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The Effect of Optimum Insulation Thickness on Energy Saving and Global Warming Potential

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Abstract: Building and construction sector in Turkey has a significant share in total energy consumption. In addition, 45% of global CO_2 emissions are also caused by these sectors. The reduction of fossil fuels used for heating in buildings and the environmental impacts caused by them has become very important in terms of energy performance and environmental protection. The most effective method of reducing heat losses occurring on the external surfaces is thermal insulation. In this study, optimum insulation thickness, energy saving, cost saving, payback period and greenhouse gas emissions were calculated with respect to different fuels for Diyarbakır province. The novelty of this study is the determination of the environmental performance as well as the energy performance of the optimum insulation thickness. Calculations were performed considering three different fuels (natural gas, coal and fuel-oil). The optimum insulation thickness was calculated using the life cycle cost method. Global warming potential is expressed as kg CO_2 equivalent ($CO_{2eq.}$) and calculated by life cycle assessment method. The optimum insulation thickness was found as 0.057 m, 0.066 m and 0.089 m for natural gas, coal, and fuel oil respectively. Payback periods were calculated as 2.85, 3.57 and 2.05 years for natural gas, coal and fuel oil, respectively. Annual avoided environmental impacts for calculated optimum insulation thicknesses were found as 17.45, 51.28 and 26.7 kg CO_{2eq}/m^2 for natural gas, coal, and fuel oil respectively.

Optimum Yalıtımı Kalınlığının Enerji Tasarrufu ve Küresel Isınma Potansiyeli Üzerine Etkisi

Anahtar Kelimeler
Enerji tasarrufu,
Optimum yalıtım kalınlığı,
Çevresel Etki,
Yaşam döngü değerlendirme

Öz: Türkiyede bina ve yapı sektörü toplam enerji tüketiminde önemli bir paya sahiptir. Ayrıca küresel CO_2 emisyonlarının %45'ine yine bu sektörler neden olmaktadır. Binalarda ısıtma amaçlı kullanılan fosil yakıtların ve bunların neden olduğu çevresel etkilerin azaltılması enerji performansı ve çevresel koruma adına çok önemli hale gelmiştir.Dış yüzeylerde meydana gelen ısı kayıplarını azaltmanın en etkili yöntemi ısı yalıtımıdır. Bu çalışmada, Diyarbakır ili için farklı yakıtlara göre optimum yalıtım kalınlığı, enerji tasarrufu, maliyet tasarrufu, geri ödeme süreleri ve sera gazı emisyonları hesaplanmıştır. Bu çalışmanın özgünlüğü optimum yalıtım kalınlığının enerji performansının yanı sıra çevresel performansının da belirlenmesidir. Hesaplamalar üç farklı yakıt (doğalgaz, kömür ve fuel-oil) dikkate alınarak yapılmıştır. Optimum yalıtım kalınlığı, yaşam döngüsü maliyet yöntemi kullanılarak hesaplanmıştır. Küresel ısınma potansiyeli, kg CO_2 eşdeğer ($CO_{2eq.}$) olarak ifade edilmiş ve yaşam döngüsü değerlendirme yöntemi ile belirlenmiştir. Doğalgaz, kömür ve fuel-oil için optimum yalıtım kalınlığı sırasıyla 0.057 m, 0.066 m ve 0.089 m olarak bulunmuştur. Geri ödeme süreleri doğalgaz, kömür ve fuel-oil için sırasıyla 2.85, 3.57 ve 2.05 yıl olarak hesaplanmıştır. Hesaplanan optimum yalıtım kalınlıkları için yıllık önlenen çevresel etkiler doğalgaz, kömür ve fuel-oil için sırasıyla 17.45, 51.28 ve 26.7 kg CO_{2eq} /m^2 olarak bulunmuştur.

1. INTRODUCTION

Residential buildings are responsible for 34% of total energy consumption. Thermal insulation applications are the most rational and easy method used for energy saving in buildings [1]. Since fossil fuels are used for heating purposes in buildings, thermal insulation application is also effective in reducing greenhouse gas emissions. Therefore, determining the optimum insulation thickness in buildings is important in terms of cost savings and environmental impact [2].

Requirements regarding the thermal insulation in Turkey are defined by TS 825 "Thermal Insulation Requirements for Buildings" [3]. For this reason, it is a requirement to determine the insulation thickness in terms of compliance with country standards, energy, and environmental saving. Minimum heat transfer coefficient (U) values required for building external components are specified in TS 825 for four different climate regions.

There are many studies in the literature on determining the optimum insulation thickness for different climate regions and fuels. In the calculations performed by life cycle cost (LCC) method, the heating degree day (HDD) and cooling degree day (CDD) values, which are a measure of the outdoor temperature, were used. In these studies, energy and cost savings have been determined with application of optimum insulation thickness (OIT) to the exterior walls of the building. Also, the economic and energy saving effects of different wall structures on OIT were also examined. In addition, economic payback period was calculated for OIT, which is determined by different insulation materials and heat sources, to the external walls. Bollutürk [4] determined optimum insulation thickness for 16 cities in Turkey with five different fuel types. Annual heating requirements of buildings in different climate regions were calculated by heating degree-days methods. Kaynaklı [5] determined the optimum insulation thickness for different fuels and architecture design in buildings in the sample of Bursa province. According to the fuel type, OIT values were found between 0.053 m and 0.124 m. Bollutürk [6] calculated optimum insulation thickness for Turkey's warmest zone. Also, energy savings and the economic payback period were determined. Uçar and Balo [7] calculated optimum insulation thickness for exterior walls located in four different climate regions. Energy saving and economical payback periods are determined for five different fuels and four different insulation materials. Ozel [8] calculated OIT for five different structure materials and two different insulation materials in the Elazig province example. According to the results, it was seen that OIT vary between 0.02m and 0.082m, and payback period vary between 1.32 and 10.33 years. Daouas [9] determined the OIT values for the exterior walls according to the annual heating and cooling load in different climate regions in Tunisia. Ekici et al. [10] calculated optimum insulation thickness, energy saving and payback period for various types of external walls with different insulation materials, fuels and climate regions. Rosti et al. [10] determined optimum insulation thickness for classic and modern walls. It has been concluded that some modern walls do not need insulation in various climate regions.

In some studies, the effects of OIT on global warming potential (GWP) were calculated by combustion equations of fuels. In these studies, the environmental impacts that will be prevented annually with the application of OIT have been determined [12-15]. In this study, OIT calculations for exterior walls were performed for Diyarbakır province. OIT for exterior walls were determined for different fuels and environmental impact were analyzed by the Life Cycle Assessment (LCA) method. In environmental analyzes, GWP was calculated according to IPCC 100a for different fuels and expressed as CO_2 equivalent. EPS has been chosen as the thermal insulation material due to its 80% market share in the exterior walls [20]. OIT and environmental calculations are performed for natural gas, coal and fuel oil. With the application of OIT, annual energy and environmental savings were calculated for each fuel. In addition, annual cost savings and economic payback periods are determined.

2. METHOD

In this study, OIT calculated for the exterior wall seen in Figure 1. The wall components consist of 2 cm inner plaster 20 cm brick and 3 cm outer plaster. EPS was chosen as thermal insulation material and natural gas, coal and fuel-oil were chosen as heat sources. Thermal properties and costs of these materials are shown in Table 1 [15].

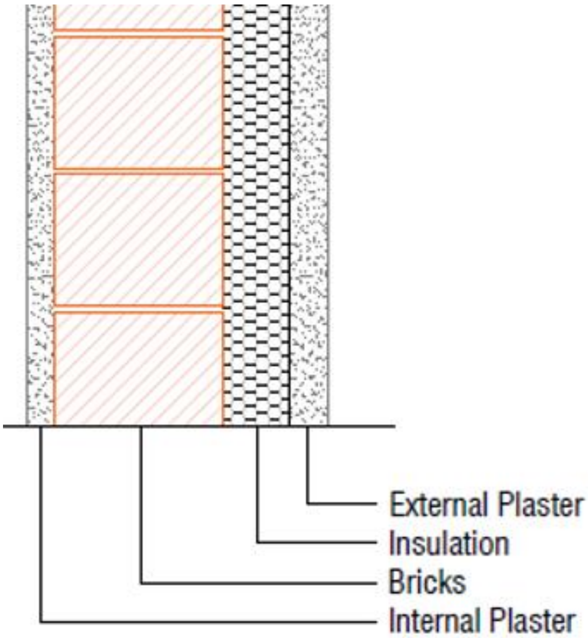

Figure 1. External wall strucrure

Table 1. Physical properties of external wall [15].

Wall structure	Thickness (m)	k (W/mK)	R(m^2K/W)
Internal plaster	0.02	0.87	0.023
Brick	0.2	0.486	0.411
External plaster	0.03	1.4	0.021
R_i			0.04
R_o			0.13

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) [17,21].

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

T_b is equilibrium temperature and, T_o 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) [17].

$$q_{,H} = \frac{86400 \times HDD \times U}{\eta} \qquad (2)$$

η represent the efficiency of the heating system, The U value including the insulation can be calculate with Equation (3).

$$U = \frac{1}{R_i + R_w + R_{ins} + R_0} \qquad (3)$$

R_i ve R_o are the thermal resistances of the air film inside and outside. R_w is the thermal resistance of the non-insulated surface and R_{ins} is represent the thermal resistance of the insulation;

$$R_{ins} = \frac{x}{k} \qquad (4)$$

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

$$R_{w,t} = R_i + R_w + R_0 \qquad (5)$$

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

$$U = \frac{1}{R_{w,t} + R_{ins}} \qquad (6)$$

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

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

2.1. Optimum Insulation Thickness

Cost analysis should be done to calculate the optimum insulation thickness. Annual heating cost analysis for unit surface area can be calculated by Equation (8) [4, 22].

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

C_{A_H} 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 (11) with interest and inflation rates [16].

İf i> g

$$r = \frac{i - g}{1 + g} \qquad (9)$$

İf g> i

$$r = \frac{g - 1}{1 + g} \qquad (10)$$

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

If i = g

$$PWF = \frac{N}{1 + i} \qquad (12)$$

i, g and N represent interest rate, inflation rate and lifetime, respectively. In this study, similar to the studies in the literature, N is chosen for 10 years. The cost of the thermal insulation material is calculated by Equation (13).

$$C_{ins} = C_y \times x \qquad (13)$$

$$C_{t_H} = C_{A_H} \times PWF + C_y \times x \qquad (14)$$

C_{t_H} , 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 for heating is calculated by Equation (15)

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

2.1.1. Payback time

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

$$A_{year} = C_H - C_{t_H} \qquad (16)$$

Payback time (PBT) for heating is determined by Equation (17). Prices, lower heating values and efficiencies of heating systems are shown in Table 2. Parameters used in calculation are shown in Table 3.

$$PBT_H = \frac{C_{ins}}{A_{year_H}} \qquad (17)$$

Table 2. Lower heating value, efficiencies, and prices of fuels [15-18]

Fuel	H_u	η	C_{fuel}
Natural Gas	34485000 J/m^3	0.9	0.36$/m^3
Coal	21112500 J/kg	0.65	0.196 $/kg
Fuel-Oil	41317000 J/kg	0.8	0.737 $/kg

Table 3. Parameter used in the calculation [16, 17].

Fuel	H_u
i	%9
g	%8.1
N	10 year
PWF	9.55
C_y	120 $/m^3
HDD	2142

2.2. Life Cycle Assessment

In this study, LCA was used to determine the environmental impacts of different heat sources on OIT. The gate to grave impact were examined and compared. According to ISO standards, an LCA study include four stages. These stages are goal and scope, life cycle inventory, life cycle impact assessment and interpretation [19].

The aim of the study is to determine the environmental benefits of thermal insulation to be applied on the wall surface. The effects of different fuels on annual environmental impact savings were evaluated. In this study, the functional unit is 1 m^2 thermal insulation material applied to the exterior walls. In environmental analyzes, GWP was calculated according to IPCC 100a for different fuels and expressed as CO_2 equivalent ($CO_{2eq.}$). LCA analyses were performed using SimaPro 9.0.0.35 software. The data used in the model were obtained from ecoinvent 3 database present in SimaPro. IPCC 2013 is the updated version of IPCC 2007, and it was developed by the International Panel on Climate Change. By this method, the impacts of climate change factors can be calculated for periods of 20, 100 and 500 years. In this study, the IPCC 2013 100a was used for calculating GWP.

3. RESULTS AND DISCUSSION

In this study, OIT has been calculated for Diyarbakır province considering different fuel types. These are natural gas, coal and fuel oil, respectively. Optimum insulation thickness, economic payback period (PP) and annual cost savings are calculated for each fuel. EPS has been chosen as the thermal insulation material due to its 80% market share in the exterior walls. OIT and PP for natural gas were found to be 0.057 m and 2.85 years, respectively. As seen in Figure 2, the lowest insulation thickness of the total cost is OIT. If the calculated OIT is applied, heat losses from the exterior walls reduce by 70% annually.

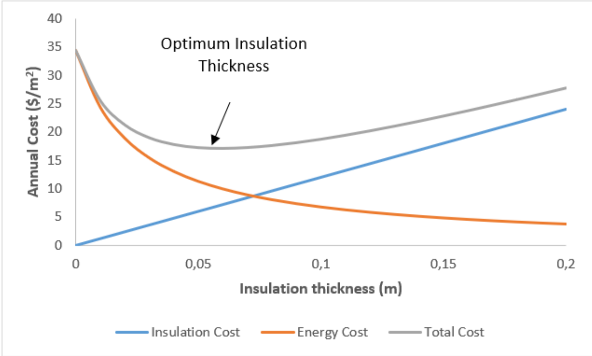

Figure 2. Annual cost of heating versus insulation- thickness for natural gas.

Figure 3 shows the heat losses and avoided environmental impact (AEI) based on insulation thickness. As the insulation thickness increases, heat losses from exterior surfaces decrease, the avoided environmental impact (AEI) increases. In the case of applying OIT (0.057 m), which is calculated for natural gas, 17.45 kg of $CO_{2eq.}$ is saved annually.

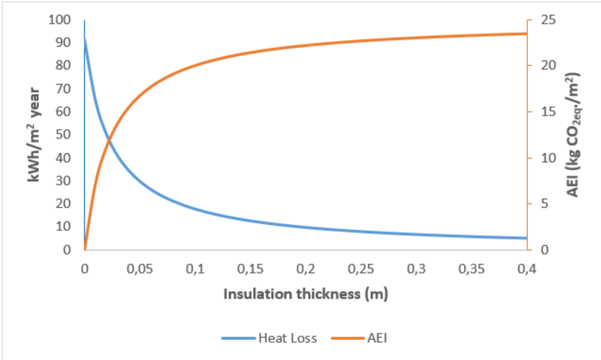

Figure 3. Heat loss and avoided environmental impact for natural gas.

As coal is used for the heat source, OIT was found to be 0.066 m as seen in Figure 4. PP was found to be 2.57 years if the OIT (0.066m) calculated for coal was applied. However, heat losses from the exterior walls will decrease by 73%.

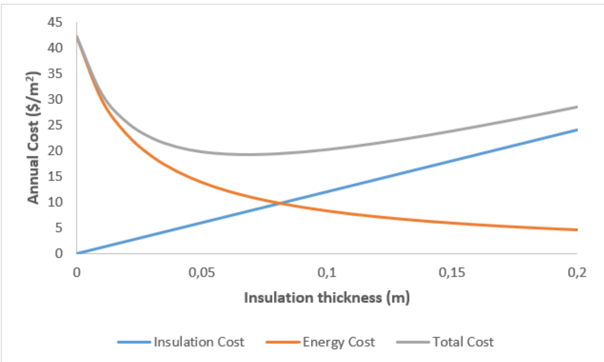

Figure 4. Annual cost of heating versus insulation- thickness for coal.

Figure 5 shows the heat losses and AEI based on insulation thickness. With the application of OIT determined for coal, the annual environmental savings calculated as 51.28 kg CO_{2eq}/m^2.

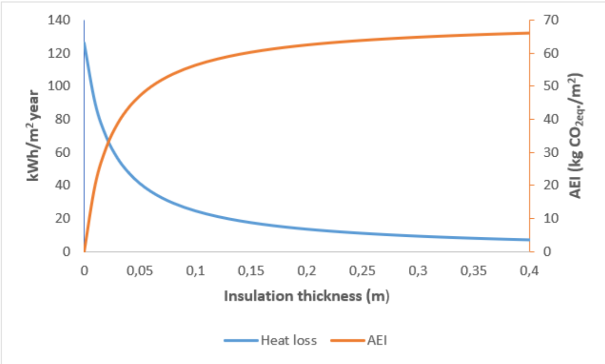

Figure 5. Heat loss and avoided environmental impact for coal.

Finally, OIT calculation was performed for fuel oil and it was found to be 0.089 m (Figure 5). PP is calculated as 2.06 years when fuel oil is used as the heat source and 0.089 m EPS is applied as insulation thickness. In addition, heat loss from external walls is reduced by 78%.

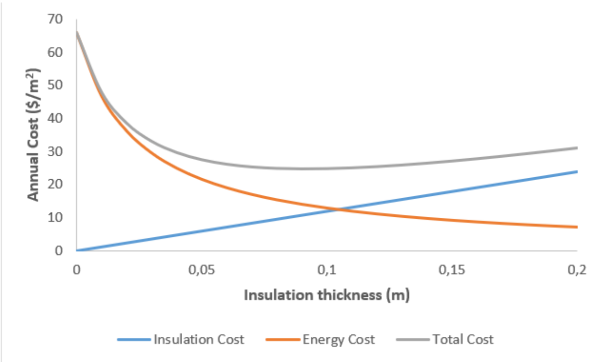

Figure 6. Annual cost of heating versus insulation- thickness for fuel oil.

In Figure 7, when fuel oil is used as a heat source, heat loss and AEI based on the insulation thickness can be seen. OIT value is calculated as 0.089 m for fuel oil and if applied, 26.7 kg of $CO_{2eq.}$ /m^2 is saved annually.

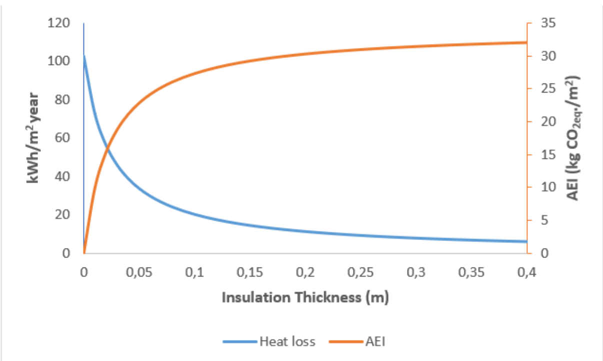

Figure 7. Heat loss and avoided environmental impact for fuel oil.

Table 4 shows the OIT, cost saving, payback pariod and avoided environmental impact values calculated for natural gas, coal and fuel oil. The highest OIT and annual savings are calculated as 0.089 m and 5.18 \$/m^2 for fuel oil. Besides, the smallest PP value was found as 2.05 years for fuel oil. The avoided environmental impact was calculated for coal and this value was found as 51.28 kg $CO_{2eq.}$ /m^2

Table 4. OIT, cost saving, payback pariod and avoided environmental impact.

	Natural Gas	Coal	Fuel Oil
OIT (m)	0.057	0.066	0.089
Ayear,H (\$/m^2)	2.4	3.09	5.18
PP (year)	2.85	2.57	2.05
AEI (kg CO_{2eq}./m^2)	17.45	51.28	26.7

4. CONCLUSION

In this study, OIT was calculated for Diyarbakır with respect to different heat sources. OIT calculations were made using the life cycle cost (LCC) method. For each heat source, annual cost savings, energy savings and heat losses on external wall were evaluated. In addition, global warming potential (GWP) was evaluated with the life cycle assessment method. GWP effects were calculated using IPCC 100a and expressed in kg of CO_{2eq}. In this study, economic analyzes were carried out by LCC method and environmental analyzes were calculated by LCA method. OIT calculations should be supported by environmental impact assessments using the LCA method. The findings are summarized as follow:

1. The optimum insulation thickness (OIT) for natural gas, coal and fuel oil was found to be as 0.057 m 0.066 m and 0.089 m, respectively. Payback periods (PP) were calculated as 2.85, 3.09, 2.05 years, respectively.

2. With the application of OIT, which is calculated for natural gas, coal and fuel oil, heat losses on the exterior walls will decrease by 70%, 73% and 78% respectively. The cost savings to be achieved were 2.4, 3.09 5.18 \$/m^2, respectively.

3. The reduction of heat losses on the external surfaces provides fuel savings. Therefore, environmental effects caused by the fuel are reduced. The environmental effects to be prevented annually with the application of the calculated OIT for each fuel are 17.45, 51.28, 26.7 kg CO_{2eq}./m^2 for natural gas coal and fuel oil, respectively.

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