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A method for determining optimum insulation thickness: Combined economic and environmental method

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ABSTRACT

In this study, an alternative and new method to determine optimum insulation thickness is presented. This method combines economic and environmental effects, and is called as Combined Economic and Environment Method (CEEM). Analyses were carried out for outside walls for Bilecik, Turkey and rockwool and glasswool were chosen as insulation materials. The presented method was compared with economic and environmental approaches. The optimum insulation thicknesses of three different methods were calculated. Optimum points were determined as 0.176 m (CEEM), 0.133 m (economic approach) and 0.227 m (environmental approach) for the rockwool and 0.185 m (CEEM), 0.140 m (economic approach) and 0.467 m (environmental approach) for the glasswool. In addition, annual cost savings and energy savings were also determined.

1. Introduction

In today's world, growing population and fast technological development lead to increases at energy consumption in terms of environmental concerns. In Turkey, 34% of the total energy consumption takes place in residential and service buildings [15]. Insulation application is the most convenient and easiest solution for the heat energy savings in buildings, because, heat transfer occurs mostly from the building envelope. In addition to energy saving or fuel saving, it also provides cost savings and causes to decrease the green house gases. Therefore, determining an optimum insulation thickness is very important for energy saving and cost balance.

In the literature, there are a great number of studies about determining optimum insulation thickness under different conditions and fuels. Some examples of these studies for the energetic and exergetic approach are as follows. According to Hassan [8], optimum insulation thickness was developed and applied for Palestine. It was found to provide saving up to 21 $/m^2 of wall area for rock wool and polystyrene insulation. Payback periods were between 1 and 1.7 years for rock wool and between 1.3 and 2.3 years for polystyrene insulation. Bolatturk [2] investigated optimum insulation thickness for different fuels and climate zones. It was found that optimum insulation thicknesses vary between 2 and 17 cm and payback periods were determined between 1.3 and 4.5 years. Ucar and Balo [21] considered four different cities to determine optimum insulation thickness. In the study conducted by Ozel [14], the optimum thickness of thermal insulation used to reduce heat losses in buildings was investigated under dynamic thermal conditions. The results show that the optimum insulation thicknesses change between 5.4 and 19.2 cm, and payback periods were found to be 3.56 and 8.85 years for different insulation materials. Yuan et al. [23] put together optimum insulation thickness and reflectivity for Japanese climate. Kaynakli [11] investigated optimal insulation thickness for four different types of fuels. Liu et al. [13] investigated optimum insulation thickness considering moisture effect for hot and cold climates in China. Ozel [16] calculated the optimum insulation thickness for cooling applications in Antalya. Ucar [22] used thermo-economic optimization to determine the optimum insulation thickness for four different cities. Dylewski and Adamczyk [6,7] investigated optimum insulation thickness in terms of economic and ecological perspective. Different building walls, thermal insulation materials, and heat energy sources of the buildings were taken into account. According to their results, the optimum thickness for ecological reasons was dramatically greater compared to economic ones. In addition to these, environmental approaches for determining the optimum insulation thickness were researched by [18,19,21,5,17].

The aim of this paper is to present a new method for determining optimum insulation. Kanbur et al. [12] presented a new method that integrates environmental costs and economic costs. In this method, environmental cost of materials, fuel and greenhouse gases are incorporated with economic variables. In this way, environmental effects

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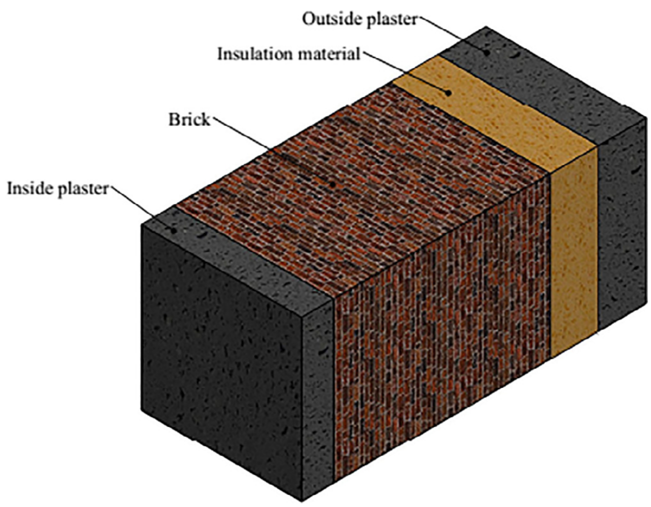

Fig. 1. Composite wall taken into account [17].

are combined with economic parameters. In this study, the method presented by Kanbur et al. is adapted for determining optimum insulation thickness, and is called as Combined Environmental and Economic Method (CEEM) by the authors. According to authors' knowledge, this method is used for the first time to determine optimum insulation thickness. In this paper, CEEM is applied and compared with economic and environmental approaches. Results are presented and discussed.

2. Analysis

A composite wall seen in Fig. 1 is taken into account. Bilecik, which is located in Marmara region in Turkey, was chosen for investigation. Analyses were made for heating season lasting nearly six months. Rockwool and glasswool were chosen as insulation materials, and efficiency of the heating system was assumed as 85%. Annual heat transfer for per m^2 (J/m^2) is (see [8]) as follows:

$$q = 86400HDDU \tag{1}$$

where HDD is the heating degree-days (°C/day), and U is the heat transfer coefficient (W/m^2°C). Annual energy loss (J/m^2) from the wall was calculated (see [8]) as follows:

$$E = \frac{86400HDDU}{\eta} \tag{2}$$

where η is the efficiency of the heating system and annual fuel consumption (kg/m^2) was computed (see [8]) as follows:

$$m_F = \frac{86400HDDU}{\eta Hu} \tag{3}$$

where Hu is lower heating value of the fuel (J/kg). More than 90% of natural gas consists of methane (CH_4), therefore methane can be used in the combustion equation. Combustion process is assumed as complete to ease calculations. Combustion equation can be written as follows:

$$CH_4 + 2\,(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2\,H_2O + 7.52\,N_2 \tag{4}$$

Annual mass of released CO_2 m_{CO_2}(kg/m^2) is:

$$m_{CO_2} = 2.75\left(\frac{86400HDDU}{\eta Hu}\right) \tag{5}$$

Heat transfer coefficients (W/m^2) for insulated and non-insulated conditions are given in Eqs. (6) and (7), respectively by Hasan [8]:

$$U_{nins} = \frac{1}{(R_{T,nins})} \tag{6}$$

$$U_{ins} = \frac{1}{\left(R_{T,nins} + \frac{x}{k}\right)} \tag{7}$$

where k (W/m°C), is the heat conductance coefficient of the insulation material, x is the insulation thickness (m), $R_{T,nins}$ is the thermal resistance of non-insulated walls (m^2 K/W).

2.1. Economic approach

In this approach, only economic parameters are considered.

Total cost are obtained by summing up insulation cost and annual fuel costs along the life cycle. The annual fuel cost per unit area is written as ($/m^2):

$$C_F = c_f m_F \tag{8}$$

where c_f is the cost of fuel ($/kg).

The fuel cost over a lifetime is calculated using the present worth factor (*PWF*), in the life cycle cost. The present worth factor depends on the inflation rate, g, and interest rate, i which is the compensation paid for the use of borrowed money, i^* is adjusted for inflation rate as shown below.

$$i^* = \begin{cases} \frac{i-g}{i+g} & ; i > g \\ \frac{g-i}{g+i} & ; i < g \end{cases} \tag{9}$$

and then *PWF* is defined as follows:

$$PWF = \begin{cases} \frac{1-(1+i^*)^{-N}}{i^*} & ; i \neq g \\ (1+i)^{-1} & ; i = g \end{cases} \tag{10}$$

where N is the lifetime of the insulation material and i^* is the interest rate adjusted for the inflation rate. Finally, the total annual fuel cost can be arranged as ($/m^2):

$$C_F = c_f PWF m_F \tag{11}$$

The cost of the insulation material ($/m^2) can be calculated as:

$$C_i = c_i x \tag{12}$$

where c_i is the cost per m^{3}of insulation material and x is the thickness of the insulation material (m). The total annual cost ($/m^2) is:

$$C_T = c_f PWF m_F + c_i x + C_{ad} = c_f \frac{86400HDD}{\eta Hu\left(R_{T,nins} + \frac{x}{k}\right)} PWF + c_i x + C_{ad} \tag{13}$$

where C_{ad} is the additional costs ($/m^2). The cost saving per unit surface area ($/m^2):

$$C_S = C_{T,nins} - C_{T,ins} \tag{14}$$

where $C_{T,nins}$ is the total annual cost of the non-insulated conditions and $C_{T,ins}$ total annual cost of the insulated conditions. The optimum insulation thickness is obtained by getting the derivative of C_T in respect to x and set equal to zero. C_T will achieve minimum, and one can see that it is the convex function in Figs. 2 and 3, value at the optimum insulation thickness and optimum point is (m):

$$x_{opt,C} = \frac{120\sqrt{6HDDc_f kPWF}}{\sqrt{c_i Hu\eta}} - kR_{T,nins} \tag{15}$$

where k is the heat conductance coefficient of the insulation material.

2.2. Combined economical and environmental method

In this analysis, environmental costs presented by Kanbur et al. [12] are considered as well as economical costs and the method used in that paper adapted to determine optimum insulation thickness. Preventing carbon releasing some methods are developed like enviroeconomic

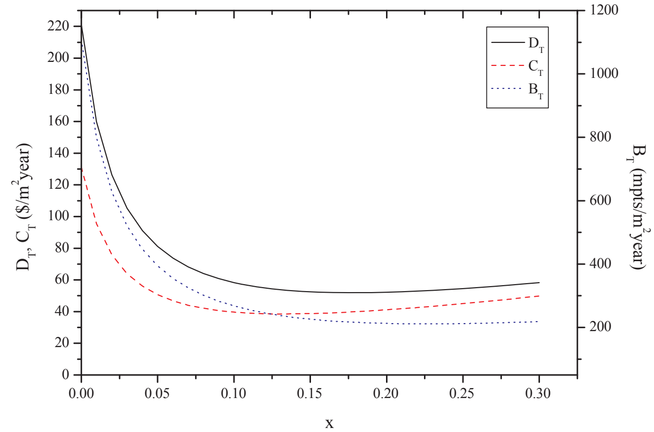

Fig. 2. Variation of annual total costs with x for rockwool.

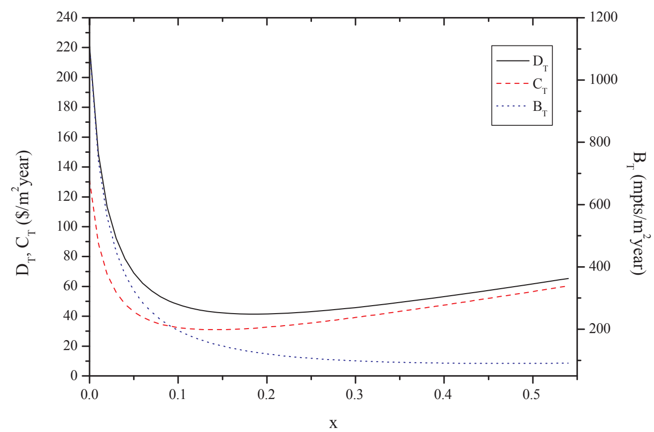

Fig. 3. Variation of annual total costs with x for glasswool.

methods. In these methods impact of emissions are converted to money (environmental costs) for per unit. This money is called as CO_2 tax or penalty (for detailed information please see [20;3]. In the analysis, environmental costs and economical costs are summed up, and in this way, environmental and economical parameters are combined. Similar steps are applied for CEEM method to determine the optimum point and cost saving. Firstly the annual cost of the fuel combined with its environmental cost ($/m^2) is shown in Eq. (16):

$$D_F = m_F(c_f + d_f) \tag{16}$$

where d_f ($/kg) is the environmental cost of the methane. The annual cost of CO_2 is written as ($/m^2):

$$D_{CO_2} = m_{CO_2}\left(d_{CO_2}\right) \tag{17}$$

where d_{CO_2} ($/kg) is the specific environmental cost of CO_2. The cost of insulation combined with environmental cost is ($/m^2):

$$D_i = \left(c_i + GWPd_{CO_2}\rho_i\right)x \tag{18}$$

where GWP is the global warming potential of the insulation material and ρi density (kg/m^3) of the insulation material. Finally, total annual environmental and economic combined cost is ($/m^2):

$$D_T = \left(D_F + D_{CO_2}\right)PWF + D_i \tag{19}$$

Cost saving is ($/m^2):

$$D_s = D_{T,nins} - D_{T,ins} \tag{20}$$

The optimum insulation thickness is obtained by obtaining the derivative of D_T in respect to x set equal to zero. D_T will achieve minimum value at the optimum insulation thickness, and the optimum point is (m):

$$x_{opt,D} = \frac{-c_i Huk\eta R_{T,nins} - d_{CO_2}GWPHuk\eta R_{T,nins}\rho_i + (487.442\sqrt{Hu}}{Hu\eta(c_i + d_{CO_2}GWP\rho_i)} \cdot \sqrt{\begin{array}{l}\left(HDDk\eta PWF\left(0.364c_f c_i + d_{CO_2}c_i + 0.364c_i d_f\right.\right.\\ \left.\left. + 0.364c_f d_{CO_2}GWP\rho_i + d_{Co_2}^2 GWP\rho_i + 0.364 d_{CO_2} d_f GWP\rho_i\right)\right)\end{array}} \tag{21}$$

2.3. Environmental methods

In this method, environmental effects are described as mpoints, which was used by Goedkoop et al. [9] and only environmental effects were taken into account. In environmental analysis, economic parameters are replaced by environmental impacts. Annual environmental impact of the insulation material is (mPts/m2):

$$B_T = bfm_F + b_{CO_2}m_{CO_2} + b_i\rho_i x \tag{22}$$

where b_f is the environmental impact of the fuel (mPts/kg), b_{CO_2} is the environmental impact of the CO_2 (mPts/kg) and b_i is the environmental impact of the insulation material (mPts/kg). The optimum insulation thickness is obtained by obtaining the derivative of B_T in respect to x set equal to zero. B_T will achieve minimum value at the optimum insulation thickness, and the optimum point is (m):

$$x_{opt,B} = \frac{487.442\sqrt{(b_{CO_2} + 0.364b_f)\,HDDHuk\eta\rho_i}}{\sqrt{b_i}Hu\eta\rho_i} - kR_{T,nins} \tag{23}$$

Saving of the environmental impact (mPts/m^2) is obtained from:

$$\boldsymbol{B}_S = B_{T,nins} - B_{T,ins} \tag{24}$$

where, B_{nins} is the annual environment impact at non-insulation conditions and B_{ins} is the environment impact at insulated conditions.

Eventually, energy saving is(J/m^2):

$$E_S = E_{nins} - E_{ins} \tag{25}$$

where, E_{nins} is the annual energy lost at non-insulation conditions and E_{ins} is the energy annual energy lost at insulated conditions.

3. Results and discussion

In this study, an alternative approach is presented for the insulation applications called Combined Economic and Environmental Method (CEEM). Bilecik was chosen for the analyses. Investigation was carried out for heating season, a composite wall was taken into account and rockwool and glasswool were chosen as insulation materials. In addition to CEEM, economic and environmental approaches were performed and results were compared. The parameters used in calculation can be found in Table 1.

In Fig. 2, the variation of the D_T, C_T, B_T for the rockwool can be seen. All of them have an optimum (minimum) point, which reduce all the costs to minimum level. They reach their minimum level, and then begin to increase. Optimum points are 0.176 m, 0.133 m and 0.227 m for the D_T, C_T and B_T respectively and corresponding values are 51.888 ($/m^2 year), 38.532 ($/m^2 year) and 211.22 (mpts/m^2 year). In the investigated range, D_T decreased to 77%, C_T decreased to 70% and B_T decreased to 81% compared to the non-insulated conditions. In Fig. 3, the change of the D_T, C_T, B_T for the glasswool is shown. Similar to previous results, they had optimum points. These points were 0.185 m, 0.140 m and 0.467 m for the D_T, C_T and B_T, respectively; and corresponding values were 41.458 ($/m^2 year), 30.990 ($/m^2 year) and 90.160 (mpts/m^2 year). D_T decreased to 81%, C_T decreased to 76% and B_T decreased to 92% compared to the non-insulation conditions. According to the results, one can see that optimum points for the glasswool are bigger than rockwool; and the cost at the optimum values for

Table 1
Parameters used in calculations [10,12,9,1,4].

Parameter	Unit	Value
Environmental impact point	mpts/kg	
Rockwool		4.2
Glasswool		2.1
Fuel		114
CO_2		5.45
Heating degree day	°C/days	2966
Boiler efficiency		0.85
Density of insulation material	kg/m^3	
Rockwool		105
Glasswool		45
i		*20%*
g		*10%*
N		*20*
k (rockwool)	W/mk	0.04
k (glaswool)	W/mk	0.032
R	m^2 K/W	0.632
c_F	\$/kg	1.68
c_i (rockwool)	\$/m^3	132
c_i (glasswool)	\$/m^3	103
d_f	\$/kg	1.06
d_{CO_2}	\$/kg	0.0327
GWP (rockwool)		1.45
GWP (glasswool)		2.2

the glasswool are smaller than the rockwool.

In Figs. 4 and 5, the savings are given for D_S, C_S and B_S for rockwool and glasswool. They reached their optimum point, and then they began to decrease. Cost saving values for D_S at the optimum points was 169.238 (\$/m^2 year) for the rockwool; and 179.677 (\$/m^2 year) for the glasswool. Glasswool provided more saving compared to rockwool. Optimum points at C_s were 92.740 (\$/m^{2}year) for rockwool; and 100.283 (\$/m^2 year) for glasswool. Similarly, the optimum point at B_T was 897.453 (mpts/m^2 year) for rockwool; and 1018.520 (mpts/m^2 year) for glasswool. According to these results, one can see that glasswool has advantage against rockwool; and CEEM approach is advantageous compared to economic approach, because savings of CEEM is nearly twice of the economic approach.

Energy savings values for rockwool and glasswool are illustrated in Fig. 6. Energy savings increase with *x* logarithmically. The increase rate is really fast until x = 0.05 m. According to the Figure, energy saving resulting from the glasswool is bigger than saving of rockwool. Maximum annual energy saving for the rockwool is equal to 0.440 (GJ/m^2 year) and is equal to 0.446 (GJ/m^2 year) for the glasswool.

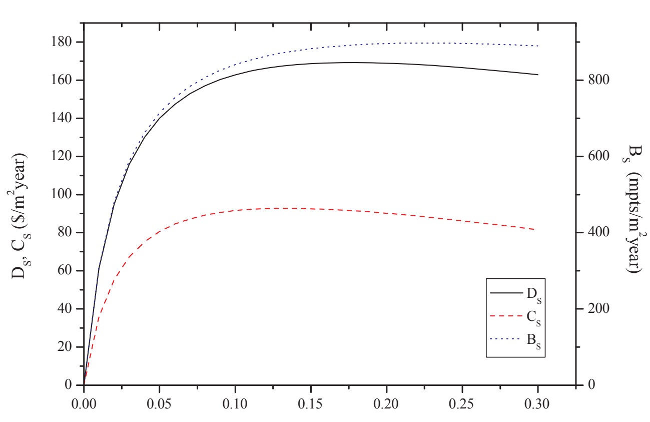

Fig. 4. Variation of annual total cost savings with x for rockwool.

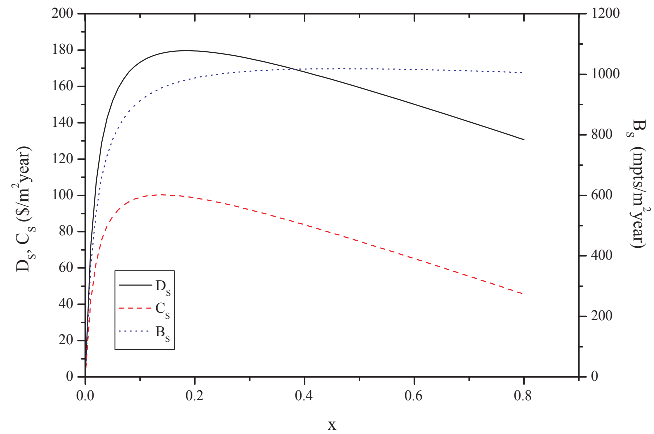

Fig. 5. Variation of annual total cost savings with x for glasswool.

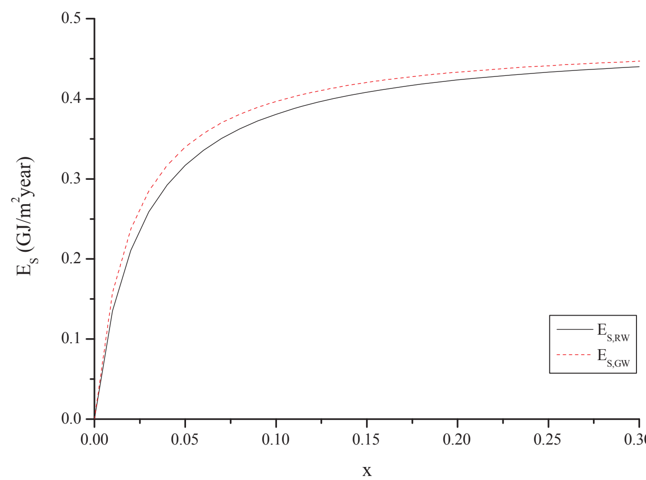

Fig. 6. Variation of annual energy savings with x for rockwool and glasswool.

4. Conclusions

Insulation applications are useful for harmful environmental impacts as well as energy saving. In the present study, an alternative method to determine optimum insulation thickness was suggested. City of Bilecik was chosen for the assessment. In this method, environmental and economic parameters were combined. Not only fuel and insulation prices, but also environmental costs of the fuel, insulation material and greenhouse gases (only CO_2wastaken into account in this study) were considered; and the cost of environmental impacts were incorporated to economic parameters. In addition, economic and environmental evaluations were performed and results were compared. The results show that CEE method has bigger optimum point than economic method and is smaller than the environmental approach. This is natural, because these two approaches were combined and economic and environmental effects were considered together in the present study. When the savings of CEEM and economic method were compared, it was determined that annual saving cost of CEEM was nearly two times bigger than economic approach. Finally, CEEM method can be an alternative method for insulation applications.

Conflict of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tsep.2019.04.004.

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