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INVESTIGATION OF THE EFFECT OF OPTIMUM INSULATION THICKNESS OF BUILDING EXTERIOR WALLS ON ENERGY CONSUMPTION AND REDUCTION OF EMISSIONS

ABSTRACT
The heating and cooling load of buildings gets reduced by preventing heat transfer to the external environment using exterior wall insulation. In addition to the saving achieved by reducing fuel consumption, the amount of harmful gases emitted into the atmosphere also gets reduced and a positive contribution is made to the environment. It is a known fact that 85% of CO_2 emission in Turkey is caused by the energy sector in Turkey. In this study, the optimum insulation thickness of exterior walls and emission per unit area was calculated for 81 provinces in Turkey. The Life Cycle Cost method was used as the approach. As a result, it was determined that while the optimum insulation thickness varied between 0.024m (İçel) and 0.149m (Ardahan), a 75%-80% reduction can be achieved in emissions. Additionally, energy savings and payback periods based on optimum insulation thickness in heating and cooling for provinces selected from five different climatic zones (Antalya, Istanbul, Ankara, Kayseri, and Erzurum) were calculated and compared. In the selected provinces, the highest energy savings and the shortest payback period were obtained for Erzurum as 46.93$/m^2 and 1.33 years.
Keywords: Degree Days, Energy Saving, Optimum Insulation Thickness, Greenhouse Gas Emission, External Walls

1. INTRODUCTION
Economic crises and depletion of energy resources across the world have made efficient use of energy necessary. More than three quarters of the energy used in buildings is used for heating and cooling. Lack of or insufficient insulation causes loss of some energy in buildings. However, it is possible to prevent this energy waste to a great extent by insulating the outer walls, which are the most heat-losing surface in buildings. Other important benefits of insulation are thermal comfort and environmental protection. Thermal insulation establishes an ideal balance between the human body and environment temperatures in buildings with insulation. A reduced fuel consumption thanks to building insulation also reduces the amount of greenhouse gas emissions, contributing to the protection of environment. In recent years, several studies have been conducted especially on energy conservation through insulation in buildings. Kürekçi determined the optimum insulation thickness by making separate calculations for 81 provinces in Turkey according to heating and cooling degree days and using four different fuels and three different insulation materials. Accordingly, net energy conservation increased, payback periods decreased for natural gas, coal, fuel-oil and LPG, respectively [1]. Açıkkalp and Yerel Kandemir presented an alternative and new method,

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called the Combined Economic and Environmental Method, in which economic and environmental impacts were combined to determine the optimum insulation thickness. By using this method, they analyzed the use of rock and glass wools on outer walls in Bilecik, Turkey, and determined the optimum points for an economic and environmental approach [2].

Alsayed and Tayeh calculated the optimum insulation thicknesses on different degree days in Palestine by using LPG for winter and electricity for summer, and concluded that insulation type and degree day value had the most important effect on optimum insulation thickness [3]. Şencan Şahin and Dikmen determined the optimum insulation thickness for different fuel types to save energy during heating buildings in winter and cooling them in summer in Denizli, Turkey, taking into account CO_2 emissions. They found that the optimum insulation thickness varied between 0.012-0.031m for heating in winter and between 0.009-0.022m for cooling in summer [4]. Karakaya performed an analysis of optimum insulation thickness, energy conservation, payback period and environmental impact during heating and cooling of buildings in Batman, Turkey. The author used four different wall components, three different types of fuel, and two different insulation materials, and determined that CO_2 and SO_2 emissions decreased by 77.00% in optimum insulation thickness compared to the uninsulated situation [5].

Ozel studied thermal, economic, and environmental effects for different wall directions in insulated buildings under dynamic thermal conditions in Kars, one of the cities with the lowest average air temperatures in Turkey. In the study, calculations were made for two different wall structures and two different insulation materials. For the heating season, the lowest heating load, optimum insulation thickness, and energy savings were achieved in the south-facing wall, while the highest heating load, optimum insulation thickness, and energy savings were achieved for the north-facing wall. When using 9 cm insulation, an 85% reduction in emissions was detected for all wall orientations [6]. In their study, Küçüktopçu and Cemek calculated the optimum insulation thickness, energy savings, payback period, and CO_2 emission rates for poultry shelters in Antalya, Samsun, Ankara, and Erzurum provinces of Turkey. Five different energy sources (coal, fuel oil, natural gas, LPG, and electricity), two different insulation materials, Extruded Polystyrene (XPS), and Expanded Polystyrene (EPS) were used in the study. The lowest CO_2 emission reduction value (39.82%) was obtained when XPS was used as the optimum insulation material and natural gas was used as the energy source in Antalya, while the highest value was obtained when EPS and LPG (83.98%) were used in Erzurum [7].

In their study, Nyers et al. analyzed the optimum energy and economical thickness of the thermal insulation layer for the outer walls. The analysis was carried out by implementing a new "investment savings" method. The mathematical model consisted of energy and economics. Analytical-numerical and graphical-numerical methods have been implemented to solve the mathematical model whose optimization criterion was the minimum payback period of the initial investment. With the developed mathematical model, the optimum thermal insulation layer thickness was obtained in Serbia in 2014 for energy and economic conditions. As an important result of the study, a 4.86 times increase in thickness is achieved with only a 1.69 times increase in investment [8]. Muddu et al. calculated the optimum insulation thickness, annual energy consumption, payback period, and CO_2 emissions for typical walls in 25 regions of Ireland. In the study, they reported that the wall type, materials, configuration, insulation type, and the type of heat energy all had significant effects on the annual cost. The calculated optimum insulation thickness in Ireland varied by 30% as a result of the increase in the number of heating days from low to high [9]. Yuan et al. determined the optimal thermal resistance of insulation materials for residences in six climate zones of Japan, with a combination of four different insulation materials and four different fuel sources. They calculated the energy cost and payback period of the outer walls per unit area. The degree-day (DD) method was used in calculations. In the study, the optimum thermal resistance decreased from Climate Zone I to VI (from low latitude to high latitude). However, the payback period for insulated buildings had an opposite trend [10]. Liu et al. presented a combination of heat and moisture transfer model that takes into account the effect of moisture transfer on heat transfer to calculate the cooling and heating transmission load. They determined the optimum insulation thickness of the exterior walls using the P1-P2 economic model. Changsha, Chengdu, and Shaoguan were chosen as the sample cities in China. The results showed that the optimum thickness of Extruded Polystyrene (XPS) ranged from 0.053 to 0.069 m and the optimum thickness of Expanded Polystyrene (EPS) ranged from 0.081 to 0.105m [11]. Sabapathy et al. performed an energy-saving analysis by using a numerical analysis for three building shell configurations in five different climate zones of India. The insulating potential of straw, which is an agricultural waste in the context of India's broad climate, was the focus of this study. They concluded that energy savings in the range of 67-96% can be achieved in the different climatic zones by introducing straw to the outer shell only 10cm in thickness [12].

2. RESEARCH SIGNIFICANCE

Carbon dioxide has the largest share of greenhouse gases. The most important source of carbon dioxide is fossil fuels. It is essential and crucial to use optimum insulation thickness in buildings for reducing fuel consumption and emission values. In this study, optimum insulation thicknesses were determined for building exterior walls located in 81 provinces in Turkey, and fuel consumption and emission values per unit area were calculated depending on the insulation thickness. When the literature was examined, no such study including all the provinces in Turkey was encountered. In this respect, the study is expected to contribute to the literature. Two different insulation materials and two different commonly used fuels were chosen in the study. The degree day method was used to analysis. However, this study examined the optimum insulation thickness of external walls and energy conservations and payback periods, comparing provinces from five different climate zones in Turkey and taking into account the heating of buildings in winter and cooling in summer. Electricity was used as an energy source for cooling. Energy conservations and payback periods were calculated for a 10-year lifetime.

3. MATERIAL AND METHOD

3.1. Optimum Insulation Thickness on External Walls

Optimum insulation thickness for external walls in buildings varies according to number of degree days, outside temperature, type of fuel, type of thermal insulation material, and economic criteria such as lifestyle, inflation and interest rate. In this study, life-cycle costing (LCC) method was used for the analysis of external walls [13, 14 and 15]. Heating and cooling degree days values are obtained from Ref. [1]. In the analysis, two different fuels (natural gas and coal) for heating and electricity for cooling and two different insulation materials (XPS and EPS), which are widely preferred in external wall insulation in Turkey, were used according to the sheathing method. Table 1 shows the properties and costs of natural gas and coal fuels used in heating and the cost of electricity used in cooling. Table 2 presents the properties of XPS and EPS insulation materials.

Table 1. Properties of fuels and system efficiency [16 and 17]

	Cost	Lower HeatingValue, H_u	System Efficiency (%)
Natural Gas	0.2868$/m^3	34.542x106 J/m^3	93
Coal	0.1921$/kg	25.122x106 J/kg	65
Electricity	0.1252$/kWh	2.5 (COP)	

Table 2. Properties of insulating materials [18]

	Heat Conduction Coefficient, λ (W/mK)	Cost($)
XPS (Extruded Polystyrene)	0.032	85
EPS (Expanded Polystyrene)	0.035	50

3.2. Calculation of the Heat Load

The heat losses in buildings generally occur through external walls, windows, ceiling, floor and air infiltration. The heat transfer coefficient U (W/m^{2}K) of a wall that includes a layer of insulation is given by:

$$U = \frac{1}{R_i+R_w+R_{ins}+R_o} \tag{1}$$

Where R_i and R_o are the inner and outer air-film thermal resistances, respectively. R_w is the total thermal resistance of the wall layers without insulation. The thermal resistance of the insulation layer R_{ins} is given by:

$$R_{ins} = \frac{x}{\lambda} \tag{2}$$

Where x and λ are the thickness and the thermal conductivity of the insulation material, respectively. If R_{wt} is the total the wall thermal resistance excluding the insulation layer resistance, equation (1) can be rewritten as:

$$U = \frac{1}{R_{wt}+R_{ins}} \tag{3}$$

The heat loss from unit surface of external wall:

$$q = U\Delta T \tag{4}$$

Where U is the overall heat transfer coefficient. The annual heat losses from unit area can be approximately calculated depending on the degree-days number as the following:

$$q_A = 86400\, DD\, U \tag{5}$$

Where DD is the degree days. The annual energy requirement for heating (E_A) can be obtained approximately by dividing the annual heat loss to the efficiency of the heating system (η_s):

$$E_A = \frac{86400\, DD}{\left(R_{wt}+\frac{x}{\lambda}\right)\eta_s} \tag{6}$$

$$m_{fA} = \frac{86400\, DD}{\left(R_{wt}+\frac{x}{\lambda}\right)H_u\, \eta_s} \tag{7}$$

The annual heating cost C_A, H ($/m^2-year) per unit area can be calculated by the equation (8):

$$C_{A,H} = \frac{86400\, HDD\, C_f}{\left(R_{wt}+\frac{x}{\lambda}\right)H_u\, \eta_s} \tag{8}$$

Where C_f is fuel cost ($/kg) and H_u is the lower heating value of the fuel (J/kg; J/m^3). The annual cooling cost per unit area can be calculated using equation (9). COP is the performance coefficient of the cooling system and it was taken as 2.5 in this study [1]:

$$C_{A,C} = \frac{86400\, CDD\, C_f}{\left(R_{wt}+\frac{x}{\lambda}\right)COP} \tag{9}$$

3.3. Optimum Insulation Thickness Calculation

The LCC is one of the methods to calculate the optimum insulation thickness. Total heating cost is evaluated together with the present-worth factor *PWF* for the lifetime of *N* years. The *PWF* depends on the inflation rate (g), and the interest rate (i). According to the interest and inflation rates, *PWF* is defined as below:

$i>g$ then,

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

$i<g$ then,

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

$$PWF = \frac{(1+r)^N - 1}{r(1+r)^N} \quad (10)$$

N life was taken as 10 years and annual interest (i) and inflation (g) rates were taken as 8.25% and 12.66%, respectively according to 2020 data [19 and 20].

The total heating cost of the insulated building is given by:

$$C_t = C_A PWF + C_I x \quad (11)$$

or

$$C_t = \frac{86400\, HDD\, C_f\, PWF}{\left(R_{wt} + \frac{x}{\lambda}\right) H_u\, \eta_s} + C_I\, x \quad (12)$$

Where C_I is the cost of insulation material in \$/m^3 and x is the insulation thickness in m. The optimum insulation thickness is obtained by minimizing equation (12). Hence, the derivative of C_t with respect to x is taken and set equal to zero from which the optimum insulation thickness x_{opt} is obtained as:

$$x_{opt} = 293.94 \left(\frac{DD\, C_f\, PWF\, \lambda}{H_u\, C_I\, \eta_s}\right)^{1/2} - \lambda\, R_{wt} \quad (13)$$

3.4. Environmental Analysis

The general chemical formula for the combustion of fuels is as follows:

$$C_k H_l O_m S_p N_r + \alpha A(O_2 + 3.76 N_2) \rightarrow kCO_2 + \frac{l}{2} H_2O + pSO_2 + (\alpha - 1)AO_2 + BN_2 \quad (14)$$

A and B can be calculated from the equilibrium formula of oxygen:

$$A = k + \frac{l}{4} + p - \frac{m}{2} \quad (15)$$

$$B = 3.76\alpha\left(k + \frac{l}{4} + p - \frac{m}{2}\right) + \frac{r}{2} \quad (16)$$

By ignoring CO and NO_x emissions, the emission amounts obtained by burning one (1) kg of fuel can be calculated using the equation (14) as follows:

$$M_{CO_2} = \frac{kCO_2}{M} \equiv kgCO_2/kgfuel \quad (17)$$

$$M_{SO_2} = \frac{pSO_2}{M} \equiv kgCO_2/kgfuel \quad (18)$$

The total amount of CO_2 and SO_2 emissions can be calculated by placing the total amount of fuel (m_{yA}) within the scope of *DD* on the right side of the above equation:

$$M_{CO_2} = \frac{44k}{M} m_{fA} \quad (19)$$

$$M_{CO_2} = \frac{3801600DDk}{M\eta_s H_u}\left(\frac{\lambda}{\lambda R_{wt} + x}\right) \quad kg/year \quad (20)$$

$$M_{SO_2} = \frac{32p}{M} m_{fA} \quad (21)$$

$$M_{SO_2} = \frac{2764800DDp}{M\eta_s H_u}\left(\frac{\lambda}{\lambda R_{wt} + x}\right) \quad kg/year \quad (22)$$

The molar weight of fuel, M can be calculated as follows:

$$M = 12k + l + 16m + 32p + 14r \quad kg/kmol \quad (23)$$

4. FINDINGS AND DISCUSSIONS

In this study, optimum insulation thickness and emission per unit area were calculated for building exterior walls in 81 provinces, in Turkey. Table 3-4 presents the calculation results for the insulation materials XPS and EPS. It can be seen in Table 3 that, when using the insulation material XPS, optimum insulation thickness for coal and natural gas varies between 0.031 and 0.105m, and 0.024 and 0.089m, respectively. The fuel consumed varies between 2.808 and 6.893kg/m^2 per year for coal and between 1.637 and 4.020kg/m^2 per year for natural gas. The CO_2 emission of coal varies between 7.618 and 18.702kg/m^2 per year, while SO_2 emission varies between 0.007 and 0.018kg/m^2 per year. The CO_2 emission of natural gas varies between 4.335 and 10.642kg/m^2 per year.As presented in Table 4, when using the insulation material EPS, optimum insulation thickness for coal and natural gas varies between 0.047 and 0.149m and 0.038 and 0.127m, respectively. The amount of fuel consumed varies between 2.277 and 5.554kg/m^2 per year for coal and between 1.330 and 3.239kg/m^2 per year for natural gas. The CO_2 emission of coal varies between 6.178 and 15.068kg/m^2 per year and SO_2 emission varies between 0.006 and 0.014kg/m^2 per year. The CO_2 emission of natural gas varies between 3.522 and 8.575 kg/m^2 per year.Whencoal is used; in the coldest city, CO_2 and SO_2 emissions were reduced by 75% when XPS were used for building insulation and by 80% when EPS was used. In the hottest city, CO_2 and SO_2 emissions were reduced by 50% when XPS were used for building insulation and by 60% when EPS was used. When naturalgas is used; in the coldest city, CO_2 emission was reduced by 40% when XPS was used for building insulation and by 45% when EPS was used. In the hottest city, CO_2 emission was reduced by 25% when XPS was used for building insulation and by 30% when EPS was used.

Table 3. Calculation results for 81 provinces of Turkey in case of use XPS insulation material

	Coal				Naturalgas		
	x_{opt} (m)	m_{fA} (kg/m^2-year)	M_{CO2} (kg/m^2-year)	M_{SO2} (kg/m^2-year)	x_{opt} (m)	m_{fA} (kg/m^2-year)	M_{CO2} (kg/m^2-year)
Adana	0.031	2.841	7.708	0.007	0.024	1.658	4.389
Adıyaman	0.052	3.956	10.735	0.010	0.042	2.308	6.111
Afyon	0.073	5.111	13.866	0.013	0.061	2.982	7.895
Ağrı	0.096	6.396	17.354	0.017	0.081	3.733	9.882
Amasya	0.062	4.520	12.264	0.012	0.051	2.639	6.986
Ankara	0.070	5.475	14.856	0.014	0.059	2.902	7.684
Antalya	0.037	3.163	8.581	0.008	0.030	1.846	4.888
Artvin	0.066	4.739	12.858	0.012	0.055	2.766	7.323
Aydın	0.040	3.351	9.093	0.009	0.033	1.956	5.178
Balıkesir	0.056	4.204	11.407	0.011	0.046	2.456	6.501
Bilecik	0.065	4.705	12.765	0.012	0.054	2.748	7.274
Bingöl	0.073	5.124	13.902	0.013	0.061	2.990	7.917
Bitlis	0.080	5.535	15.018	0.014	0.067	3.228	8.546
Bolu	0.073	5.105	13.850	0.013	0.061	2.980	7.889
Burdur	0.065	4.662	12.650	0.012	0.054	2.720	7.202
Bursa	0.056	4.212	11.428	0.011	0.046	2.460	6.512
Çanakkale	0.054	4.065	11.029	0.010	0.044	2.372	6.279
Çankırı	0.073	5.143	13.955	0.013	0.061	3.003	7.950
Çorum	0.075	5.227	14.181	0.014	0.063	3.053	8.083
Denizli	0.050	3.877	10.518	0.010	0.041	2.263	5.991
Diyarbakır	0.061	4.451	12.077	0.012	0.050	2.595	6.871
Edirne	0.062	4.532	12.298	0.012	0.052	2.644	7.001
Elazığ	0.070	4.954	13.440	0.013	0.058	2.891	7.654
Ercincan	0.076	5.309	14.404	0.014	0.064	3.095	8.195
Erzurum	0.102	6.678	18.119	0.018	0.086	3.898	10.319
Eskişehir	0.076	5.307	14.398	0.014	0.064	3.099	8.204
Gaziantep	0.058	4.312	11.700	0.011	0.048	2.514	6.655
Giresun	0.053	4.037	10.954	0.010	0.044	2.356	6.237
Gümüşhane	0.079	5.466	14.830	0.014	0.066	3.189	8.442

Hakkari	0.083	5.661	15.360	0.015	0.070	3.304	8.748
Hatay	0.038	3.214	8.722	0.008	0.030	1.876	4.966
Isparta	0.069	4.911	13.325	0.013	0.057	2.866	7.588
İçel	0.031	2.808	7.618	0.007	0.024	1.637	4.335
İstanbul	0.055	4.150	11.261	0.011	0.045	2.422	6.411
İzmir	0.038	3.215	8.723	0.008	0.030	1.876	4.698
Kars	0.101	6.640	18.016	0.017	0.085	3.875	10.259
Kastamonu	0.077	5.361	14.546	0.014	0.065	3.129	8.285
Kayseri	0.077	5.363	14.551	0.014	0.065	3.138	8.307
Kırklareli	0.063	4.585	12.439	0.012	0.052	2.674	7.080
Kırşehir	0.073	5.142	13.951	0.013	0.061	2.999	7.970
Kocaeli	0.054	4.061	11.019	0.010	0.044	2.373	6.282
Konya	0.073	5.118	13.886	0.013	0.061	2.988	7.971
Kütahya	0.074	5.161	14.003	0.013	0.061	3.012	7.975
Malatya	0.067	4.769	12.938	0.012	0.055	2.784	7.370
Manisa	0.048	3.765	10.215	0.010	0.039	2.197	5.817
K.Maraş	0.051	3.908	10.603	0.010	0.042	2.280	6.038
Mardin	0.058	4.307	11.686	0.011	0.048	2.511	6.648
Muğla	0.055	4.171	11.316	0.011	0.046	2.431	6.435
Muş	0.084	5.741	15.577	0.015	0.071	3.348	8.865
Nevşehir	0.076	5.292	14.360	0.014	0.064	3.088	8.176
Niğde	0.073	5.140	13.946	0.013	0.061	2.998	7.938
Ordu	0.054	4.084	11.082	0.011	0.044	2.382	6.306
Rize	0.054	4.104	11.136	0.011	0.045	2.392	6.333
Sakarya	0.055	4.117	11.171	0.011	0.045	2.402	6.359
Samsun	0.054	4.107	11.143	0.011	0.045	2.396	6.344
Siirt	0.057	4.257	11.550	0.011	0.047	2.482	6.572
Sinop	0.055	4.166	11.303	0.011	0.046	2.431	6.435
Sivas	0.083	5.640	15.304	0.015	0.069	3.294	8.721
Tekirdağ	0.059	4.334	11.760	0.011	0.048	2.528	6.692
Tokat	0.065	4.708	12.773	0.012	0.054	2.747	7.272
Trabzon	0.052	3.994	10.837	0.010	0.043	2.330	6.169
Tunceli	0.071	5.008	13.588	0.013	0.059	2.922	7.736
Şanlıurfa	0.047	3.727	10.112	0.010	0.039	2.174	5.756
Uşak	0.066	4.722	12.811	0.012	0.055	2.756	7.297
Van	0.083	5.671	15.387	0.015	0.070	3.306	8.752
Yozgat	0.082	5.626	15.265	0.015	0.069	3.280	8.684
Zonguldak	0.058	4.319	11.720	0.011	0.048	2.520	6.672
Aksaray	0.069	4.925	13.362	0.013	0.058	2.876	7.614
Bayburt	0.093	6.190	16.796	0.016	0.074	3.612	9.562
Karaman	0.071	4.992	13.544	0.013	0.059	2.913	7.711
Kırıkkale	0.069	4.909	13.320	0.013	0.058	2.865	7.584
Batman	0.054	4.106	11.140	0.011	0.045	2.396	6.343
Şırnak	0.049	4.367	11.849	0.011	0.049	2.548	6.717
Bartın	0.062	4.534	12.303	0.012	0.052	2.647	7.007
Ardahan	0.105	6.893	18.702	0.018	0.089	4.020	10.642
Iğdır	0.072	5.055	13.715	0.013	0.060	2.948	7.806
Yalova	0.055	4.129	11.202	0.011	0.045	2.407	6.374
Karabük	0.061	4.452	12.079	0.012	0.050	2.623	6.944
Kilis	0.049	3.792	10.290	0.010	0.040	2.215	5.864
Osmaniye	0.038	3.192	8.660	0.008	0.030	1.866	4.939
Düzce	0.059	4.371	11.861	0.011	0.049	2.550	6.752

Table 4. Calculation results for 81 provinces of Turkey in case of use EPS insulation material

	Coal				Naturalgas		
	x_{opt} (m)	m_{fA} (kg/m^2-year)	M_{CO2} (kg/m^2-year)	M_{SO2} (kg/m^2-year)	x_{opt} (m)	m_{fA} (kg/m^2-year)	M_{CO2} (kg/m^2-year)
Adana	0.048	2.302	6.247	0.006	0.039	1.342	3.554
Adıyaman	0.076	3.174	8.612	0.008	0.063	1.853	4.906
Afyon	0.105	4.101	11.128	0.011	0.089	2.392	6.332
Ağrı	0.137	5.129	13.916	0.013	0.116	2.993	7.924
Amasya	0.090	3.624	9.833	0.009	0.076	2.116	5.603
Ankara	0.102	3.988	10.822	0.010	0.085	2.327	6.161
Antalya	0.056	2.561	6.950	0.006	0.046	1.493	3.952
Artvin	0.096	3.802	10.317	0.010	0.080	2.235	5.917
Aydın	0.062	2.704	7.338	0.007	0.050	1.597	4.181
Balıkesir	0.082	3.372	9.150	0.009	0.069	1.969	5.213
Bilecik	0.095	3.774	10.239	0.010	0.080	2.202	5.830

Bingöl	0.105	4.129	11.202	0.011	0.089	2.400	6.355
Bitlis	0.115	4.437	12.038	0.011	0.098	2.591	6.859
Bolu	0.105	4.094	11.109	0.011	0.088	2.390	6.328
Burdur	0.094	3.737	10.140	0.010	0.079	2.181	5.773
Bursa	0.082	3.409	9.250	0.009	0.069	1.980	5.241
Çanakkale	0.079	3.271	8.874	0.008	0.066	1.903	5.038
Çankırı	0.106	4.134	11.217	0.011	0.089	2.422	6.413
Çorum	0.108	4.204	11.407	0.011	0.091	2.458	6.507
Denizli	0.074	3.129	8.490	0.008	0.062	1.817	4.810
Diyarbakır	0.088	3.570	9.688	0.009	0.074	2.083	5.515
Edirne	0.091	3.635	9.863	0.009	0.076	2.130	5.639
Elazığ	0.101	3.985	10.812	0.010	0.085	2.327	6.162
Ercincan	0.110	4.265	11.573	0.011	0.093	2.488	6.586
Erzurum	0.144	5.375	14.585	0.014	0.123	3.127	8.279
Eskişehir	0.110	4.268	11.580	0.011	0.093	2.489	6.590
Gaziantep	0.085	3.467	9.408	0.009	0.071	2.016	5.338
Giresun	0.078	3.259	8.842	0.008	0.065	1.903	5.039
Gümüşhane	0.114	4.394	11.922	0.011	0.096	2.573	6.813
Hakkari	0.119	4.548	12.340	0.012	0.100	2.671	7.071
Hatay	0.058	2.581	7.003	0.006	0.047	1.520	4.024
Isparta	0.100	3.948	10.711	0.010	0.084	2.298	6.084
İçel	0.047	2.277	6.178	0.006	0.038	1.330	3.522
İstanbul	0.081	3.331	9.037	0.000	0.068	1.944	5.147
İzmir	0.058	2.578	6.996	0.006	0.047	1.519	4.021
Kars	0.143	5.346	14.506	0.014	0.122	3.113	8.242
Kastamonu	0.111	4.323	11.730	0.011	0.094	2.510	6.646
Kayseri	0.111	4.325	11.734	0.011	0.094	2.511	6.648
Kırklareli	0.092	3.684	9.997	0.009	0.077	2.156	5.707
Kırşehir	0.106	4.124	11.189	0.011	0.089	2.416	6.397
Kocaeli	0.079	3.265	8.859	0.008	0.066	1.904	5.041
Konya	0.105	4.126	11.194	0.011	0.089	2.399	6.350
Kütahya	0.106	4.157	11.279	0.011	0.090	2.414	6.391
Malatya	0.096	3.827	10.383	0.010	0.081	2.243	5.937
Manisa	0.071	3.021	8.197	0.008	0.059	1.777	4.706
K.Maraş	0.075	3.146	8.537	0.008	0.062	1.846	4.887
Mardin	0.085	3.459	9.385	0.009	0.071	2.022	5.353
Muğla	0.081	3.369	9.140	0.009	0.068	1.959	5.186
Muş	0.121	4.605	12.493	0.012	0.102	2.698	7.144
Nevşehir	0.121	3.920	10.635	0.010	0.102	2.297	6.081
Niğde	0.106	4.122	11.185	0.011	0.089	2.415	6.395
Ordu	0.079	3.298	8.949	0.008	0.066	1.923	5.092
Rize	0.080	3.295	8.940	0.008	0.066	1.940	5.137
Sakarya	0.080	3.318	9.004	0.008	0.067	1.932	5.116
Samsun	0.080	3.306	8.969	0.008	0.067	1.925	5.096
Siirt	0.084	3.411	9.256	0.009	0.070	1.997	5.287
Sinop	0.081	3.369	9.140	0.009	0.068	1.959	5.186
Sivas	0.118	4.546	12.334	0.012	0.100	2.651	7.018
Tekirdağ	0.086	3.475	9.428	0.009	0.072	2.028	5.370
Tokat	0.095	3.788	10.277	0.010	0.080	2.207	5.844
Trabzon	0.077	3.215	8.724	0.008	0.064	1.880	4.979
Tunceli	0.102	4.047	10.979	0.010	0.086	2.361	6.250
Şanlıurfa	0.070	3.016	8.183	0.008	0.058	1.762	4.665
Uşak	0.095	3.811	10.341	0.010	0.080	2.221	5.881
Van	0.119	4.556	12.360	0.012	0.101	2.654	7.026
Yozgat	0.118	4.517	12.256	0.012	0.100	2.634	6.973
Zonguldak	0.085	3.486	9.460	0.009	0.071	2.038	5.396
Aksaray	0.100	3.976	10.789	0.010	0.084	2.325	6.157
Bayburt	0.132	4.980	13.511	0.013	0.112	2.908	7.699
Karaman	0.102	4.020	10.907	0.010	0.086	2.345	6.209
Kırıkkale	0.100	3.951	10.729	0.010	0.084	2.311	6.117
Batman	0.080	3.300	8.954	0.008	0.067	1.922	5.088
Şırnak	0.086	3.531	9.581	0.009	0.072	2.061	5.458
Bartın	0.091	3.638	9.872	0.009	0.076	2.132	5.644
Ardahan	0.149	5.554	15.068	0.014	0.127	3.239	8.575
Iğdır	0.104	4.053	10.996	0.010	0.087	2.380	6.302
Yalova	0.080	3.336	9.053	0.009	0.067	1.943	5.144
Karabük	0.088	3.601	9.772	0.009	0.074	2.097	5.551
Kilis	0.072	3.052	8.281	0.008	0.060	1.777	4.706
Osmaniye	0.575	2.560	6.946	0.006	0.047	1.498	3.967
Düzce	0.086	3.531	9.581	0.009	0.072	2.061	5.458

However, one province from each of five climate zones in Turkey, including Antalya, Istanbul, Ankara Kayseri and Erzurum, were selected and compared for heating and cooling seasons. Fuel and electricity costs were determined, and optimum insulation thickness, net energy conservations and annual payback periods were calculated for each province. The effect of using insulation materials on annual combustion products were examined depending on insulation thickness. Figure 1 gives the optimum points indicating minimum total cost for heating and cooling loads in Antalya, Istanbul, Ankara, Kayseri and Erzurum. As insulation thickness increases, heating load and fuel cost decrease, but insulation cost increases. However, the total cost of fuel and insulation decreases up to a point, then increases again. The point referring to the minimum total cost indicates the optimum insulation thickness.

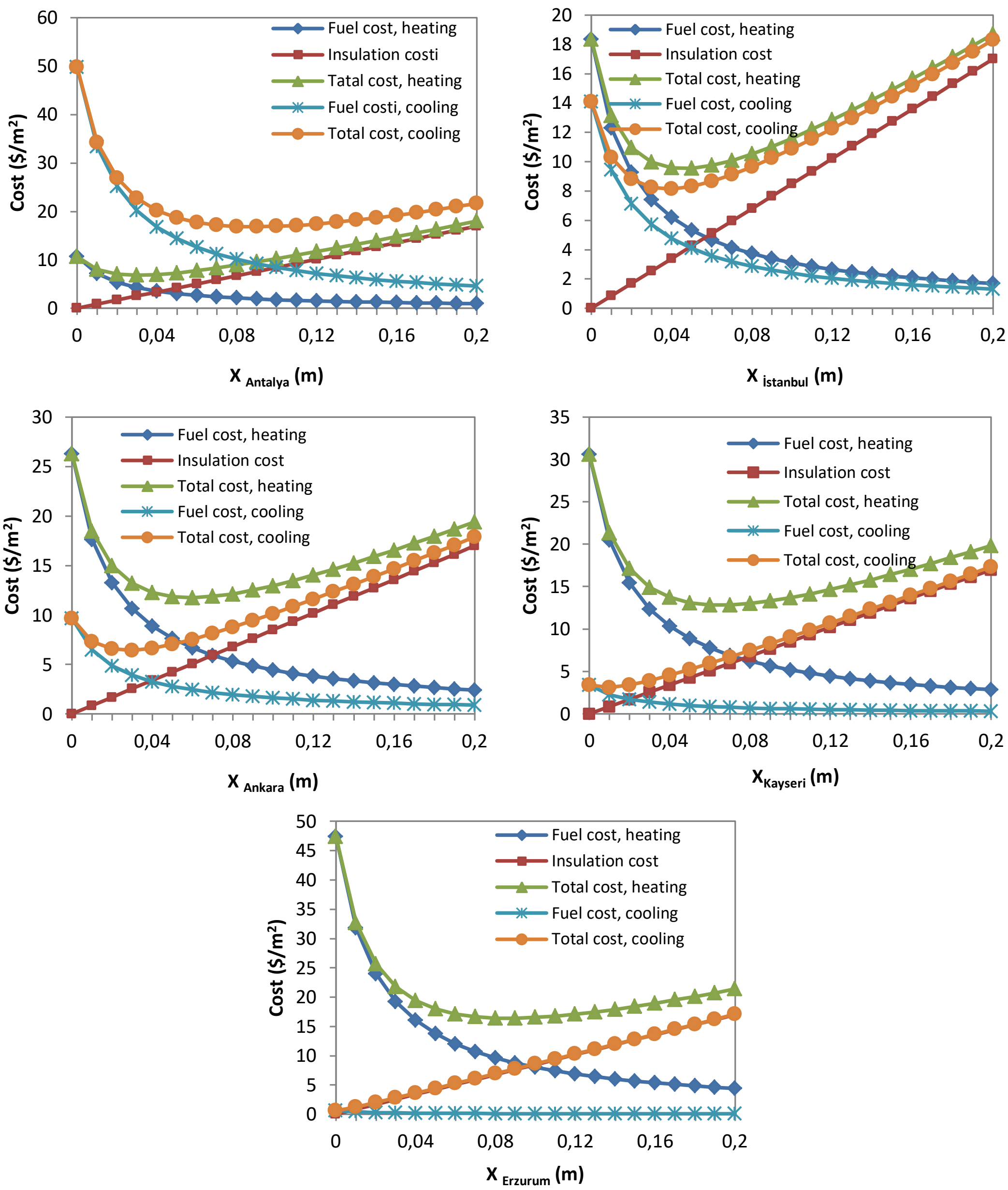

Figure 1. Optimum insulation thickness in heating and cooling

Figure 2 shows the effect of annual energy conservations on insulation thickness for different energy sources (natural gas and coal) in cause of use of XPS and EPS insulation materials in heating. A higher energy conservation was obtained when coal was used as fuel type. The highest energy conservation was achieved in Erzurum, which is the coldest province in all cases, while the lowest energy conservations was achieved in Antalya, the hottest province.

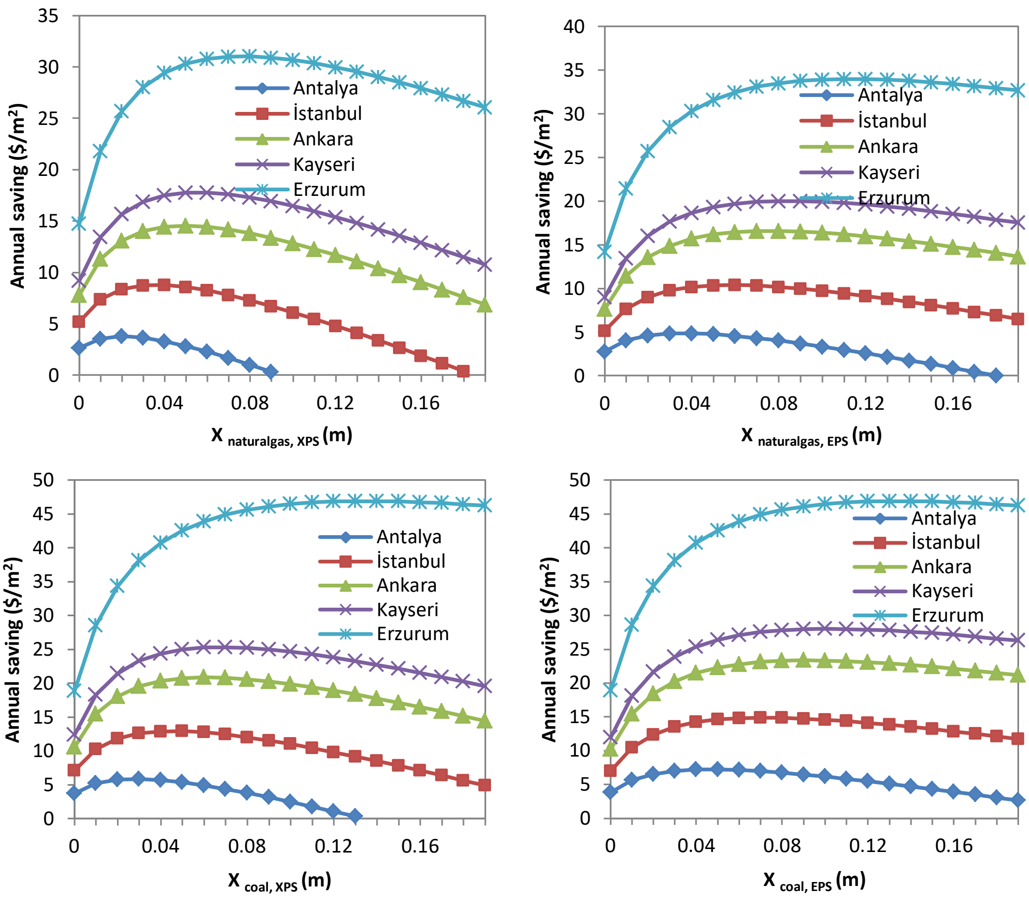

Figure 2. The effect of annual savings on insulation thickness

Table 5 presents the values recorded at the optimum point for each province, and gives the energy conservation calculated per unit area and the payback period values in case of application of optimum insulation thickness for different insulation materials and fuel types on external walls. The optimum insulation thickness varied according to type of fuels used in heating (natural gas, coal) and cooling (electricity) and insulation materials (XPS and EPS). As expected, the maximum energy conservation and the shortest payback period were achieved in the same case. The shortest payback periods for heating and cooling were obtained in Erzurum and Antalya, respectively. A higher energy conservation was achieved when EPS and coal were used in Erzurum and when EPS and coal were used in Antalya. By using XPS insulation material for climatic conditions in Antalya, the optimum insulation thicknesses were obtained as 0.030 m for heating with natural gas and 0.051 m for cooling with electricity. These values were found as 0.045 and 0.018 for Istanbul, 0.059 and 0.011 for Ankara, 0.065 and <0 for Kayseri and 0.086 and <0 for Erzurum. In the case of using EPS insulation material, higher values were obtained in all provinces.

Table 5. Optimum values, savings and payback period in heating and cooling

Insulation Material	Heating				Cooling			
	Fuel	x_{opt} (m)	Energy saving ($/m^2)	Payback period (years)	Fuel	x_{opt} (m)	Energy Saving ($/m^2)	Payback Period (years)
Antalya								
XPS	NaturalGas	0.030	3.78	2.80	Electricity	0.051	11.19	1.94
	Coal	0.037	5.89	2.37				
EPS	NaturalGas	0.046	4.87	2.18	Electricity	0.076	13.00	1.67
	Coal	0.056	7.23	1.93				
İstanbul								
XPS	NaturalGas	0.045	8.79	2.08	Electricity	0.018	1.35	4.53
	Coal	0.055	12.94	1.86				
EPS	NaturalGas	0.068	10.40	1.76	Electricity	0.030	2.02	3.03
	Coal	0.081	14.89	1.62				
Ankara								
XPS	NaturalGas	0.059	14.54	1.80	Electricity	0.011	0.54	7.75
	Coal	0.070	20.90	1.65				
EPS	NaturalGas	0.085	16.59	1.58	Electricity	0.021	0.99	4.23
	Coal	0.102	23.35	1.48				
Kayseri								
XPS	NaturalGas	0.065	17.76	1.72	Electricity	<0	0.01	-
	Coal	0.077	25.33	1.59				
EPS	NaturalGas	0.094	20.03	1.52	Electricity	0.003	0.02	-
	Coal	0.111	28.02	1.43				
Erzurum								
XPS	NaturalGas	0.086	31.04	1.52	Electricity	<0	-	-
	Coal	0.102	43.43	1.43				
EPS	NaturalGas	0.123	34.01	1.39	Electricity	<0	-	-
	Coal	0.144	46.93	1.33				

Figure 3 shows the changes of annual fuel consumption and CO_2 and SO_2 emissions in heating with coal according to insulation thickness. As insulation thickness increased, annual fuel consumption and greenhouse gas emissions decreased. Although this decrease varied slightly according to the type of insulation material, it has become horizontal after a point. The highest and lowest values were obtained in Erzurum and Antalya, respectively.

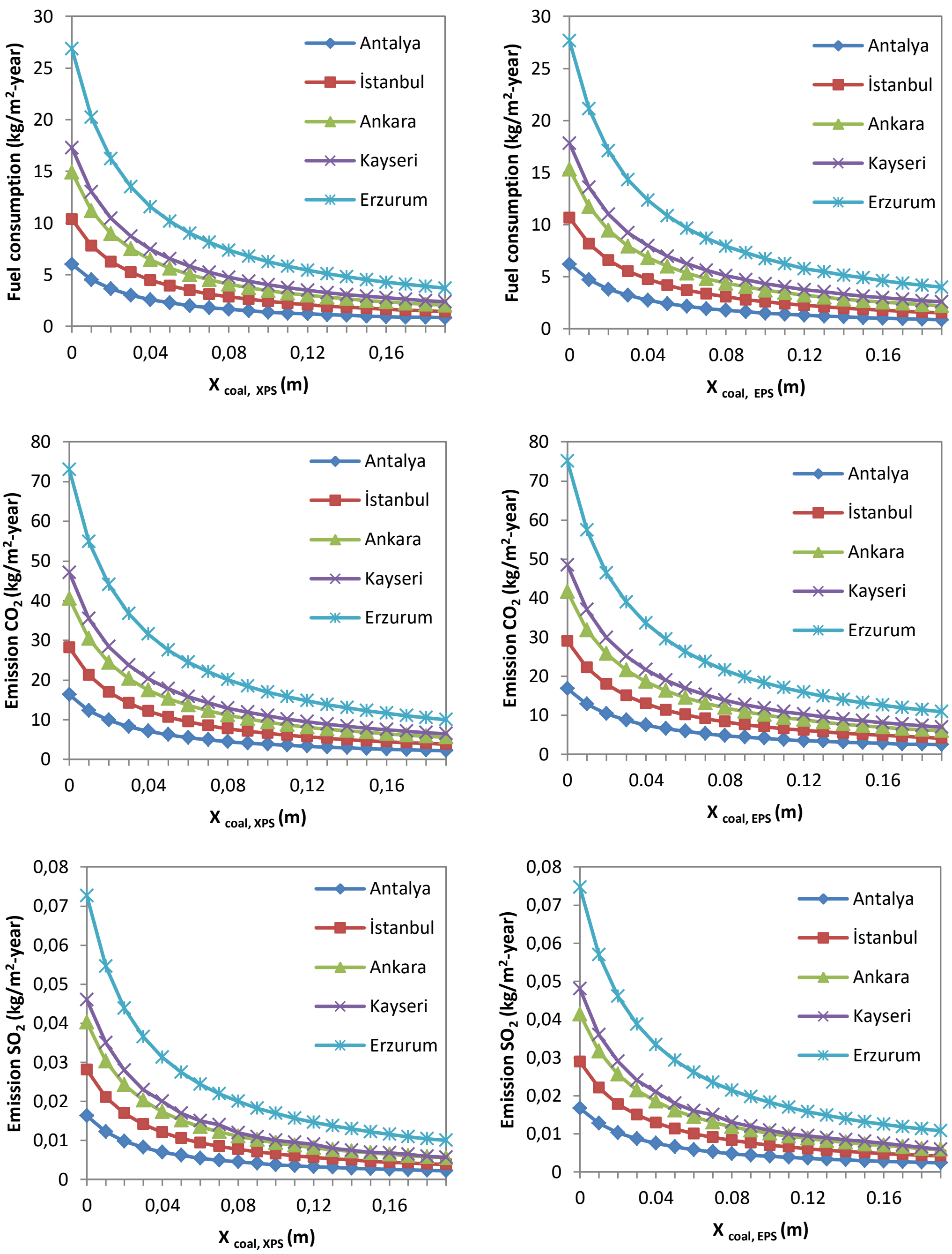

Figure 3.Fuel consumption and emissions

5. CONCLUSION

The application of optimum insulation thickness in buildings is essential for reducing fuel consumption and emissions. In this study, the optimum insulation thickness and emission values per unit area were calculated for building exterior walls located in 81 provinces. As the outdoor temperature decreases, the impact of insulation thickness on energy saving and emission becomes more apparent. It was observed that a maximum 75%-80% reduction of emission can be achieved depending on the insulation thickness.

However, one province from five different climatic zones in Turkey (Antalya, Istanbul, Ankara, Kayseri, Erzurum) were compared and the following results were obtained. The optimum insulation thicknesses were compared in all zones, and the optimum insulation thickness for cooling was higher in Antalya, the hottest province, while the optimum insulation thickness for heating was higher in other regions. The value of optimum insulation thickness for cooling was negative in Erzurum. Approximately 7 times higher energy conservation was achieved in Erzurum, the coldest province, compared to Antalya, the hottest province. In addition, the optimum insulation thickness and energy conservation in all provinces were higher for coal than natural gas. Since XPS has lower thermal conductivity, the optimum insulation thicknesses obtained in all provinces were lower for XPS than EPS. In conclusion, a significant energy conservation can be achieved through optimum insulation thickness of external walls in buildings. Due to increased energy demand and insufficiency of existing resources to meet it, it is extremely important and indispensable for Turkey to prevent energy wastes by using natural resources more efficiently and to prevent environmental pollution by reducing energy costs and fuel consumption, thus to create a positive effect against global warming.

CONFLICT OF INTEREST

The author declared no conflict of interest.

FINANCIAL DISCLOSURE

The author declare that this study has received no financial support.

DECLARATION OF ETHICAL STANDARDS

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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