Kaynaklı and Yamankaradeniz [9] determined the annual fuel costs for the use of natural gas as a fuel with different insulation thicknesses for two different wall types in various climate regions in Turkey.

Gölcü et al. [10] used a life-cycle cost analysis method to calculate the optimum external wall insulation thicknesses, the energy savings and simple payback periods for heating of buildings in the Denizli province of Turkey, based on the use of different energy sources, such as imported coal and fuel oil. Uçar and Balo [11] used a degree-day method and a life-cycle cost analysis method to calculate the optimum insulation thicknesses of the outer walls, the energy savings and simple payback periods for four cities located in four different regions of Turkey (Mersin, Elazığ, Şanlıurfa and Bitlis), five different energy types (coal, natural gas, fuel-oil, LPG and electricity) and three different insulation materials (expanded polystyrene, extruded polystyrene, and rock wool).

Kon and Yüksel [12] conducted a complex three-part study (focused on business and service bureaus, training halls and textile production) in Balıkesir province to determine the optimum insulation thickness and the achievable savings for the exterior walls of buildings. Ozkan and Onan [13], using a new approach, investigated the effects of altering the glazing area percentage of windows, which ranged from 10 to 50%, on the optimum insulation thickness for four regions in Turkey.

Mahlia et al. [14], who analysed the relationship between the thickness of the insulation materials selected for the building walls and the thermal conductivity, found a polynomial function that showed a non-linear relationship between the thermal conductivity and the optimum thickness of the insulation material. This particular study was designed for Malaysia, which is a hot and humid country and does not typically undergo major changes in atmospheric temperature. Kürekçi [15] carried out a similar study to determine the optimum insulation thicknesses required in Turkey's 81 provincial centres, with calculations made based on four different fuels (natural gas, coal, fuel-oil and propane (LPG)) and 5 different insulation materials (extruded polystyrene, expanded polystyrene, glass wool, rock wool and polyurethane).

Ulaş [16] investigated four different heat insulation regions and three different types of fuel for the amount of carbon dioxide released into the atmosphere as a result of the combustion of fuel consumed. The optimum insulation thickness was compared with the insulation thicknesses determined according to TS 825 calculation method. Three different insulation materials (Expanded Polystyrene, Extruded Polystyrene and Glass Wool) and three different fuels (Lignite and Mineral Coal, Natural Gas and Fuel-Oil) were used. The lowest carbon dioxide emissions were found when natural gas is used for Region 1, while the highest carbon dioxide emissions were detected when lignite and coal are used in Region 4.

Hasan [17] calculated the optimum insulation thicknesses for four types of fuel and two insulating materials for Palestine by using the degree-of-day and life cost analysis approach. As a result, he pointed out that the period of payback period for stone wool insulation is between 1.3-2.3 years, for polystyrene insulation is 1-1.7 years. Özel and Pıhtılı [18] calculated the optimum thickness of the insulation applied to the exterior walls for Adana, Elazığ, Erzurum, İstanbul and İzmir considering the heating and cooling degree-day values.

Gürel and Daşdemir [19] calculated the optimum insulation thicknesses and energy savings for heating and cooling loads in Aydın, Edirne, Malatya and Sivas selected from different climatic regions. XPS and EPS were chosen as insulation material in the outer wall. As fuel, natural gas is used for heating and electricity is used for cooling. The results demonstrated that the optimum thickness varies between 0.036 and 0.1 m depending on the insulation material and province selected, the energy savings are between 12.08 ₺ / m² and 58.28 ₺ / m², and payback period vary between 1.5 and 2.52 years.

3. Mathematical Method

3.1 Heating degree-day approach

The base temperature is the temperature at which the generated inner temperature will compensate for the heat loss from the outside. Consequently, the assessment of HDD values depends upon numerous elements including various structural features such as the category of walling, the level of insulation, the presence of air leakage, accessibility of incident sunlight, and so on, as well as the specific climatic circumstances and the personal inclinations of the people using the building. Thus, the number of degree-days is calculated according to the equation (1).

$$HDD = \sum_{j=1}^N (T_b - T_{o,j}) \text{ if } (T_o < T_b) \tag{1}$$

$$HDD = 0 \text{ if } (T_o > T_b) \tag{2}$$

where T_b is base temperature, $T_{o,j}$ is daily mean outside air temperature recorded at a meteorology station, N is the number of days provided that $T_o < T_b$ in a heating season. Therefore, heating degree-day values are calculated as $T_o < T_b$. As it can be seen from equation (2), HDD values only take on positive values.

Turkey is divided into four climate regions for each province according to heating degree-day numbers identified by TS 825 on the map indicated in Fig. 1 below. Region 1 represents the least energy requirement for heating and Region 4 represents the region where energy is needed the most. In this study, the base temperature for heating purpose is assumed as 17.5 °C to calculate heating degree-day values. In the study, insulation analysis was performed for sandwich-type insulated wall-type insulated wall structure using the HDD values of Muğla, Kocaeli, Ankara and Ardahan, which are determined from General of State Meteorology Affairs. Properties and number of heating degree-days of the cities referred to in this study are given in Table 1.

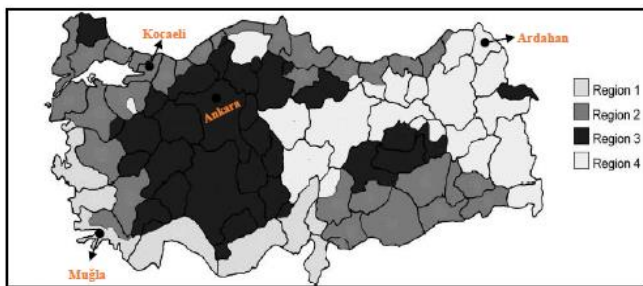


Fig. 1. HDD regions identified by TS 825 in Turkey [21].

The amount of energy required to heat a building, relative to a specific base or reference temperature, is evaluated by the heating degree day (HDD) method.

Table 1. Climate regions and certain data for selected cities

Region	City	Altitude (m)	Longitude (°)	Latitude (°)	HDD (°C-day)
1 st	Muğla	661	28.36 E	37.22 N	1560
2 nd	Kocaeli	465	29.88 E	40.85 N	1762
3 rd	Ankara	896	32.86 E	39.93 N	2425
4 th	Ardahan	1915	42.78 E	41.13 N	4687

3.2 The structure of the external walls

Heat is broadly lost to the building via the exterior walls, windows, floors and ceilings and by ingress of air from the exterior. The majority of heat is lost to buildings through exterior walls constructed of conventional building materials such as perforated bricks, concrete and wood. Hence, the present work took into consideration only heat loss via the external walls in order to evaluate the optimum insulation thickness [22]. The thermal insulation on the outer walls is applied in three ways; internally externally or sandwiched between two walls. Insulation applications are usually carried out by a wall model with a composite structure called a sandwich-type wall. The structure of sandwich-type wall makes up of 3 cm internal plaster, 22 cm horizontal hollow brick, insulation material, 22 cm horizontal hollow brick, and 4 cm external plaster. This structure is used in calculations for analyzed cities. In this case study, a sandwich-type insulated wall depicted in Fig. 2 is examined considering six different insulation materials, namely Extruded polystyrene (XPS), Expanded polystyrene (EPS), Glass wool (GW), Rock wool (RW), Polyisocyanurate (PIR), and Polyurethane (PUR) are pointed out in Table 2 with their thermal conductivities and costs.

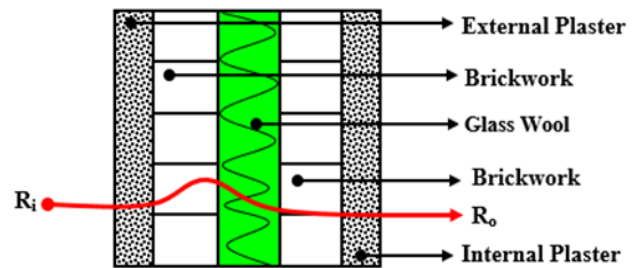


Fig. 2. A cross-view of the sandwich-type insulated wall structure.

Table 2. Parameters of the insulation wall [23]

Insulation material	$k_{ins.}$ (W/mK)	$C_{ins.}$ (₺/m ³)
Extruded polystyrene (XPS)	0.031	300
Expanded polystyrene (EPS)	0.039	200
Glass wool (GW)	0.040	100
Rock wool (RW)	0.040	145
Polyurethane (PUR)	0.024	450
Polyisocyanurate (PIR)	0.023	400

3.3 Heating load for external walls

The transfer of heat into and out of the building, via the walls, involves the processes of radiation, conduction and convection. Solar radiation can be directly absorbed at the outer surface of the walls to produce heat which is then transferred through the bulk of the wall. Further heat can be transferred by convective movements of the atmosphere in contact with both exterior and interior wall surfaces. The amount of heat lost per unit surface area of external wall is obtained from the equation (3) [24].

$$Q = U \times (T_i - T_o) \tag{3}$$

where U is the total heat transfer coefficient of the wall, T_i is the indoor air temperature and T_o is the outdoor air temperature.

The overall heat transfer coefficient of the outside wall (U) that includes a layer of insulation is given by equation (4) [23].

$$U = \frac{1}{R_i + R_w + \frac{x_{ins}}{k_{ins}} + R_o} \tag{4}$$

where R_i and R_o are the heat transfer coefficients of the inside and outside environment respectively, R_w is the thermal resistance of the wall without insulation, x and k are the thickness and thermal conductivity coefficient of the insulation material, respectively. The values of $R_i = 0.13$ W/m²K and $R_o = 0.04$ m²K/W are used for heat transfer coefficients on the inside and outside of the building.

Total resistance of the non-insulated wall layer $R_{w,t}$ is determined by help of the equation (5) below and a brief summary of physical and thermal properties of building construction materials is presented in Table 3 below.

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

Table 3. Physical and thermal properties of building construction materials of the external wall

Wall structure	Thickness (m)	k (W/mK)	R (m ² K/W)
Internal plaster	0.03	0.87	0.034
Hollow brick	0.22	0.84	0.262
Insulation	See Table 2 for further information		
Hollow brick	0.22	0.84	0.262
External plaster	0.04	0.87	0.046
R_i			0.13
R_o			0.04
$R_{w,t}$			0.774

then, total heat transfer coefficient U is expressed as in the following equation (6).

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

Using the HDD concept, annual heat loss for a unit surface area can be found through the following equation (7) [25].

$$q_{year} = 86400 \times HDD \times U \tag{7}$$

The annual amount of energy required for heating by the heat loss from the unit surface of the outer wall is obtained by

dividing the annual heat loss by the efficiency (η) of the combustion system.

$$E = \frac{q_{year}}{\eta} \tag{8}$$

Equation (7) is substituted into equation (8), then the amount of annual heating energy requirement can be written the following equation (9) [11].

$$E_H = \frac{86400 \times HDD}{\left(R_{w,t} + \frac{x_{ins.}}{k_{ins.}}\right) \times \eta} \tag{9}$$

LHV, efficiencies and prices of various heating systems are indicated in Table 4 below.

Table 4. Fuel costs (C_f) and lower heating values (LHV) of heating systems and efficiencies of fuel (η) [26]

Fuel type	LHV	η (%)	Fuel cost (cf)
Coal (imported)	29.295x10 ⁶ J/kg	66	0.94 ₺/kg
Natural gas	34.526x10 ⁶ J/m ³	90	1.08 ₺/m ³
Propane (LPG)	46.453x10 ⁶ J/kg	88	6.8 ₺/kg
Fuel-oil no:4	40.594x10 ⁶ J/kg	80	2.77 ₺/kg
Motorin	42.636x10 ⁶ J/kg	83	5.49 ₺/kg
Electricity	3.599x10 ⁶ J/kWh	99	0.42 ₺/kWh

3.4 Annual energy cost and calculation of the optimum insulation thickness

The annual fuel cost is obtained by multiplying the amount of fuel to be used per year by the unit price of the fuel. The annual cost of fuel for unit surface area, which is the unit price of the fuel, can be calculated the following equation (11).

$$C_H = m_f \cdot C_f \quad (11)$$

Equation (11) can be rewritten as equation (12):

$$C_H = \frac{86400 \times HDD \times C_f \times PWF}{\left(R_{w,t} + \frac{x_{ins.}}{k_{ins.}}\right) \times \eta \times LHV} \quad (12)$$

where PWF is present value and C_f is the fuel cost in ₺/kg, ₺/m³ or ₺/kWh depending on the fuel type, which can be taken from Table 4 above.

Expected lifetime (LT) and the PWF must be evaluated together while calculating the total heating cost. The PWF value depends on the actual interest rate (r) and time. The interest rate adjusted for inflation rate (i^*) is given by the following equations (13) and (14) [21, 27].

$$i^* = \frac{i - g}{i + g}, \quad \text{for } (i > g) \quad (13)$$

$$i^* = \frac{i + g}{i - g}, \quad \text{for } (i < g) \quad (14)$$

where g is the inflation rate. In this case, PWF is determined by aid of the equation (15):

$$PWF = \frac{(1 + i^*)^{LT} - 1}{i^* (1 + i^*)^{LT}} \quad (15)$$

where LT is the expected lifetime, which is taken to be 15 years. If $i=g$, then

$$PWF = \frac{LT}{1 + i} \quad (16)$$

Lifetime, interest and inflation rate values employed in calculating the PWF are summarized in Table 5.

Table 5. Parameters used in the calculations

Interest rate (i)	9 %
Inflation rate (g)	8.53 %
Lifetime (LT)	15-years
Present worth factor (PWF)	8.58

Since the cost of insulation will increase in proportion to the unit thickness of the insulation material, the cost of insulation is given by the following equation (17).

$$C_{ins} = C_y \cdot x_{ins} \quad (17)$$

The total cost of heating the insulated building in Turkish Lira is given by the equation (18) below.

$$C_{t,H} = C_f \cdot PWF + C_{t,ins} \quad (18)$$

Equation (12) is substituted into equation (18) and then the total heating cost can be written as indicated in the following equation (19).

$$C_{t,H} = \frac{86400 \times HDD \times C_f \times PWF}{\left(R_{w,t} + \frac{x_{ins.}}{k_{ins.}}\right) \times \eta \times LHV} + C_y \cdot x_{ins} \quad (19)$$

Optimum insulation thickness minimizing the total heating cost is calculated with the equation (20) below [6, 7, 10, 11, 27].

$$X_{opt,H} = 293.94 \times \left(\frac{HDD \times C_f \times PWF \times k_{ins}}{LHV \times C_y \times \eta} \right)^{\frac{1}{2}} - k_{ins} \times R_{w,t} \quad (20)$$

As shown by equation (20) above, optimum insulation thickness varies depending on the properties of the wall, insulation material, unit price of fuel, PWF, inflation rate, the fuel type, and the total number of heating degrees-days.

3.5 Simple payback period

In situations where interest rates vary, it is important to consider the period of payback as it is not possible to estimate the long-term interest rate. Interest rates can be estimated to be sensitive for up to 1-2 years. The simple payback period (SPP) is not a method of measuring the economic viability of an investment, but is a method that calculates how many years' incomes will meet expenses. The C_H in the formula represents pre-insulation heating energy costs. Annual total net saving amount for buildings heated is calculated with equation (21) and SPP_H is calculated with equation (22) [21].

$$A_{year,H} = C_H - C_{t,H} \quad (21)$$

$$SPP_H = \frac{C_{ins.}}{A_{year,H}} \quad (22)$$

SPP_H is only meaningful for short periods (typically less than one year) as it does not take into account the time value of money.

4. Results and Discussions

As a widely-used approach for facilitating normalization in the context of energy consumption, the present research employed the HDD technique to determine the optimum insulation thickness for application to the outer walls. Drawing on a sample of four Turkish cities, each situated in a contrasting area of the country characterized by varying climatic conditions, optimum insulation thickness was identified for six categories of fuel and insulation resources. In turn, it was possible for the researcher to determine optimum insulation thickness, energy consumption, and payback period after the insulation materials had been applied to the exterior walls.

Ultimately, insulation and fuel expenses were identified as the central dimensions which impact the overall yearly expense associated with insulating a building, and it should be noted that the loss or gain of thermal energy is lowered for a building that has been insulated. Furthermore, the degree to which the applied insulation is thick is directly and proportionally correlated with the level of heat loss or gain, thereby meaning that overall expense falls in conjunction with a decrease in the thermal energy requirement to heat the unit area. Nevertheless, the fact should not be overlooked that the expense required to apply insulation increases at an almost exponential rate when the thickness of the insulation rises. Subsequently, owing to the elevated insulation expense, overall expense increases significantly once a notable threshold – namely, the optimum insulation thickness figure – has been exceeded. If insulation can be applied at the optimum insulation thickness, the overall cost is minimized to the greatest possible degree. The fuel cost, the insulation cost and the total heating cost relationship with the change of the thickness of the insulation material for selected cities over the 15-year lifetime are shown in the following Fig. 3. As can be seen from Fig. 3, the insulation cost increases linearly while the fuel cost decreases with increasing insulation thickness.

The total cost shows a similar tendency to change depending on the insulation thickness, but the total cost for Ardahan is much higher than for the other cities for all six insulation materials. The total cost of the sum of the cost of fuel and insulation is reduced by a certain value and then increased after this level. In the equation given in (19), the annual heating cost for the non-insulated wall was calculated by taking $x = 0$. Then, in the same equation, total insulation cost was found for the insulated wall by determining the insulation thickness. The heating cost obtained for non-insulated wall of the building is subtracted from the heating cost obtained for the insulated building, and then the annual saving is calculated.

Energy savings are directly proportional to the climatic conditions of the region, and the energy savings for sandwich-type wall. Fig. 4 shows the comparison of energy savings of all insulation materials examined for four cities in case heating requirement is only supplied by Propane (LPG) as an energy source. The optimum insulation thickness is achieved when the savings start to drop as the thickness of insulation material is increased.

The energy saving value becomes maximum at the optimum insulation thickness point. For example, in Ankara, the energy savings is nearly 198.3 ₺/m² at a certain thickness for Polyurethane (PUR), whilst the energy savings for Polyisocyanurate (PIR) is about 288.5 ₺/m². The energy savings in Kocaeli reaches maximum value which is roughly 192 ₺/m² for Polyurethane (PUR) at the optimum insulation thickness. As can be seen from Fig. 4, annual savings for EPS remain the same after a certain insulation thickness (about 0.18 m).

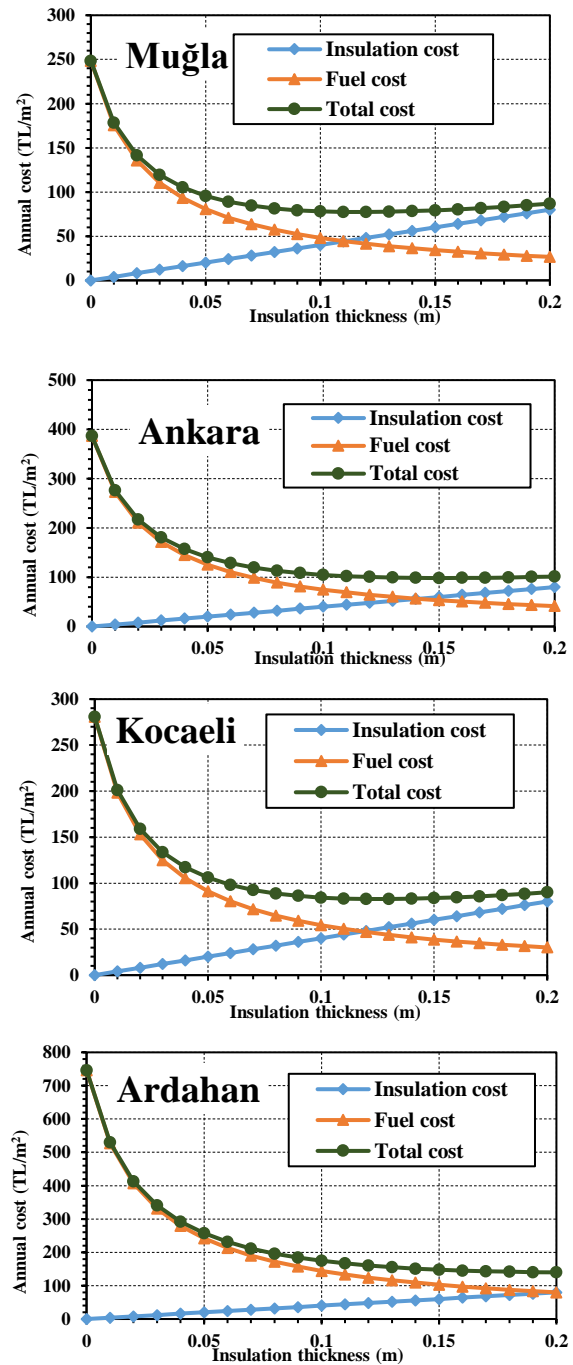


Fig. 3. Effect of insulation thickness of Polyurethane (PUR) on the total cost in case heating energy requirement is only using Propane (LPG) in selected cities.

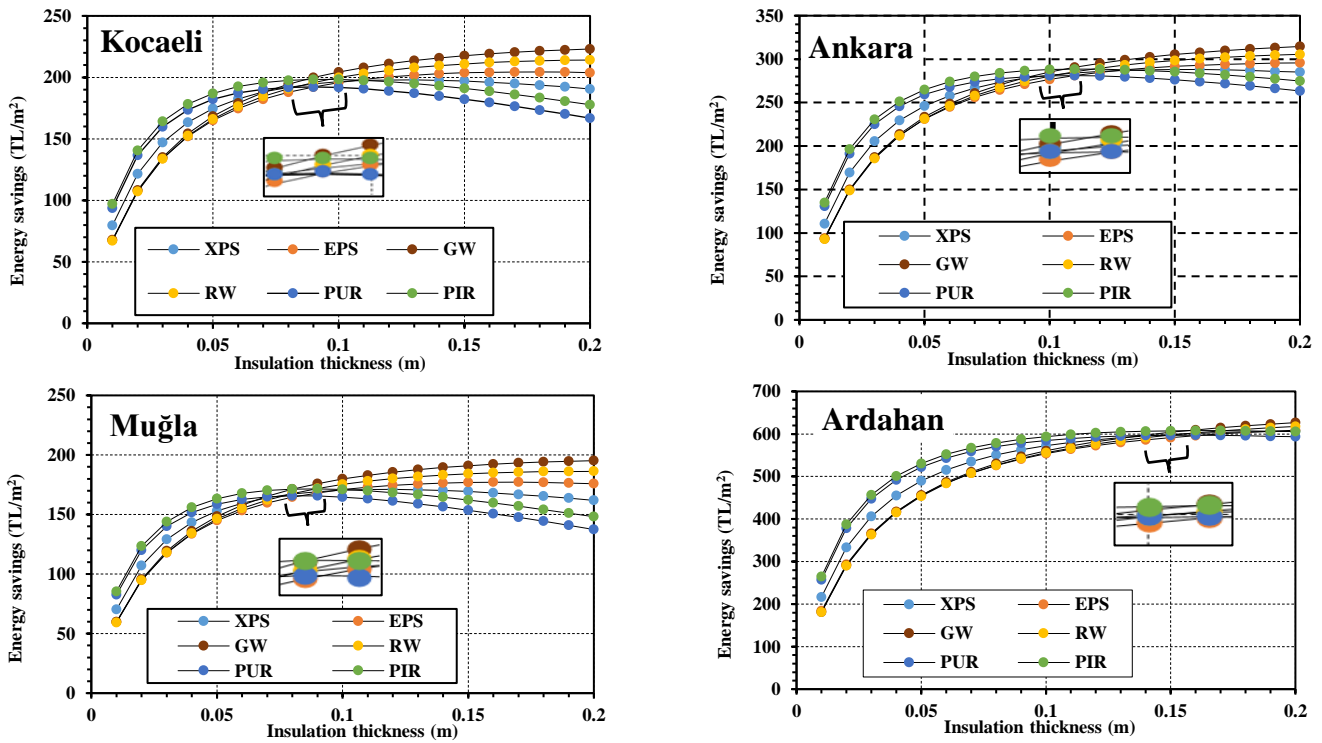


Fig. 4. Comparison of energy savings of all insulation materials for four cities in case heating requirement is only supplied by Propane (LPG) in selected cities.

Optimum insulation thickness is the value that makes the total cost minimum. The optimum insulation thicknesses, energy savings and payback periods for various fuels were calculated for Muğla, Kocaeli, Ankara, and Ardahan selected from four heating degree-day regions, which are given in Tables 6-9. To summarize Tables 6-9, while energy savings are obtained with 117.7 ₺/m² for RW at the optimum insulation thickness (about 24.8 cm) in case of using Propane (LPG) as an energy source in Muğla, energy savings are achieved with 479 ₺/m² for RW at the optimum insulation thickness (about 45 cm) in case of using propane (LPG) as an energy source in Ardahan. Whereas it is determined that the highest energy savings were achieved using Propane (LPG) for all insulation material types, it is detected that the lowest energy savings were attained using natural gas for all insulation material types. Fig. 5 presents optimum insulation

thickness versus various heating systems for different insulation materials in cities of Muğla, Kocaeli, Ankara, and Ardahan.

The variation at the optimum insulation thicknesses determined by HDDs for natural gas and various insulation materials is shown in Fig. 6 below. As the number of HDDs increases, the optimum insulation thickness enhances in parallel and it is clearly seen that glass wool (GW) is significantly higher than the rest insulation materials due to its high thermal conductivity. It is also seen that the optimum insulation thickness is higher in the cases where the HDD value is large, that is, in colder climates. When using EPS as an insulation material, the optimum insulation thickness decreases compared to RW and GW.

Table 6. Optimum insulation thickness, energy savings and payback periods of Muğla for various fuels

Fuel type	Muğla					
	Insulation material type					
	XPS	EPS	PUR	PIR	RW	GW
<i>Optimum insulation thickness (m)</i>						
Natural gas	0,041	0,060	0,028	0,031	0,097	0,076
LPG (propan)	0,118	0,165	0,083	0,088	0,248	0,201
Motorin	0,113	0,158	0,080	0,084	0,238	0,193
Electricity	0,096	0,134	0,067	0,071	0,204	0,164
Fuel-oil no.4	0,078	0,110	0,055	0,058	0,169	0,135
Coal (imported)	0,053	0,076	0,037	0,040	0,120	0,095
<i>Energy savings (TL/m²)</i>						
Natural gas	16,828	17,391	16,399	16,861	19,774	18,426
LPG (propan)	106,470	109,070	104,161	106,633	117,731	113,151
Motorin	98,302	100,774	96,111	98,457	109,039	104,663
Electricity	71,591	73,600	69,829	71,717	80,434	76,795
Fuel-oil no.4	49,007	50,544	47,679	49,102	55,926	53,035
Coal (imported)	25,095	25,973	24,375	25,148	29,325	27,479
<i>Payback period (years)</i>						
Natural gas	0,810	0,748	0,860	0,806	0,770	0,446
LPG (propan)	0,357	0,324	0,388	0,355	0,326	0,190
Motorin	0,371	0,337	0,403	0,369	0,339	0,197
Electricity	0,432	0,392	0,469	0,429	0,394	0,230
Fuel-oil no.4	0,516	0,468	0,559	0,513	0,470	0,274
Coal (imported)	0,693	0,633	0,745	0,689	0,641	0,373

Table 7. Optimum insulation thickness, energy savings and payback periods of Kocaeli for various fuels

Fuel type	Kocaeli					
	Insulation material type					
	XPS	EPS	PUR	PIR	RW	GW
<i>Optimum insulation thickness (m)</i>						
Natural gas	0,045	0,065	0,031	0,034	0,105	0,082
LPG (propan)	0,127	0,177	0,090	0,095	0,265	0,215
Motorin	0,122	0,170	0,086	0,091	0,255	0,207
Electricity	0,103	0,144	0,073	0,077	0,218	0,176
Fuel-oil no.4	0,084	0,118	0,059	0,063	0,181	0,146
Coal (imported)	0,058	0,082	0,040	0,043	0,130	0,103
<i>Energy savings (TL/m²)</i>						
Natural gas	17,126	20,060	14,512	17,310	29,772	24,647
LPG (propan)	181,205	189,021	174,090	181,703	213,809	200,920
Motorin	165,952	173,459	159,121	166,429	197,296	184,897
Electricity	116,309	122,702	110,506	116,715	143,097	132,471
Fuel-oil no.4	74,754	80,016	69,993	75,088	96,920	88,091
Coal (imported)	31,597	35,281	28,290	31,829	47,313	40,994
<i>Payback period (years)</i>						
Natural gas	0,796	0,649	0,972	0,785	0,511	0,333
LPG (propan)	0,210	0,187	0,232	0,208	0,180	0,107
Motorin	0,220	0,196	0,244	0,218	0,187	0,112
Electricity	0,266	0,235	0,296	0,264	0,221	0,133
Fuel-oil no.4	0,338	0,296	0,381	0,335	0,271	0,165
Coal (imported)	0,550	0,466	0,642	0,544	0,397	0,250

Table 8. Optimum insulation thickness, energy savings and payback periods of Ankara for various fuels

Fuel type	Ankara					
	Insulation material type					
	XPS	EPS	PUR	PIR	RW	GW
Optimum insulation thickness (m)						
Natural gas	0,057	0,081	0,040	0,043	0,128	0,102
LPG (propan)	0,153	0,212	0,108	0,114	0,316	0,257
Motorin	0,147	0,204	0,104	0,110	0,304	0,248
Electricity	0,125	0,174	0,088	0,093	0,261	0,212
Fuel-oil no.4	0,103	0,144	0,073	0,077	0,218	0,176
Coal (imported)	0,072	0,102	0,050	0,054	0,157	0,126
Energy savings (TL/m2)						
Natural gas	39,709	42,607	37,126	39,891	52,202	47,139
LPG (propan)	288,078	295,797	281,051	288,570	320,278	307,549
Motorin	265,662	273,076	258,915	266,133	296,617	284,372
Electricity	192,192	198,506	186,460	192,593	218,649	208,154
Fuel-oil no.4	129,778	134,976	125,075	130,108	151,671	142,951
Coal (imported)	63,094	66,734	59,828	63,324	78,618	72,376
Payback period (years)						
Natural gas	0,433	0,382	0,483	0,429	0,356	0,215
LPG (propan)	0,159	0,144	0,174	0,158	0,143	0,084
Motorin	0,166	0,150	0,181	0,165	0,149	0,087
Electricity	0,195	0,176	0,213	0,194	0,173	0,102
Fuel-oil no.4	0,238	0,213	0,261	0,236	0,208	0,123
Coal (imported)	0,342	0,304	0,379	0,340	0,290	0,173

Table 9. Optimum insulation thickness, energy savings and payback periods of Ardahan for various fuels

Fuel type	Ardahan					
	Insulation material type					
	XPS	EPS	PUR	PIR	RW	GW
Optimum insulation thickness (m)						
Natural gas	0,089	0,124	0,062	0,066	0,190	0,153
LPG (propan)	0,221	0,307	0,158	0,165	0,451	0,370
Motorin	0,213	0,295	0,152	0,159	0,435	0,356
Electricity	0,183	0,254	0,130	0,136	0,375	0,306
Fuel-oil no.4	0,152	0,211	0,108	0,113	0,315	0,256
Coal (imported)	0,109	0,152	0,077	0,081	0,230	0,186
Energy savings (TL/m2)						
Natural gas	88,02	88,98	87,25	88,07	92,82	90,69
LPG (propan)	462,30	466,18	458,83	462,55	478,95	472,23
Motorin	429,66	433,36	426,36	429,89	445,56	439,13
Electricity	321,78	324,82	319,08	321,97	335,00	329,61
Fuel-oil no.4	228,54	230,91	226,47	228,69	239,04	234,70
Coal (imported)	125,74	127,17	124,55	125,83	132,41	129,56
Payback period (years)						
Natural gas	0,302	0,280	0,322	0,301	0,297	0,168
LPG (propan)	0,144	0,132	0,155	0,143	0,137	0,078
Motorin	0,149	0,136	0,160	0,148	0,141	0,081
Electricity	0,170	0,156	0,183	0,169	0,162	0,093
Fuel-oil no.4	0,199	0,183	0,214	0,198	0,191	0,109
Coal (imported)	0,260	0,240	0,278	0,259	0,252	0,144

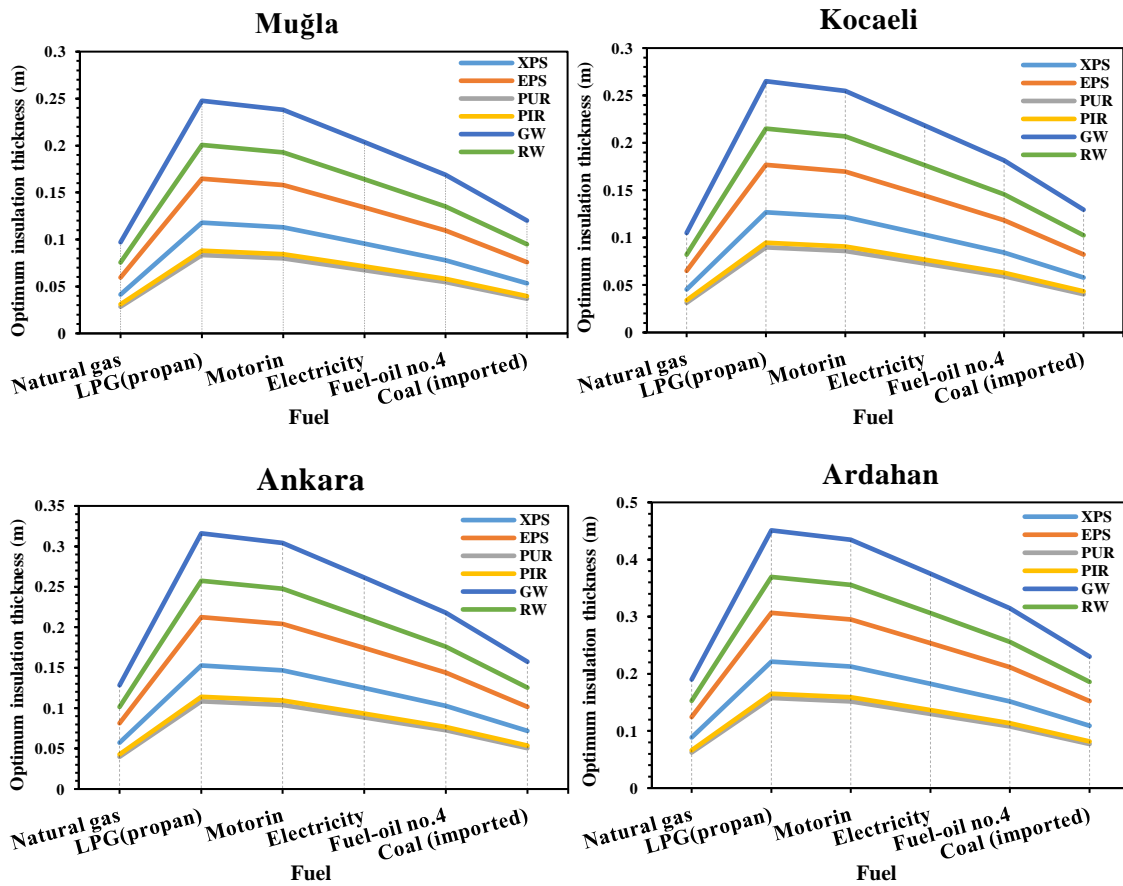


Fig. 5. Optimum insulation thickness versus various heating systems for different insulation materials in cities of Muğla, Kocaeli, Ankara, and Ardahan.

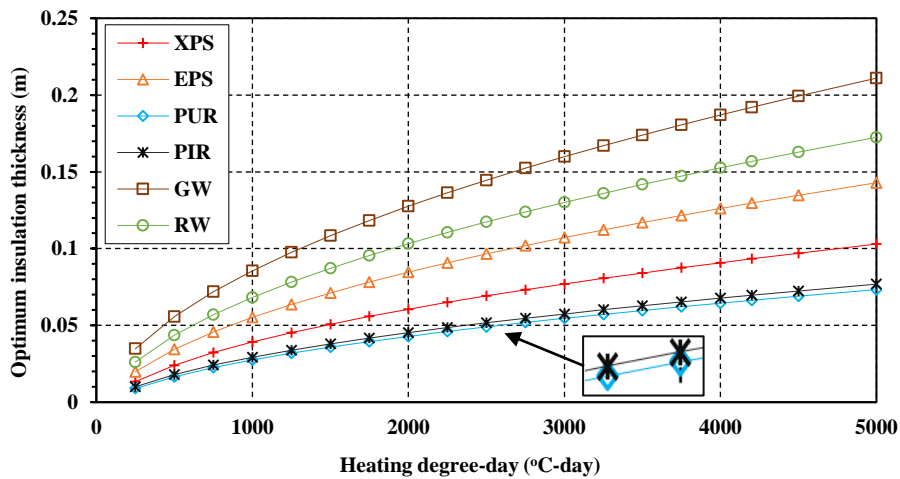


Fig. 6. Alteration of optimum insulation thickness depending on HDDs for different insulation materials in case of utilizing natural gas as an energy source.

5. Conclusions

Thermal insulation is based on two main issues: energy use and the environment. Energy use is a strategic, macro concept in all countries. For example, Turkey is not rich in terms of energy sources, with 60% of its energy requirements being imported from other countries. This is enhancing at an annual rate of 4.4% [6]. Reductions in heating needs can be achieved by minimizing heat losses, so the outer walls of buildings must

be insulated with appropriate insulation materials. These materials are indispensable in the construction of energy efficient buildings; however, achieving the full energy savings potential requires the determination of a solution that optimizes insulation thickness, insulation costs and energy savings.

In this study, insulation material was examined to detect its optimum thickness, as well as its energy savings over a period of 15 years; this includes payback periods in the cities

selected from four different climate regions in Turkey. While calculations were made, six types of energy fuel and insulation materials were considered for sandwich-type wall structure.

The results verify that the optimum insulation thicknesses ranges from 4.1–22.1 cm for XPS, 6–30.7 cm for EPS, 2.8–15.8 cm for PUR, 3.1–16.5 cm for PIR, 9.7–45.1 cm for RW and 7.6–37 cm for GW. The amount of energy savings ranged from 16.8–462.3 $\text{₺}/\text{m}^2$ for XPS, 17.4–466.2 $\text{₺}/\text{m}^2$ for EPS, 16.4–458.8 $\text{₺}/\text{m}^2$ for PUR, 16.9–462.6 $\text{₺}/\text{m}^2$ for PIR, 19.8–479 $\text{₺}/\text{m}^2$ for RW and 18.4–472.2 $\text{₺}/\text{m}^2$ for GW. The payback periods ranged from 0.078– 0.860 years. Based on these data, the greatest energy savings for the four cities is achieved using LPG. Furthermore, the insulation optimum thickness on the exterior walls of the building varies according to the number of heating degree-days and the insulation material used. The increase in fuel costs clearly demonstrates the importance of insulation in residential buildings. Insulation is also necessary for a greater sensitivity to environmental issues, in order to reduce the amount of energy used for heating purposes and the consequent emissions of flue gases into the environment.

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