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Optimum insulation thickness of the piping system with combined economic and environmental method

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ABSTRACT

In the present study, an alternative method combining economic and environmental costs is suggested for the pipe insulation. This method is called as combined economic and environment method (CEEM). Bilecik, which is located in the Marmara region, Turkey, is chosen. Rockwool and glass wool are chosen as insulation materials. The optimum insulation thicknesses of three different methods including CEEM, economic, and environmental approaches are calculated and compared. Optimum points are 0.46 m (CEEM), 0.39 m (economic approach), and 0.54 m (environmental approach) for rockwool; and 0.46 m (CEEM), 0.40 m (economic approach), and 0.59 m (environmental approach) for glass wool. In addition, annual cost savings and energy savings are determined.

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Combined economic and environmental method; energy saving; global warming potential; optimum insulation thickness; pipe insulation

Introduction

Because of the growing population and rapid technological development, there is an increase in energy consumption. In Turkey, 34% of the total energy consumption takes place in residential and service buildings (National Energy Conservation Center 2006). This excessive energy consumption needs to be decreased, and a larger portion of this excessive energy can be reduced by insulation applications. In addition to energy and cost saving, decreasing greenhouse gases plays an important role, and some environmental assessments should be performed too. Piping systems are widely used in heating and ventilation systems, and in industrial and chemical applications. These systems are complicated, and long distance piping systems transport high energy capacity fluids; thus, thermal insulation gains importance.

In the literature, there has been increasing attention to determine optimum insulation thickness for pipes. Zaki and Al-Turki (2000) conducted an economic analysis for pipes and they chose rockwool and silicate as insulation materials. Kecebas, Alkan, and Bayhan (2011) used thermo-economic method to evaluate optimum insulation thickness for pipes. Kayfeci, Yabanova, and Kecebas (2014) used artificial neural network to calculate optimum insulation thickness for pipes. Sahin (2004) investigated the pipe insulation thickness under extraterrestrial radiation conditions. Ozturk, Karabay, and Bilgen (2006) compared four methods for determining optimum insulation thickness for pipes. Basogul and Kecebas (2011) investigated the environmental assessment of insulation pipes in district heating pipelines. Yildiz and Ersoz (2015) calculated the optimum insulation thickness for pipes in an air-conditioning system. Environmental impact for the optimum insulation is investigated in Özel et al. (2014, 2015a, 2015b, 2017) and Daldal et al. (2015, 2016).

A novel method including economic and environmental variables was presented by Kanbur et al. (2017). This method provides a measure for evaluating the environmental cost of materials, fuel, and

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greenhouses gasses together with economic variables and environmental effects, which can be combined with economic parameters. In this research, the method presented by Kanbur et al. is adopted for determining optimum insulation thickness for pipes, which is called as combined environmental and economic method (CEEM) by the authors. In this paper, CEEM is applied and compared with economic and environmental approaches. The results are presented and discussed later.

Analysis

The methodology applied in this paper can be described in this paragraph. In the literature, all researches investigating optimum insulation thickness are focused on economic or environmental parameters. Economic approach includes fuel and insulation material costs and insulation applications are long-term processes, that's why, present worth of the money must be incorporated into calculations. Thus, power factor is determined by using inflation and interest rate during the assumed time. After the total cost of are determined, optimum insulation thickness is defined for the system. In the environmental evaluation, environmental effects of the insulation material, fuel, or combustion gas are taken from the Eco-indicator 99 or 95 (Goedkoop and Spriensma 2000), in which environmental effects are described as mpoint/points. In this approach, these environmental impacts are used instead of costs and same analyses are done with the economic approach, and optimum insulation thickness is defined for the environmental aspect. A new method is presented in this paper that combines economic and environmental approach. In this method, costs and environmental impacts are combined, and the optimum thickness is calculated for this approach in a similar way to the other two approaches.

In the analysis, economic and environmental approaches as well as CEEM are investigated. Environmental concerns have been increasing in the last decades, and these concerns must be taken into account as well as economic concerns. Determining insulation thickness is important to decrease energy, economic variables, and environmental effects. The piping system considered by the authors is illustrated in Figure 1. Natural gas is chosen as fuel in the heating system. Bilecik, which is located in the Marmara region in Turkey, is chosen for investigations, and calculations are made for heating season lasting nearly 6 months. Turkey has a standard called as TS 825 for "heat insulation rules in buildings." According to the TS 825, four different degree-day regions were determined in Turkey. Broad information about these degree-day regions can be obtained from this standard (Dasdemir et al. 2017). According to TS 825, minimum mean temperature for the Bilecik is -0.3°C in January (Turkish Standard Institute 2008). Hence, in the calculations, ambient temperature is assumed as 0°C , hot fluid temperature is assumed as 90°C , and heating period is chosen as 180 days in a year. Rockwool and glass wool are chosen as insulation materials, and the efficiency of the heating system is assumed as 85%. All calculations are done for unit pipe, which is selected 2 inc for ANSI/ASME B 36.10", length and annual process. Parameters used in this study can be seen in Table 1. Annual heating loss from the pipe (J/m) system is calculated as

$$q = 86400 \cdot 180 \cdot (T_{hf} - T_a) \cdot U \quad (1)$$

where T_{hf} is the hot fluid temperature ($^{\circ}\text{C}$), T_a is the ambient temperature ($^{\circ}\text{C}$), and U is the heat transfer coefficient ($\text{W}/\text{m}\cdot\text{K}$). Annual energy consumption is (J/m) (Özel et al. 2017)

$$E = \frac{q}{\eta} \quad (2)$$

Annual fuel consumption (m_F) for unit length of the pipe (kg/m) is defined as (Özel et al. 2017)

$$m_F = \frac{E}{H_u} \quad (3)$$

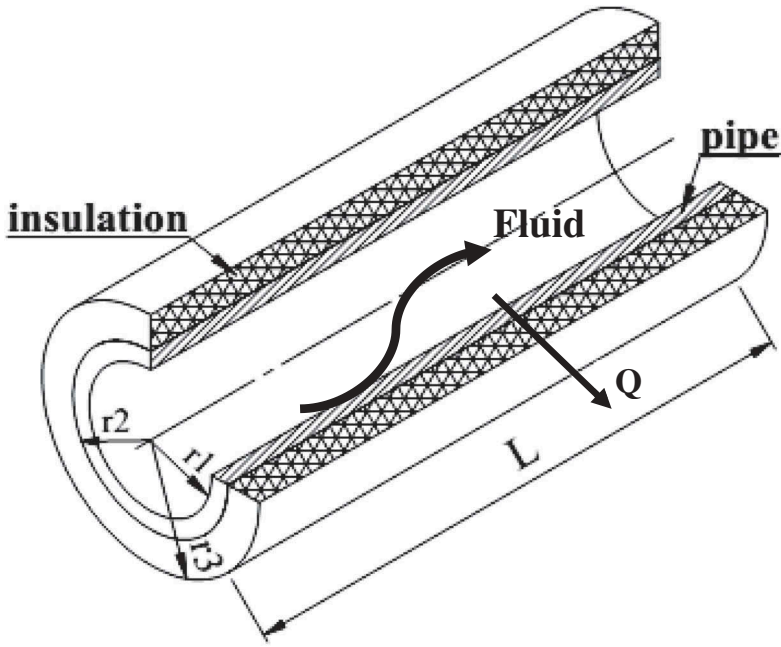
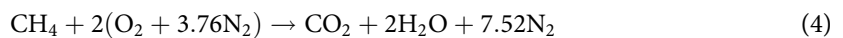


Figure 1. Investigated pipe system.

Table 1. Parameters used in calculations (Kanbur et al. 2017; Goedkoop and Spriensma 2000; Ardente et al. 2008).

Parameter	Unit	Value
Environmental impact point	mpts/kg	
Rockwool		4.2
Glass wool		2.1
Fuel		114
CO ₂		5.45
Boiler efficiency		0.85
Density of insulation material	kg/m ³	
Rockwool		105
Glass wool		45
c_F	\$/kg	1.68
c_{ins} (rockwool)	\$/m ³	132
c_{ins} (glass wool)	\$/m ³	103
d_F	\$/kg	1.06
d_{CO_2}	\$/kg	0.0327
d_F	\$/kg	1.06
GWP (rockwool)		1.45
GWP (glass wool)		2.2

where H_u is the lower heating value of the fuel (J/kg). Methane (CH₄) can be assumed as natural gas, because natural gas consists of more than 90% methane. Combustion process is assumed to be complete for facilitating calculations, and the combustion reaction is shown as follows (Özel et al. 2017):



CO₂ emission (kg/m) can be described as follows:

$$m_{CO_2} = 2.75m_F \quad (5)$$

Heat transfer coefficients (W/m.K) for no-insulation and insulation pipe conditions are shown in Eqs (6) and (7), respectively:

$$U_{nins} = \frac{1}{R_i + R_p + R_o} = \frac{1}{R_{T,nins}} \quad (6)$$

$$U_{ins} = \frac{1}{R_i + R_p + R_{ins} + R_o} = \frac{1}{R_{T,ins}} \quad (7)$$

$$A_i = 2\pi.L.r_1 \text{ and } A_o = 2\pi.L.r_2 \quad (8)$$

where k_p is thermal conductivity (W/m.K) of pipe, r_1 and r_2 are respectively the outer and internal radii of the pipe, and A_i and A_o are respectively the inside and outside surface areas of the pipe (Özel et al. 2017):

The total internal resistance of insulated piping system is (Özel et al. 2017)

$$R_{T,ins} = \frac{1}{h_i.A_i} + \frac{\ln(r_2/r_1)}{2\pi.L.k_p} + \frac{\ln(r_3/r_2)}{2\pi.L.k_{ins}} + \frac{1}{h_o.A_o^*} \quad (9)$$

where k_{ins} is the thermal conductivity of insulation material (W/m.K) and r_3 is the outer radius of the insulated pipe or it can be called as insulation thickness. Also, h_i and h_o are the convection heat transfers (W/m²K) of the inside and outside surfaces of the piping system, respectively. A_o^* the outside surface area of the insulated pipe:

$$A_o^* = 2\pi L r_3 \quad (10)$$

Economic approach

In this approach, life-cycle cost method is applied. Total cost are the sum of annual fuel cost and insulation thickness. The annual fuel cost per unit length (\$/m) is written as (Özel et al. 2017)

$$c_F = c_F.m_F \quad (11)$$

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

The present worth factor (PWF) is calculated to define cost during the lifetime. PWF is incorporated with inflation rate, g , and interest rate, i . Interest rate i^* adapted for inflation can be calculated as

$$i^* = \begin{cases} \frac{i-g}{1+g} & ; \quad i > g \\ \frac{g-i}{1+i} & ; \quad i < g \end{cases} \quad (12)$$

and PWF is written as follows:

$$PWF = \begin{cases} \frac{1-(1+i^*)^{-N}}{i^*} & ; \quad i \neq g \\ (1+i)^{-1} & ; \quad i = g \end{cases} \quad (13)$$

where N is the lifetime of the insulation material and i^* is the interest rate adjusted for the inflation rate. Here, N is assumed as 10 years, i is assumed as 10%, and $i = g$. The annual fuel cost can be arranged as (Özel et al. 2017)

$$C_F = c_f.PWF.m_F \quad (14)$$

The total cost of the insulation material (\$/m) is (Özel et al. 2017)

$$C_{ins} = c_i \cdot V \quad (15)$$

where c_i is the cost per m^3 of insulation material and V is the volume of the insulation material (m^3). The total annual (\$/m) is (Özel et al. 2017)

$$C_T = c_f \cdot PWF \cdot m_F + c_i \cdot V_{ins} \quad (16)$$

The annual cost saving per unit surface length is given by

$$C_S = C_{T,nins} - C_{T,ins} \quad (17)$$

Combined economic and environmental method

In this approach, environmental costs presented in Kanbur et al. (2017) are considered. In the analysis, environmental costs and economic costs are combined, and environmental and economic parameters are considered together. In the CEEM, same steps, which is applied in the economic method, are used for determining optimum point and cost saving. First, the combined cost of the fuel is shown in Eq. (19). Determining optimum insulation thickness and cost saving can be calculated similarly.

$$D_F = m_F \cdot (c_F + d_F) \quad (18)$$

where D_F is the environmental cost of the methane. The cost of CO_2 is described as

$$D_{CO_2} = m_{CO_2} \cdot (d_{CO_2}) \quad (19)$$

where d_{CO_2} is the environmental cost of CO_2 . The cost of insulation combined with environmental cost is

$$D_{ins} = (c_{ins} + GWP \cdot d_{CO_2} \cdot \rho_{ins}) \cdot V \quad (20)$$

where D_{ins} is the environmental cost of the insulation material, GWP is the global warming potential of the insulation material, and ρ_{ins} is the density (kg/m^3) of the insulation material. The total environmental and economic combined cost is written as follows:

$$D_T = (D_F + D_{CO_2})PWF + D_{ins} \quad (21)$$

Combined cost saving is

$$D_S = D_{T,nins} - D_{T,ins} \quad (22)$$

Environmental methods

In this method, environmental effects are described as mpoints (Goedkoop and Spriensma 2000) and only environmental effects are taken into account in this analysis. In the environmental analysis, economic variables are replaced by environmental. In the environmental analysis, economic variables are replaced by .Total environmental impact of the pipe system (mPts/m) is (Özel et al. 2017):

$$B_T = b_F m_F + b_{CO_2} m_{CO_2} + b_{ins} \rho_{ins} V_{ins} \quad (23)$$

where b_F is the environmental impact of fuel (mPts/kg), b_{CO_2} is the environmental impact of CO_2 (mPts/kg), b_{ins} is the environmental impact of insulation material (mPts/kg), ρ_{ins} (kg/m^3) is the density of the insulation material, and V_{ins} (m^3) is the volume of the insulation material. The net saving of the environmental impact of the pipe system (mPts/m) is (Özel et al. 2017)

$$B_{T,S} = B_{T,S,nins} - B_{T,S,ins} \quad (24)$$

The net saving of the heat energy loss ($E_S, J/m$) is the difference between the energy consumption at the non-insulation conditions and energy consumption in insulation conditions:

$$E_S = E_{nins} - E_{ins} \quad (25)$$

where E_{nins} (J/m) is the energy consumption at the non-insulation conditions and E_{ins} (J/m) is the energy consumption at insulation conditions.

Results and discussion

In the present study, an approach is suggested for insulation applications called as CEEM. Investigation location is chosen as Bilecik for the analysis. Investigation is performed for heating season, and pipe system is considered. Insulation materials are chosen as rockwool and glass wool. In addition, economic and environmental approaches are investigated, and the results are compared with each other. Parameters used in the calculation can be found in Table 1.

In Figure 2, one can see the change of D_T , C_T , B_T with insulation thickness for the rockwool. All of these have an optimum point, which makes a minimum of D_T , C_T , and B_T . Optimum insulation thickness of the D_T , C_T , and B_T are 0.46, 0.39, and 0.54 m, respectively. According to the results, D_T decreases from 925.621 to 116.340 \$/m year, C_T decreases from 549.55 to 76.033 \$/m year, and B_T decreases from 4,640.62 to 536.817 mpts/m year. In Figure 3, change of D_T , C_T , B_T with insulation thickness for the glass wool may be seen. Similar results of rockwool, D_T , C_T , and B_T have optimum points that are equal to 0.47, 0.40, and 0.59 m, respectively. Between the investigated range, D_T decreases from 784.481 to 92.593 \$/m year, C_T decreases from 465.751 to 60.578 \$/m year, and B_T decreases from 3,932.78 to 360.464 mpts/m year. As it is seen from the results, D_T and C_T have close optimum points for the rockwool and glass wool; however, values at the optimum point of the rockwool are bigger than those of the glass wool.

In Figures 4 and 5, savings of $D_{T,S}$, $C_{T,S}$, and $B_{T,S}$ are shown. For the rockwool, $D_{T,S}$ has 2,733.55 \$/m year cost saving at the optimum point; similarly, $C_{T,S}$ has 1,615.80 \$/m year cost saving at the optimum point and $B_{T,S}$ has 13,751.90 mpts/m year environmental saving at the optimum point. For the glass wool, $D_{T,S}$ has 2,757.30 \$/m year cost saving at the optimum point, similarly $C_{T,S}$ has 1,631.27 \$/m year cost saving at the optimum point and $B_{T,S}$ has 13,928.3 mpts/m year

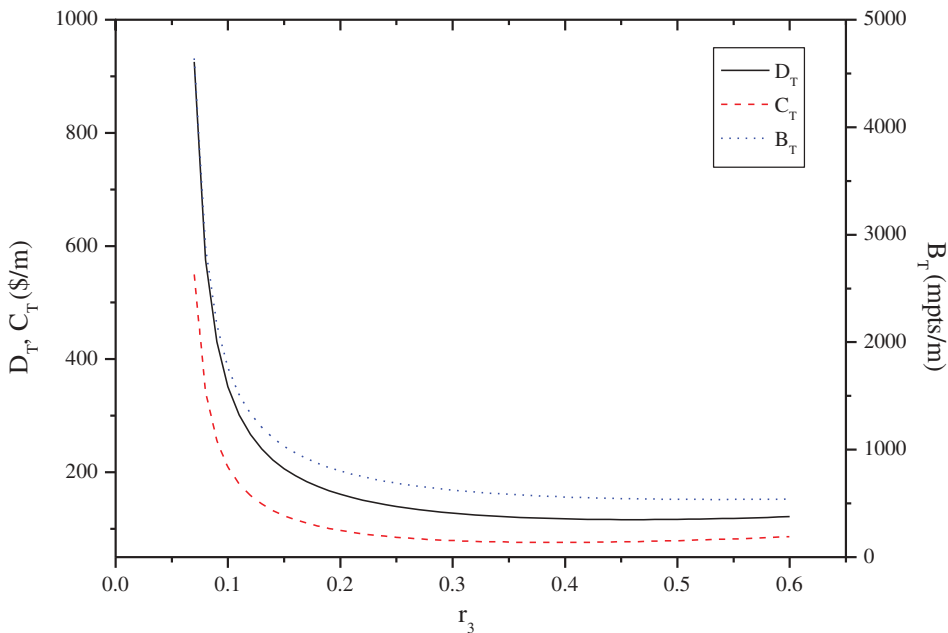


Figure 2. Change of D_T , C_T , B_T with insulation thickness for rockwool.

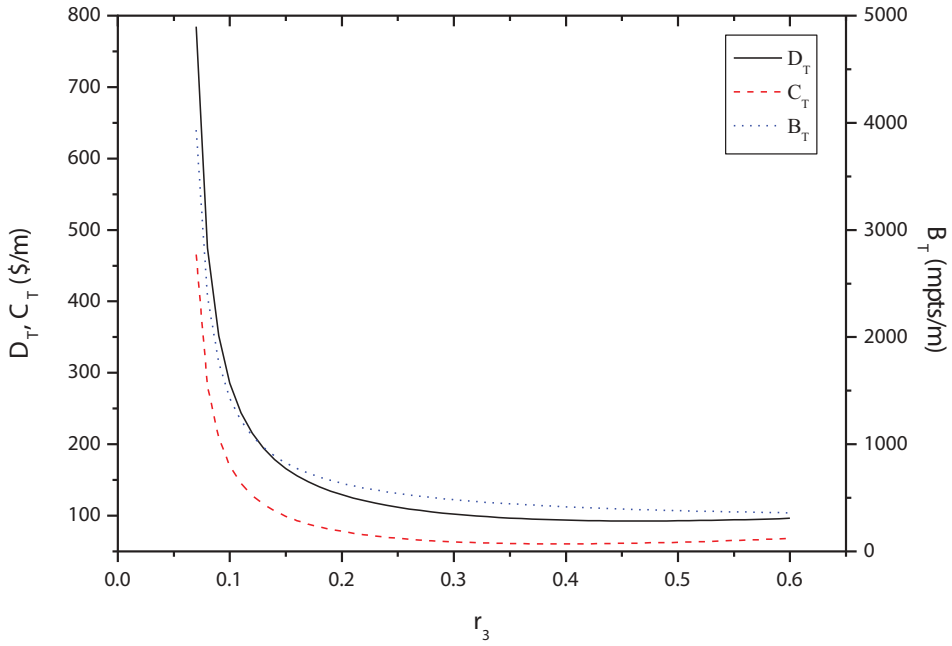


Figure 3. Change of D_T , C_T , B_T with insulation thickness for glass wool.

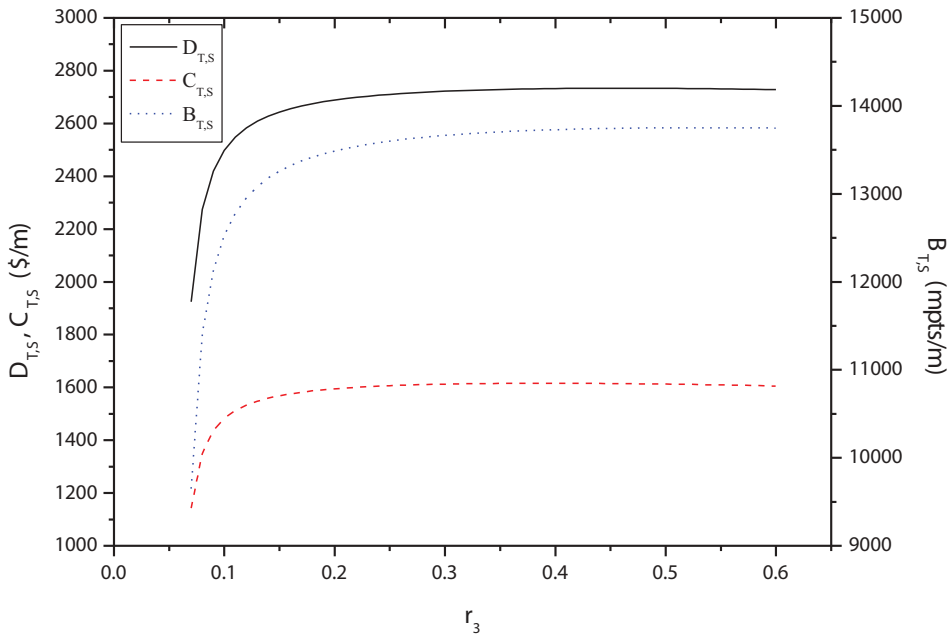


Figure 4. Change of savings of D_T , C_T , B_T with insulation thickness for rockwool.

environmental saving at the optimum point. Comparing the results, the cost saving of $D_{T,S}$ is nearly two times than $C_{T,S}$, and the saving values of glass wool are bigger those of than rockwool.

Energy saving values for rockwool and glass wool are revealed in Figure 6. Energy savings increase with r logarithmically. Increasing rate is really fast until $r = 0.15$. According to the figure,

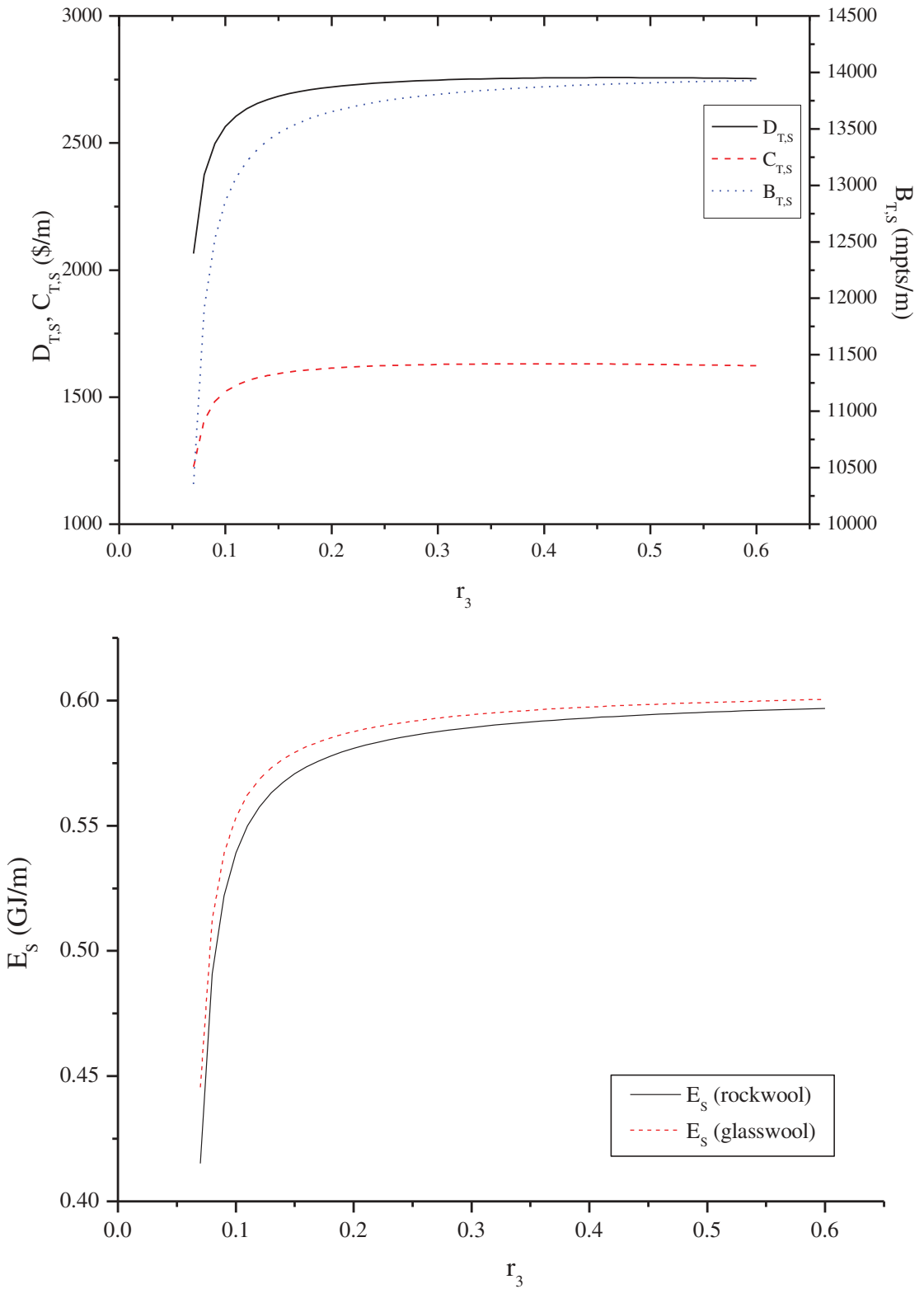


Figure 5. Change of savings of D_T , C_T , B_T with insulation thickness for glass wool.

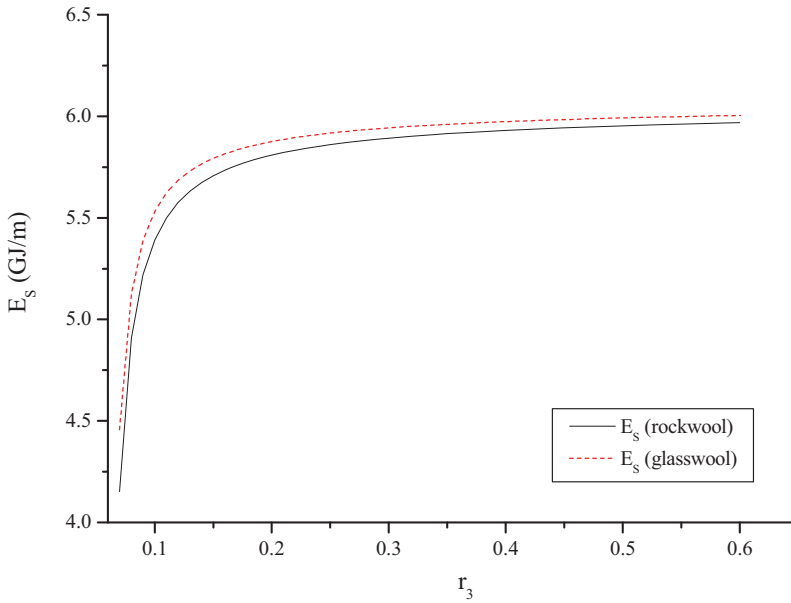


Figure 6. Energy savings with insulation thickness for rockwool and glass wool.

energy saving results for the glass wool is bigger than those of rockwool. Maximum energy saving for the rockwool is equal to 5.97GJ/m year and for the glass wool is equal to 6 GJ/m year.

Conclusions

In this study, an alternative method called as CEEM is presented. Not only fuel and insulation prices but also environmental costs of the fuel, insulation material, and greenhouse gasses (only CO₂ is taken into account in this study) are considered, and cost of environmental impacts are incorporated with the economic parameters. Bilecik is chosen as investigated location, and a pipe system is considered. The results of CEEM is compared with the results of the economic and environmental approaches. Results show that CEEM has a bigger optimum point than economic method and is smaller than environmental approaches. The annual cost saving of CEEM is nearly two times bigger than the economic approach. Finally, CEEM can be considered an alternative method for the insulation application, and in this way, economic and environmental parameters can be regarded together.

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