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Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers

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ABSTRACT

The energy requirement of developing countries such as Turkey increase every single year. The energy consumption of this country is divided into four main sectors: industrial, residential, transportation and agriculture. The residential sector accounts for 33% of used energy. Uninsulated old buildings, as well as inadequate insulation in new construction poses massive economic burden to this country, forcing it to over-rely on fuels from abroad.

In this study, the optimum insulation thicknesses required in Turkey's 81 provincial centers are determined. The calculations are made on the basis of four different fuels (natural gas, coal, fuel oil and liquefied petroleum gas) and 5 different insulation materials (extruded polystyrene, expanded polystyrene, glass wool, rock wool and polyurethane). Three different cases have been considered: buildings heated but not cooled, cooled but not heated, and both heated and cooled; optimum required insulation thicknesses in accordance with each case are calculated. Optimum insulation thicknesses, total net saving amount, reimbursement period change according to the fuels and insulation materials are calculated on the basis of 5 different provincial centers (İzmir, İstanbul, Ankara, Sivas and Erzurum) selected according to their degree/day values.

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1. Introduction

Energy sources are limited and fuel-use polluting to the environment, finding ways to save energy has become compulsory. 33% of energy-use in Turkey is for heating purposes. In the literature, though methods such as radiant heating systems that utilize low temperature heating sources exist [1], since the majority of buildings in Turkey do not have insulation, a significant portion of this quantity may be recovered through proper insulation. It is very important to properly select the type of insulant, applying insulation at optimum thickness considering investment and operating costs [2]. The importance of thermal insulation is based primarily on two main concepts: energy and environment. This can be expanded to include the need for healthy and comfortable spaces. Energy is a strategic, macro concept for all countries. It is obvious that Turkey is not very rich in sources of energy; 60–65% of energy need is imported. Further, this need increases at a rate of 4% annually [3,4].

Thermal insulation constitutes the most important leg of policies developed all over the world depending on the concept of energy efficiency. In Turkey, residential and construction sectors consume 1/3 of energy, and with their large potential for energy saving, have cause increased interest in the energy efficiency sector [5]. TS 825 "Thermal Insulation Requirements for Buildings" [6] intends to ensure energy saving by limiting the quantity of energy utilized for heating buildings, which comprises a significant share in Turkey's energy consumption [7]. To calculate DD values for 81 provincial centers in Turkey, a minimum 15–20 years of average long-term temperature values was used [8,9].

Dombaycı et al. [10] calculated the optimum insulation thickness for Denizli by using two different insulants and five different fuel types. Çomaklı and Yüksel [11] calculated the optimum insulation thickness for the three coldest cities in the fourth DD zone of Turkey in accordance with the TS Standard no 825 on Rules of Heat Insulation in Buildings. Bolattürk [12] calculated the optimum insulation thickness and payback periods for five different fuel types in 16 cities from four climatic zones of Turkey. In another study [13], the author calculated the optimum insulation thickness of external walls of buildings situated in the first climatic zone of Turkey

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Nomenclature

$A_{year,H}$	Difference of annual total heating cost ($/m^2 year)
$A_{year,H,C}$	Difference of annual total heating and cooling cost ($/m^2 year)
C	Annual energy cost for unit surface without insulated ($/m^2 year)
$C_{A,C}$	Total cooling cost ($/m^2 year)
$C_{A,H}$	Total heating cost ($/m^2 year)
CDD	Cooling degree-day value, (°C-days)
C_{fuel}	Cost of the fuel ($/m^3, $/kg)
$C_{ins.}$	Cost of the insulant ($/m^2)
COP	Coefficient of performance
$C_{t,C}$	Total cooling cost of the insulated building ($/m^2 year)
$C_{t,H}$	Total heating cost of the insulated building ($/m^2 year)
$C_{t,H,C}$	Total heating and cooling cost of the insulated building ($/m^2 year)
C_y	Cost of the insulant ($/m^3)
DD	Degree-day value (°C-days)
EPS	Expanded polystyrene
$E_{year,C}$	Annual energy need for cooling (J/m^2 year)
$E_{year,H}$	Annual energy need for heating (J/m^2 year)
g	Inflation rate (%)
HDD	Heating degree-day value (°C-days)
Hu	Low heat value of the fuel (J/kg, J/m^3)
i	Interest rate (%)
k	Thermal conductivity of insulation (W/mK)
LPG	Liquefied Petroleum Gas
N	Lifetime (year)
pp	Payback period (year)
PWF	Present Worth Factor
q	Annual heat loss (W/m^2)
r	Actual interest rate
R	Heat transfer resistance (m^{2}K/W)
R_i	Inside heat transfer resistance (m^{2}K/W)
$R_{ins.}$	Thermal resistance of the insulant (m^{2}K/W)
R_o	Outside heat transfer resistance (m^{2}K/W)
R_w	Thermal resistance of wall layers without insulation (m^{2}K/W)
$R_{w,t}$	Thermal resistance of non-insulated wall (m^{2}K/W)
T	Temperature (K)
U	Total heat transfer coefficient (W/m^{2}K)
x	Insulation thickness (m)
x_{opt}	Optimum insulation thickness (m)
XPS	Extruded polystyrene
η	Efficiency of the combustion system

Subscripts

A	Annual
C	Cooling
e	Electricity
fuel	Fuel
H	Heating
H,C	Heating and cooling
i	Inside
ins.	Insulation
o	Outside
opt	Optimum
t	Total

in consideration of the annual heating and cooling loads, and then determined the payback period by means of the P1–P2 method.

Kaynaklı [14] determined the optimum insulation thickness for the Bursa province by calculating the degree-hour values for the heating season in consideration of outdoor ambient air temperature values between 1992 and 2005. Özel and Pıhtılı [15] calculated the optimum thickness of insulation applied to external walls for the Adana, Elazığ, Erzurum, Istanbul and Izmir provinces in consideration of the heating and cooling degree-day values. Uçar and Balo [16] used three different methods for typical externally insulated walls, for Izmir, Diyarbakır, Uşak and Bayburt cities chosen from four different climate regions with life-cycle cost optimization 0.073–0.077–0.101–0.138 m respectively. Hasan [17] calculated the optimum insulation thicknesses for four fuel types and two insulants across a degree-day and life-cycle cost analysis approach. As a result, the author reported that the payback period ranges between 1.3–2.3 years for insulation with rock wool and 1–1.7 years for insulation with polystyrene.

Kurekci et al. [18] calculated optimum insulation thicknesses, payback periods and energy gain savings values for 6 fuels for heating and for 2 insulants for 4 degree-day regions in Turkey. In another study, authors [19] calculated optimum insulation thickness, payback periods and energy saving values for two fuels and five insulants for all provinces in Turkey. Liu et al. [20], calculated the extruded polystyrene (XPS) and expanded polystyrene (EPS) insulation materials' optimum insulation thickness for three provinces (Changsha, Chengdu and Shaoguan) selected in China. It has been detected that optimum thickness of XPS is 0.053–0.069 m while the optimum thickness of EPS is between 0.081–0.105 m. Nematchoua et al. [21] calculated the optimum insulation thickness, energy saving values and reimbursement terms in case of usage of EPS insulation materials at concrete and soil blocks in Cameroon. Ozel [22] detected the insulation thickness of the buildings within warm climates. The author performed the study only for the Antalya province of Turkey and effectuated the calculations via the Matlab program by using the finite difference method. Consequently, the author discovered that 3.6, 3.1, 4 and 4 cm insulation should be used for the south, north, east and west, respectively. Ozkan and Onan [23] investigated the effects of altering the glazing area percentage of windows, which ranged from 10 to 50%, on the optimum insulation thickness with a new approach for four regions in Turkey. In another study, the existing building stock in Turkey has been investigated depending on parameters such as the height and the area. The total energy savings for the country are calculated to be 41.7 billion US$ [24]. Axaopolos et al. [25] determined the optimum insulation thickness in the external walls of the buildings in Cyprus Larnaca by considering the wind speed and direction as well as the heating and cooling durations. It has been detected that the optimum insulation thickness is between 4.25 m and 15.5 m while the reimbursement terms are between 5.47 and 12.11 years.

When current literature is reviewed, it is seen that studies conducted usually chose four provinces from four different climate zones and calculated optimum insulation thickness. In the studies, variable number of fuel-insulant is generally taken as 2. In this study, using heating and cooling DD values and life-cycle cost analysis method, heating, cooling for four different fuels and five different insulants for 81 provincial centers in Turkey, and optimum insulation thickness of external walls for buildings both heated and cooled, and payback periods were calculated. Some residences used are only heated and some buildings, though rarely are only cooled. Office type buildings may be both heated and cooled. In this study, optimum insulation thicknesses required for the intended use of a

Table 1
Heating and cooling degree-day values of all provinces in Turkey [8,9].

No.	City	HDD	CDD	No.	City	HDD	CDD	No.	City	HDD	CDD
1	Adana	874	796	28	Giresun	1765	108	55	Samsun	1826	76
2	Adiyaman	1695	824	29	Gümushane	3234	40	56	Siirt	1958	747
3	Afyon	2828	58	30	Hakkari	3470	184	57	Sinop	1879	92
4	Agri	4423	35	31	Hatay	1119	614	58	Sivas	3444	27
5	Amasya	2210	159	32	Isparta	2607	88	59	Tekirdag	2032	112
6	Ankara	2677	109	33	Icel	852	585	60	Tokat	2399	97
7	Antalya	1083	562	34	Istanbul	1865	159	61	Trabzon	1724	91
8	Artvin	2429	58	35	Izmir	1118	559	62	Tunceli	2716	353
9	Aydin	1213	601	36	Kars	4772	2	63	Sanliurfa	1503	940
10	Balikesir	1914	226	37	Kastamonu	3112	23	64	Usak	2414	127
11	Bilecik	2397	101	38	Kayseri	3113	38	65	Van	3476	32
12	Bingol	2838	361	39	Kiriklareli	2274	185	66	Yozgat	3422	20
13	Bitlis	3311	105	40	Kirsehir	2857	85	67	Zonguldak	2020	50
14	Bolu	2821	22	41	Kocaeli	1786	204	68	Aksaray	2626	131
15	Burdur	2351	183	42	Konya	2836	101	69	Bayburt	4149	8
16	Bursa	1920	177	43	Kutahya	2880	35	70	Karaman	2698	119
17	Canakkale	1789	249	44	Malatya	2461	407	71	Kirikkale	2609	128
18	Cankiri	2864	76	45	Manisa	1535	570	72	Batman	1823	763
19	Corum	2958	24	46	K. Maras	1653	649	73	Sirnak	2065	184
20	Denizli	1627	469	47	Mardin	2004	755	74	Bartin	2226	44
21	Diyarbakir	2142	640	48	Mugla	1879	369	75	Ardahan	5137	0,3
22	Edirne	2224	195	49	Mus	3563	208	76	Igdır	2764	276
23	Elazig	2653	337	50	Nevsehir	3033	47	77	Yalova	1843	123
24	Erzincan	3047	130	51	Nigde	2856	63	78	Karabuk	2145	85
25	Erzurum	4827	7	52	Ordu	1804	119	79	Kilis	1554	689
26	Eskisehir	3049	27	53	Rize	1820	81	80	Osmaniye	1103	584
27	Gaziantep	2009	521	54	Sakarya	1833	155	81	Düzce	2065	35

Table 2
Physical properties of the materials of external wall.

Wall structure	Thickness (m)	k (W/mK)	R (m^2 K/W)
Internal plaster (lime-based)	0.02	0.87	0.023
Bricks	0.13	0.45	0.289
External plaster (cement-based)	0.03	1.4	0.021
R_i			0.13
R_o			0.04
$R_{w,t}$			0.503

given building, according to its heating or cooling situation, selection of different fuels and different insulants were calculated.

2. Method

2.1. The structure of the external walls

Heat losses and gains in buildings generally occur through external walls, windows, roof, floors and air infiltration. In this study, the optimum insulation thickness has been calculated in consideration of heat losses and gains only occurring through the external walls.

DD values are essentially related to equilibrium temperature chosen. Equilibrium temperature can be taken as exterior temperature at a time when neither heating nor cooling is required in a building. This equilibrium temperature may differ from one building to another. This change may be determined according to desired interior temperature, thermal properties of the building and manner of use. Traditionally, heating DD numbers may be calculated with an equilibrium temperature of either 14° C, 16° C or 18° C, and cooling DD numbers with 22° C, 24° C or 26° C as 18 °C, cooling DD value as 22 °C [8,9]. Table 1 shows equilibrium temperature used in the calculations, heating DD number value as 18 °C, cooling DD value as 22 °C [8,9]. The studies conducted on this subject are summarized as follows.

The external wall of a building is externally-insulated, composed of a 2 cm internal plaster, 13 cm bricks, insulant and a 3 cm external plaster as shown in Fig. 1 below. Physical characteristics of constituents of the wall are given in Table 2. In calculations, only the heat losses and gains occurring through external walls were considered to calculate the optimum insulation thickness.

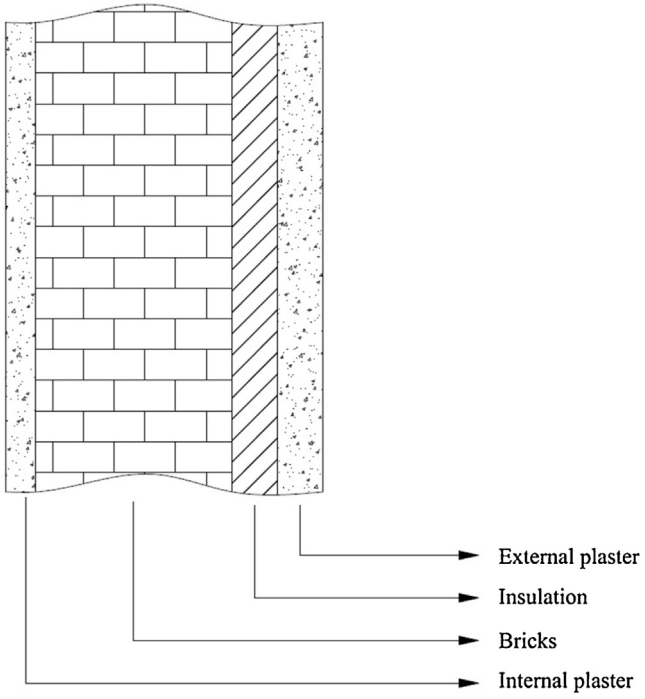


Fig. 1. External wall structure.

In this study, optimum insulation thicknesses of external walls were calculated by using four different fuel types and five different insulants (Table 3) for heating and cooling in buildings in all cities of Turkey. Specifications of fuel types used in the study are shown in Table 4.

Table 3
Parameters of the insulation wall.

Insulation	k (W/mK)	C_y ($/m^3)
Extruded polystyrene (XPS)	0.031	180
Expanded polystyrene (EPS)	0.039	120
Glass wool	0.040	75
Rock wool	0.040	80
Polyurethane	0.024	260

Table 4
Low heat value, efficiencies and prices of fuels [27].

Fuel	Hu	η	Price (C_{fuel})
Natural gas	34485000 J/m^3	0.90	0.385 $/m^3
Coal	25080000 J/kg	0.65	0.273 $/kg
Fuel-oil	40546000 J/kg	0.80	0.766 $/kg
LPG	45980000 J/kg	0.88	1.921 $/kg

2.2. Heating and cooling load for external walls

Heat loss occurring in unit surface of the external wall is calculated with Eq. (1)

$$q = U \times \Delta T \tag{1}$$

U is heat transfer coefficient and ΔT is the difference between the outside ambient temperature and the constant inside ambient temperature. Accordingly, the annual heat losses and gains occurring in unit surface are calculated by using U and the degree-day value [2,3].

$$q_{year,H} = 86400 \times HDD \times U \tag{2}$$

$$q_{year,C} = 86400 \times CDD \times U \tag{3}$$

Total heat transfer coefficient for a typical wall is

$$U = \frac{1}{R_i + R_w + R_{ins.} + R_o} \tag{4}$$

R_i and R_o are the heat transfer coefficients of the inside and outside environment respectively and R_w is the heat transfer resistance of wall layers without heat insulation. $R_{ins.}$ is the thermal resistance of the insulant and calculated as follows:

$$R_{ins.} = \frac{x}{k} \tag{5}$$

x and k are the thickness and thermal conductivity of insulation respectively. Total resistance of the non-insulated wall layer $R_{w,t}$ is

$$R_{w,t} = R_i + R_w + R_o \tag{6}$$

then, total heat transfer coefficient U is expressed as

$$U = \frac{1}{R_{w,t} + R_{ins.}} \tag{7}$$

Annual energy need for heating $E_{year,H}$ is calculated as follows:

$$E_{year,H} = \frac{86400 \times HDD}{(R_{w,t} + R_{ins.}) \times \eta} \tag{8}$$

Annual energy need for cooling $E_{year,C}$ is calculated as follows:

$$E_{year,C} = \frac{86400 \times CDD}{(R_{w,t} + R_{ins.}) \times COP} \tag{9}$$

The COP in the formula is cooling system coefficient of performance.

2.3. Calculation of the optimum insulation thickness and annular cost of energy

By applying insulation to buildings' external walls, heat loss and gain through the building surface is significantly reduced. However, a cost analysis should be performed to determine the optimum insulation thickness. Annual energy cost for unit surface $C_{A,H}$ and $C_{A,H}$ are calculated with the following equation:

$$C_{A_H} = \frac{86400 \times HDD \times C_{fuel}}{(R_{wt} + R_{ins.}) \times Hu \times \eta} \tag{10}$$

$$C_{A,C} = \frac{86400 \times CDD \times C_e}{(R_{wt} + R_{ins.}) \times COP} \tag{11}$$

C_{fuel} is the unit fuel price. Hu is the heating value of the fuel and η is the efficiency of the heating system. C_e is the cost of electricity.

The life cycle cost analysis method was used in calculating the optimum insulation thickness. Annual energy cost was calculated based upon the present worth factor and the lifetime determined [2,7,10]. The present worth factor is calculated based upon the inflation and interest rates as follows:

If $i > g$:

$$r = \frac{i - g}{1 + g} \tag{12}$$

If $g > i$:

$$r = \frac{g - i}{1 + i} \tag{13}$$

$$PWF = \frac{(1+r)^N - 1}{r \times (1+r)^N} \tag{14}$$

If $i = g$:

$$PWF = \frac{N}{1 + i} \tag{15}$$

PWF is the present worth factor, i is the interest rate, g is the inflation rate, r is actual interest rate and N is the lifetime. Next, insulation cost is calculated as follows:

$$C_{ins.} = C_y \times x \tag{16}$$

Ultimately, the total heating cost of an insulated building as per the life cycle cost analysis is calculated as follows:

$$C_{t_H} = C_{A,H} \times PWF + C_y \times x \tag{17}$$

Ultimately, the total cooling cost of an insulated building as per the life cycle cost analysis is calculated as follows:

$$C_{t,c} = C_{A,c} \times PWF + C_y \times x \tag{18}$$

Ultimately, the total heating and cooling cost of an insulated building as per the life cycle cost analysis is calculated as follows:

$$C_{t_{H,C}} = C_{A,H} \times PWF + C_{A,C} \times PWF + C_y \times x \tag{19}$$

Optimum insulation thickness minimizing the total heating cost is calculated with the equation below [2,7,10,11,12,17].

$$x_{opt,H} = 293.94 \times \left(\frac{HDD \times C_{fuel} \times PWF \times k}{Hu \times C_y \times \eta} \right)^{1/2} - k \times R_{w,t} \tag{20}$$

Optimum insulation thickness minimizing the total cooling cost is calculated with the equation below.

$$x_{opt,C} = 293.94 \times \left(\frac{CDD \times C_e \times PWF \times k}{C_y \times COP} \right)^{1/2} - k \times R_{w,t} \tag{21}$$

Optimum insulation thickness minimizing the total heating and cooling cost is calculated with the equation below [14,26].

$$x_{opt_{H,C}} = 293.94 \times \left(\frac{HDD \times C_{fuel} \times PWF \times k}{Hu \times C_y \times \eta} + \frac{CDD \times C_e \times PWF \times k}{C_y \times COP} \right)^{1/2} - k \times R_{w,t} \tag{22}$$

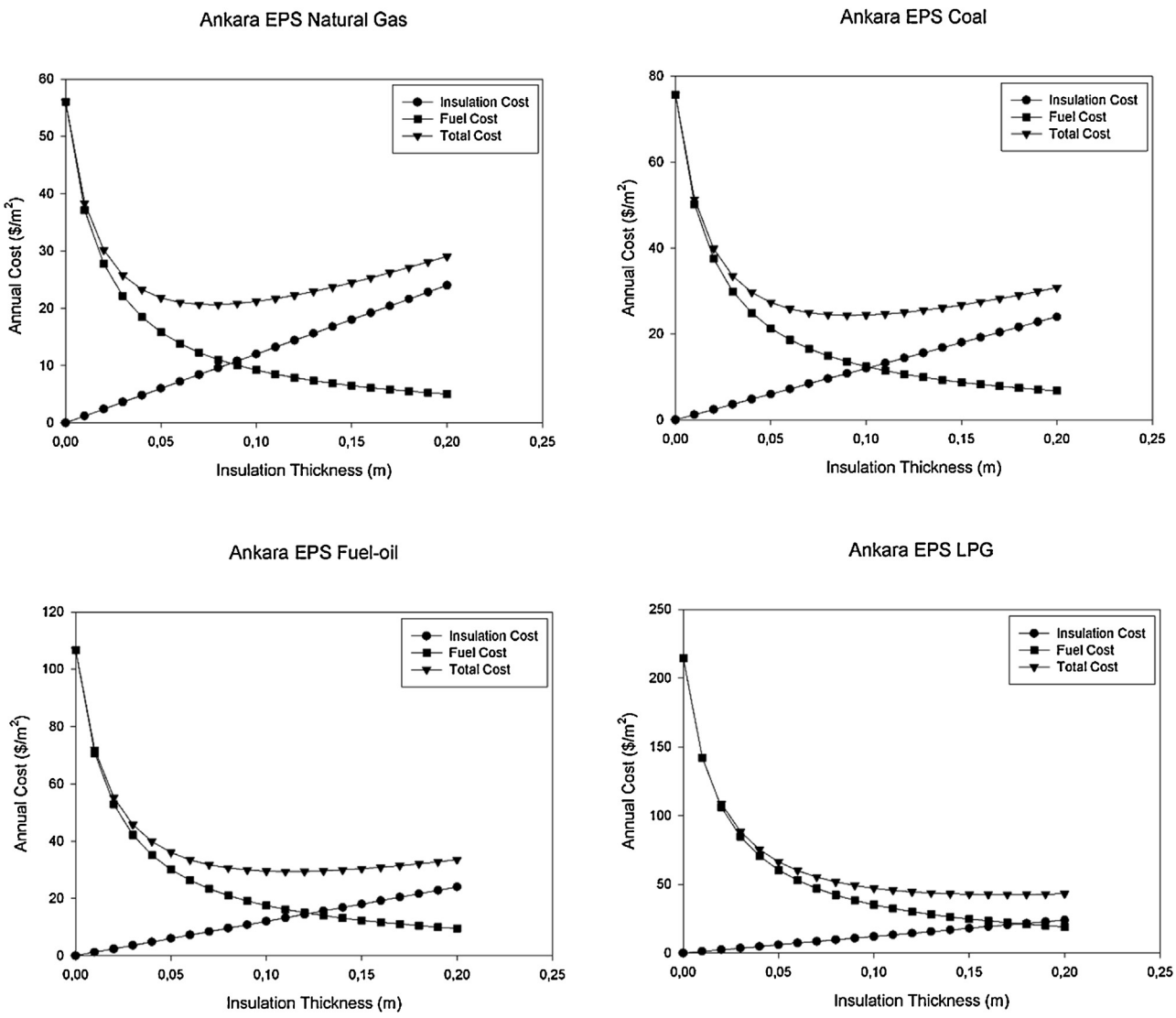


Fig. 2. Annual cost of heating versus insulation- thickness by insulation thicknesses for expanded polystyrene (EPS) for Ankara.

2.4. Payback period

Annual total net saving amount for buildings heated but not cooled is calculated with Eq. (23); annual total net saving amount for buildings both heated and cooled is calculated with Eq. (24). The C_H and C_{HC} in the formula represents pre-insulation heating and heating-cooling energy costs.

$$A_{year,H} = C_H - C_{t,H} \quad (23)$$

$$A_{year,H,C} = C_{H,C} - C_{t,H,C} \quad (24)$$

Payback period

$$pp_H = \frac{C_{ins.}}{A_{year,H}} \quad (25)$$

$$pp_{H,C} = \frac{C_{ins.}}{A_{year,H,C}} \quad (26)$$

3. Results and discussion

While increasing insulation thickness increases initial investment cost, operating costs decrease. In this study, optimum insulation thicknesses for external walls were calculated by using heating and cooling degree-day values for buildings only heated, only cooled and both heated and cooled. Calculations were repeated for four fuels and five insulants for all cities in Turkey.

Table 5
Parameters used in the calculations.

Interest rate (i)	8.25%
Inflation rate (g)	7.91%
Life cycle (N)	10 years
Present Worth Factor (PWF)	9.83

Life cycle, interest and inflation values employed in calculating the present worth factor are summarized in Table 5.

As insulation thickness increases initial investment cost also increases. Operating expenses decrease with insulation thickness. The total cost, achieved by adding these two values, first decreases upon increase of insulation thickness, and after a minimum value, it increases again. The cost curve total's minimum point shows optimum insulation thickness. Fig. 2 shows buildings heated only, thickness of EPS insulant and cost of investment, fuel cost and variations of total costs by fuels for Ankara province. EPS insulant was chosen due to the fact that it is most preferred for insulating external walls. When the figure is reviewed, optimum thickness for EPS insulant was found as 0.076 m when natural gas is used as fuel, 0.092 m for coal, 0.112 m for fuel-oil and 0.168 m for LPG. The

Table 6
Optimum insulation thickness by insulant types for natural gas fuel in all provinces.

Natural gas																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Adana	874	796	0.024	0.020	0.038	0.035	0.030	0.054	0.050	0.043	0.074	0.048	0.041	0.071	0.017	0.014	0.027
Adiyaman	1695	824	0.040	0.021	0.051	0.057	0.030	0.072	0.077	0.044	0.097	0.074	0.042	0.093	0.029	0.015	0.036
Afyon	2828	58	0.056	0.000	0.057	0.079	0.000	0.080	0.106	0.000	0.107	0.102	0.000	0.103	0.040	0.000	0.041
Ağri	4423	35	0.074	0.000	0.074	0.103	0.000	0.104	0.138	0.000	0.138	0.133	0.000	0.133	0.054	0.000	0.054
Amasya	2210	159	0.048	0.000	0.050	0.067	0.002	0.070	0.091	0.008	0.095	0.088	0.007	0.091	0.034	0.000	0.036
Ankara	2677	109	0.054	0.000	0.055	0.076	0.000	0.078	0.103	0.003	0.105	0.099	0.002	0.101	0.039	0.000	0.040
Antalya	1083	562	0.029	0.014	0.038	0.041	0.022	0.054	0.058	0.033	0.074	0.055	0.031	0.071	0.020	0.010	0.027
Artvin	2429	58	0.051	0.000	0.051	0.072	0.000	0.073	0.097	0.000	0.098	0.093	0.000	0.094	0.037	0.000	0.037
Aydin	1213	601	0.031	0.016	0.041	0.045	0.023	0.058	0.062	0.035	0.079	0.060	0.033	0.076	0.022	0.011	0.029
Balikesir	1914	226	0.043	0.003	0.046	0.061	0.007	0.065	0.084	0.013	0.089	0.080	0.012	0.085	0.031	0.002	0.033
Bilecik	2397	101	0.050	0.000	0.052	0.071	0.000	0.073	0.096	0.002	0.098	0.092	0.002	0.094	0.036	0.000	0.037
Bingöl	2838	361	0.056	0.009	0.060	0.079	0.014	0.084	0.106	0.022	0.113	0.102	0.021	0.109	0.040	0.006	0.043
Bitlis	3311	105	0.062	0.000	0.063	0.087	0.000	0.088	0.116	0.003	0.118	0.112	0.002	0.114	0.045	0.000	0.045
Bolu	2821	22	0.056	0.000	0.056	0.079	0.000	0.079	0.106	0.000	0.106	0.102	0.000	0.102	0.040	0.000	0.040
Burdur	2351	183	0.050	0.002	0.052	0.070	0.004	0.073	0.095	0.010	0.099	0.091	0.009	0.095	0.036	0.000	0.037
Bursa	1920	177	0.043	0.001	0.046	0.061	0.004	0.065	0.084	0.010	0.088	0.080	0.009	0.084	0.031	0.000	0.033
Çanakkale	1789	249	0.041	0.004	0.045	0.059	0.008	0.063	0.080	0.015	0.086	0.077	0.014	0.083	0.030	0.003	0.032
Çankiri	2864	76	0.056	0.000	0.057	0.079	0.000	0.081	0.107	0.000	0.108	0.103	0.000	0.104	0.041	0.000	0.041
Çorum	2958	24	0.058	0.000	0.058	0.081	0.000	0.081	0.109	0.000	0.109	0.105	0.000	0.105	0.042	0.000	0.042
Denizli	1627	469	0.039	0.012	0.045	0.055	0.018	0.064	0.075	0.028	0.087	0.072	0.027	0.084	0.028	0.008	0.032
Diyarbakir	2142	640	0.047	0.017	0.055	0.066	0.024	0.077	0.090	0.036	0.103	0.086	0.035	0.099	0.034	0.011	0.039
Edirne	2224	195	0.048	0.002	0.050	0.068	0.005	0.071	0.092	0.011	0.096	0.088	0.010	0.092	0.034	0.001	0.036
Elaziğ	2653	337	0.054	0.008	0.058	0.076	0.012	0.081	0.102	0.021	0.109	0.098	0.020	0.105	0.039	0.005	0.042
Erzincan	3047	130	0.059	0.000	0.060	0.083	0.000	0.084	0.111	0.005	0.113	0.107	0.005	0.109	0.042	0.000	0.043
Erzurum	4827	7	0.078	0.000	0.078	0.109	0.000	0.109	0.145	0.000	0.145	0.139	0.000	0.139	0.056	0.000	0.056
Eskişehir	3049	27	0.059	0.000	0.059	0.083	0.000	0.083	0.111	0.000	0.111	0.107	0.000	0.107	0.042	0.000	0.043
Gaziantep	2009	521	0.045	0.013	0.051	0.063	0.020	0.072	0.086	0.031	0.098	0.083	0.029	0.094	0.032	0.009	0.037
Giresun	1765	108	0.041	0.000	0.043	0.058	0.000	0.060	0.079	0.003	0.082	0.076	0.002	0.079	0.029	0.000	0.030
Gümüşhane	3234	40	0.061	0.000	0.061	0.086	0.000	0.086	0.115	0.000	0.115	0.110	0.000	0.111	0.044	0.000	0.044
Hakkari	3470	184	0.064	0.002	0.066	0.089	0.004	0.092	0.119	0.010	0.123	0.115	0.009	0.118	0.046	0.001	0.047
Hatay	1119	614	0.029	0.016	0.039	0.042	0.024	0.056	0.059	0.035	0.077	0.057	0.033	0.073	0.021	0.011	0.028
Isparta	2607	88	0.053	0.000	0.054	0.075	0.000	0.076	0.101	0.001	0.103	0.097	0.000	0.099	0.038	0.000	0.039
İçel	852	585	0.024	0.015	0.034	0.034	0.023	0.049	0.049	0.034	0.068	0.047	0.032	0.065	0.017	0.010	0.024
İstanbul	1865	159	0.043	0.000	0.045	0.060	0.002	0.063	0.082	0.008	0.086	0.079	0.007	0.083	0.031	0.000	0.032
İzmir	1118	559	0.029	0.014	0.039	0.042	0.022	0.055	0.059	0.033	0.075	0.057	0.031	0.072	0.021	0.010	0.028
Kars	4772	2	0.077	0.000	0.077	0.108	0.000	0.108	0.144	0.000	0.144	0.138	0.000	0.138	0.056	0.000	0.056
Kastamonu	3112	23	0.060	0.000	0.060	0.084	0.000	0.084	0.112	0.000	0.113	0.108	0.000	0.108	0.043	0.000	0.043
Kayseri	3113	38	0.060	0.000	0.060	0.084	0.000	0.084	0.112	0.000	0.113	0.108	0.000	0.109	0.043	0.000	0.043
Kiriklareli	2274	185	0.049	0.002	0.051	0.069	0.004	0.072	0.093	0.010	0.097	0.089	0.009	0.093	0.035	0.001	0.037
Kirşehir	2857	85	0.056	0.000	0.057	0.079	0.000	0.081	0.107	0.000	0.108	0.103	0.000	0.104	0.041	0.000	0.041
Kocaeli	1786	204	0.041	0.003	0.044	0.059	0.005	0.062	0.080	0.012	0.085	0.077	0.011	0.082	0.030	0.001	0.032
Konya	2836	101	0.056	0.000	0.057	0.079	0.000	0.080	0.106	0.002	0.108	0.102	0.002	0.104	0.040	0.000	0.041
Kütahya	2880	35	0.057	0.000	0.057	0.080	0.000	0.080	0.107	0.000	0.108	0.103	0.000	0.104	0.041	0.000	0.041
Malatya	2461	407	0.051	0.010	0.056	0.072	0.016	0.079	0.097	0.025	0.106	0.094	0.024	0.102	0.037	0.007	0.040
Manisa	1535	570	0.037	0.015	0.045	0.053	0.022	0.064	0.073	0.033	0.087	0.070	0.032	0.084	0.027	0.010	0.032
K. Maraş	1653	649	0.039	0.017	0.048	0.056	0.025	0.068	0.076	0.037	0.092	0.073	0.035	0.088	0.028	0.012	0.034
Mardin	2004	755	0.045	0.019	0.054	0.063	0.028	0.076	0.086	0.041	0.102	0.083	0.039	0.099	0.032	0.013	0.039
Muğla	1879	369	0.043	0.009	0.048	0.061	0.014	0.067	0.083	0.023	0.091	0.079	0.021	0.088	0.031	0.006	0.034
Muş	3563	208	0.065	0.003	0.067	0.091	0.006	0.094	0.121	0.012	0.125	0.117	0.011	0.120	0.047	0.001	0.048
Nevşehir	3033	47	0.059	0.000	0.059	0.082	0.000	0.083	0.110	0.000	0.111	0.106	0.000	0.107	0.042	0.000	0.043
Niğde	2856	63	0.056	0.000	0.057	0.079	0.000	0.080	0.107	0.000	0.108	0.103	0.000	0.104	0.041	0.000	0.041
Ordu	1804	119	0.042	0.000	0.043	0.059	0.000	0.061	0.081	0.004	0.083	0.077	0.003	0.080	0.030	0.000	0.031
Rize	1820	81	0.042	0.000	0.043	0.059	0.000	0.061	0.081	0.000	0.083	0.078	0.000	0.080	0.030	0.000	0.031
Sakarya	1833	155	0.042	0.000	0.044	0.060	0.002	0.063	0.081	0.008	0.085	0.078	0.007	0.082	0.030	0.000	0.032
Samsun	1826	76	0.042	0.000	0.043	0.059	0.000	0.061	0.081	0.000	0.083	0.078	0.000	0.080	0.030	0.000	0.031
Siirt	1958	747	0.044	0.019	0.053	0.062	0.028	0.075	0.085	0.041	0.101	0.081	0.039	0.097	0.032	0.013	0.038
Sinop	1879	92	0.043	0.000	0.044	0.061	0.000	0.062	0.083	0.001	0.085	0.079	0.001	0.081	0.031	0.000	0.032
Sivas	3444	27	0.063	0.000	0.064	0.089	0.000	0.089	0.119	0.000	0.119	0.115	0.000	0.115	0.046	0.000	0.046
Tekirdağ	2032	112	0.045	0.000	0.047	0.064	0.000	0.066	0.087	0.004	0.089	0.083	0.003	0.086	0.032	0.000	0.033
Tokat	2399	97	0.050	0.000	0.052	0.071	0.000	0.073	0.096	0.002	0.098	0.092	0.001	0.094	0.036	0.000	0.037
Trabzon	1724	91	0.040	0.000	0.042	0.057	0.000	0.059	0.078	0.001	0.081	0.075	0.001	0.077	0.029	0.000	0.030
Tunceli	2716	353	0.055	0.008	0.059	0.077	0.013	0.082	0.103	0.022	0.110	0.099	0.021	0.106	0.039	0.005	0.042
Şanliurfa	1503	940	0.037	0.023	0.050	0.052	0.034	0.070	0.072	0.048	0.094	0.069	0.046	0.091	0.026	0.016	0.036
Uşak	2414	127	0.051	0.000	0.052	0.071	0.000	0.073	0.096	0.005	0.099	0.093	0.004	0.095	0.036	0.000	0.037
Van	3476	32	0.064	0.000	0.064	0.089	0.000	0.090	0.120	0.000	0.120	0.115	0.000	0.116	0.046	0.000	0.046
Yozgat	3422	20	0.063	0.000	0.063	0.089	0.000	0.089	0.119	0.000	0.119	0.114	0.000	0.114	0.046	0.000	0.046
Zonguldak	2020	50	0.045	0.000	0.046	0.064	0.000	0.064	0.086	0.000	0.088	0.083	0.000	0.084	0.032	0.000	0.033
Aksaray	2626	131	0.053	0.000	0.055	0.075	0.000	0.077	0.101	0.005	0.104	0.097	0.005	0.100	0.038	0.000	0.040
Bayburt	4149	8	0.071	0.000	0.071	0.100	0.000	0.100	0.133	0.000	0.133	0.128	0.000	0.128	0.051	0.000	0.051
Karaman	2698	119	0.054	0.000	0.056	0.076	0.000	0.078	0.103	0.004	0.105	0.099	0.003	0.101	0.039	0.000	0.040
Kirikkale	2609	128	0.053	0.000	0.055	0.075	0.000	0.077	0.101	0.005	0.104	0.097	0.004	0.100	0.038	0.000	0.039
Batman	1823	763	0.042	0.019	0.052	0.059	0.029	0.073	0.081	0.042	0.098	0.078	0.040	0.095	0.030	0.014	0.037

Table 6 (*Continued*)

Natural gas																
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Şirnak	2065	184	0.046	0.002	0.048	0.064	0.004	0.068	0.088	0.010	0.092	0.084	0.009	0.088	0.033	0.001	0.034
Bartin	2226	44	0.048	0.000	0.049	0.068	0.000	0.068	0.092	0.000	0.093	0.088	0.000	0.089	0.034	0.000	0.035
Ardahan	5137	0.3	0.081	0.000	0.081	0.113	0.000	0.113	0.150	0.000	0.150	0.144	0.000	0.144	0.059	0.000	0.059
Iğdir	2764	276	0.055	0.005	0.058	0.078	0.009	0.082	0.104	0.017	0.110	0.101	0.016	0.106	0.040	0.003	0.042
Yalova	1843	123	0.042	0.000	0.044	0.060	0.000	0.062	0.082	0.005	0.085	0.078	0.004	0.081	0.030	0.000	0.031
Karabük	2145	85	0.047	0.000	0.048	0.066	0.000	0.068	0.090	0.000	0.092	0.086	0.000	0.088	0.034	0.000	0.034
Kilis	1554	689	0.037	0.018	0.047	0.053	0.026	0.066	0.073	0.039	0.090	0.070	0.037	0.087	0.027	0.012	0.034
Osmaniye	1103	584	0.029	0.015	0.039	0.042	0.023	0.055	0.059	0.034	0.075	0.056	0.032	0.072	0.021	0.010	0.028
Düzce	2065	35	0.046	0.000	0.046	0.064	0.000	0.065	0.088	0.000	0.088	0.084	0.000	0.085	0.033	0.000	0.033

Table 7
Optimum insulation thickness by insulant types for coal fuel in all provinces.

Coal																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Adana	874	796	0.031	0.020	0.043	0.044	0.030	0.061	0.061	0.043	0.083	0.059	0.041	0.080	0.022	0.014	0.031
Adiyaman	1695	824	0.049	0.021	0.058	0.069	0.030	0.082	0.093	0.044	0.110	0.090	0.042	0.106	0.035	0.015	0.042
Afyon	2828	58	0.068	0.000	0.068	0.095	0.000	0.095	0.126	0.000	0.127	0.122	0.000	0.123	0.049	0.000	0.049
Ağri	4423	35	0.088	0.000	0.089	0.123	0.000	0.124	0.163	0.000	0.164	0.157	0.000	0.158	0.064	0.000	0.064
Amasya	2210	159	0.058	0.000	0.060	0.081	0.002	0.084	0.109	0.008	0.112	0.105	0.007	0.108	0.042	0.000	0.043
Ankara	2677	109	0.065	0.000	0.066	0.092	0.000	0.093	0.122	0.003	0.124	0.118	0.002	0.120	0.047	0.000	0.048
Antalya	1083	562	0.036	0.014	0.044	0.051	0.022	0.062	0.071	0.033	0.085	0.068	0.031	0.082	0.026	0.010	0.032
Artvin	2429	58	0.062	0.000	0.062	0.086	0.000	0.087	0.116	0.000	0.117	0.111	0.000	0.112	0.044	0.000	0.045
Aydin	1213	601	0.039	0.016	0.047	0.055	0.023	0.067	0.076	0.035	0.090	0.073	0.033	0.087	0.028	0.011	0.034
Balikesir	1914	226	0.053	0.003	0.055	0.074	0.007	0.078	0.100	0.013	0.105	0.097	0.012	0.101	0.038	0.002	0.040
Bilecik	2397	101	0.061	0.000	0.062	0.086	0.000	0.087	0.115	0.002	0.117	0.110	0.002	0.112	0.044	0.000	0.045
Bingöl	2838	361	0.068	0.009	0.071	0.095	0.014	0.100	0.127	0.022	0.133	0.122	0.021	0.128	0.049	0.006	0.051
Bitlis	3311	105	0.074	0.000	0.075	0.104	0.000	0.105	0.138	0.003	0.140	0.133	0.002	0.135	0.054	0.000	0.055
Bolu	2821	22	0.068	0.000	0.068	0.095	0.000	0.095	0.126	0.000	0.127	0.121	0.000	0.122	0.049	0.000	0.049
Burdur	2351	183	0.060	0.002	0.062	0.085	0.004	0.087	0.113	0.010	0.117	0.109	0.009	0.112	0.043	0.000	0.045
Bursa	1920	177	0.053	0.001	0.055	0.075	0.004	0.077	0.101	0.010	0.104	0.097	0.009	0.100	0.038	0.000	0.040
Çanakkale	1789	249	0.051	0.004	0.054	0.071	0.008	0.075	0.096	0.015	0.102	0.093	0.014	0.098	0.036	0.003	0.039
Çankiri	2864	76	0.068	0.000	0.069	0.095	0.000	0.096	0.127	0.000	0.129	0.123	0.000	0.124	0.049	0.000	0.050
Çorum	2958	24	0.070	0.000	0.070	0.097	0.000	0.098	0.130	0.000	0.130	0.125	0.000	0.125	0.050	0.000	0.050
Denizli	1627	469	0.048	0.012	0.053	0.067	0.018	0.075	0.091	0.028	0.101	0.087	0.027	0.097	0.034	0.008	0.038
Diyarbakir	2142	640	0.057	0.017	0.064	0.080	0.024	0.089	0.107	0.036	0.119	0.103	0.035	0.115	0.041	0.011	0.046
Edirne	2224	195	0.058	0.002	0.060	0.082	0.005	0.085	0.110	0.011	0.113	0.106	0.010	0.109	0.042	0.001	0.043
Elaziğ	2653	337	0.065	0.008	0.068	0.091	0.012	0.096	0.122	0.021	0.128	0.117	0.020	0.123	0.047	0.005	0.049
Erzincan	3047	130	0.071	0.000	0.072	0.099	0.000	0.101	0.132	0.005	0.134	0.127	0.005	0.129	0.051	0.000	0.052
Erzurum	4827	7	0.093	0.000	0.093	0.130	0.000	0.130	0.171	0.000	0.171	0.165	0.000	0.165	0.068	0.000	0.068
Eskişehir	3049	27	0.071	0.000	0.071	0.099	0.000	0.099	0.132	0.000	0.132	0.127	0.000	0.128	0.051	0.000	0.051
Gaziantep	2009	521	0.055	0.013	0.060	0.077	0.020	0.085	0.103	0.031	0.113	0.099	0.029	0.109	0.039	0.009	0.043
Giresun	1765	108	0.050	0.000	0.051	0.071	0.000	0.072	0.096	0.003	0.098	0.092	0.002	0.094	0.036	0.000	0.037
Gümüşhane	3234	40	0.073	0.000	0.074	0.103	0.000	0.103	0.136	0.000	0.137	0.132	0.000	0.132	0.053	0.000	0.053
Hakkari	3470	184	0.077	0.002	0.078	0.107	0.004	0.109	0.142	0.010	0.145	0.137	0.009	0.140	0.055	0.001	0.057
Hatay	1119	614	0.037	0.016	0.045	0.052	0.024	0.064	0.072	0.035	0.087	0.069	0.033	0.084	0.026	0.011	0.033
Isparta	2607	88	0.064	0.000	0.065	0.090	0.000	0.091	0.120	0.001	0.122	0.116	0.000	0.118	0.046	0.000	0.047
İçel	852	585	0.030	0.015	0.039	0.043	0.023	0.056	0.060	0.034	0.077	0.058	0.032	0.074	0.021	0.010	0.028
İstanbul	1865	159	0.052	0.000	0.054	0.073	0.002	0.076	0.099	0.008	0.102	0.095	0.007	0.098	0.037	0.000	0.039
İzmir	1118	559	0.037	0.014	0.045	0.052	0.022	0.063	0.072	0.033	0.086	0.069	0.031	0.083	0.026	0.010	0.032
Kars	4772	2	0.093	0.000	0.093	0.129	0.000	0.129	0.170	0.000	0.170	0.164	0.000	0.164	0.067	0.000	0.067
Kastamonu	3112	23	0.072	0.000	0.072	0.100	0.000	0.101	0.134	0.000	0.134	0.129	0.000	0.129	0.052	0.000	0.052
Kayseri	3113	38	0.072	0.000	0.072	0.100	0.000	0.101	0.134	0.000	0.134	0.129	0.000	0.129	0.052	0.000	0.052
Kiriklareli	2274	185	0.059	0.002	0.061	0.083	0.004	0.086	0.111	0.010	0.115	0.107	0.009	0.110	0.043	0.001	0.044
Kirşehir	2857	85	0.068	0.000	0.069	0.095	0.000	0.096	0.127	0.000	0.129	0.122	0.000	0.124	0.049	0.000	0.050
Kocaeli	1786	204	0.051	0.003	0.053	0.071	0.005	0.075	0.096	0.012	0.101	0.093	0.011	0.097	0.036	0.001	0.038
Konya	2836	101	0.068	0.000	0.069	0.095	0.000	0.096	0.127	0.002	0.128	0.122	0.002	0.124	0.049	0.000	0.050
Kütahya	2880	35	0.068	0.000	0.069	0.096	0.000	0.096	0.128	0.000	0.128	0.123	0.000	0.124	0.049	0.000	0.050
Malatya	2461	407	0.062	0.010	0.066	0.087	0.016	0.093	0.116	0.025	0.124	0.112	0.024	0.119	0.045	0.007	0.048
Manisa	1535	570	0.046	0.015	0.053	0.065	0.022	0.074	0.088	0.033	0.100	0.084	0.032	0.096	0.033	0.010	0.038
K. Maraş	1653	649	0.048	0.017	0.056	0.068	0.025	0.078	0.092	0.037	0.105	0.088	0.035	0.101	0.035	0.012	0.040
Mardin	2004	755	0.054	0.019	0.063	0.077	0.028	0.088	0.103	0.041	0.118	0.099	0.039	0.113	0.039	0.013	0.045
Muğla	1879	369	0.052	0.009	0.056	0.074	0.014	0.079	0.099	0.023	0.107	0.095	0.021	0.103	0.038	0.006	0.041
Muş	3563	208	0.078	0.003	0.080	0.109	0.006	0.111	0.144	0.012	0.147	0.139	0.011	0.142	0.056	0.001	0.058
Nevşehir	3033	47	0.071	0.000	0.071	0.099	0.000	0.099	0.132	0.000	0.132	0.127	0.000	0.127	0.051	0.000	0.051
Niğde	2856	63	0.068	0.000	0.069	0.095	0.000	0.096	0.127	0.000	0.128	0.122	0.000	0.123	0.049	0.000	0.050
Ordu	1804	119	0.051	0.000	0.052	0.072	0.000	0.074	0.097	0.004	0.099	0.093	0.003	0.096	0.037	0.000	0.038

Table 7 (*Continued*)

Coal																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Rize	1820	81	0.051	0.000	0.052	0.072	0.000	0.073	0.097	0.000	0.099	0.094	0.000	0.095	0.037	0.000	0.038
Sakarya	1833	155	0.051	0.000	0.053	0.072	0.002	0.075	0.098	0.008	0.101	0.094	0.007	0.097	0.037	0.000	0.038
Samsun	1826	76	0.051	0.000	0.052	0.072	0.000	0.073	0.098	0.000	0.099	0.094	0.000	0.095	0.037	0.000	0.038
Siirt	1958	747	0.054	0.019	0.062	0.076	0.028	0.087	0.102	0.041	0.116	0.098	0.039	0.112	0.039	0.013	0.045
Sinop	1879	92	0.052	0.000	0.053	0.074	0.000	0.075	0.099	0.001	0.101	0.095	0.001	0.097	0.038	0.000	0.038
Sivas	3444	27	0.076	0.000	0.076	0.107	0.000	0.107	0.141	0.000	0.142	0.136	0.000	0.137	0.055	0.000	0.055
Tekirdağ	2032	112	0.055	0.000	0.056	0.077	0.000	0.079	0.104	0.004	0.106	0.100	0.003	0.102	0.040	0.000	0.040
Tokat	2399	97	0.061	0.000	0.062	0.086	0.000	0.087	0.115	0.002	0.117	0.110	0.001	0.112	0.044	0.000	0.045
Trabzon	1724	91	0.049	0.000	0.050	0.070	0.000	0.071	0.094	0.001	0.096	0.091	0.001	0.092	0.035	0.000	0.036
Tunceli	2716	353	0.066	0.008	0.069	0.092	0.013	0.097	0.123	0.022	0.129	0.119	0.021	0.125	0.048	0.005	0.050
Şanliurfa	1503	940	0.045	0.023	0.056	0.064	0.034	0.079	0.087	0.048	0.107	0.083	0.046	0.103	0.032	0.016	0.041
Uşak	2414	127	0.061	0.000	0.063	0.086	0.000	0.088	0.115	0.005	0.118	0.111	0.004	0.113	0.044	0.000	0.045
Van	3476	32	0.077	0.000	0.077	0.107	0.000	0.108	0.142	0.000	0.143	0.137	0.000	0.138	0.055	0.000	0.056
Yozgat	3422	20	0.076	0.000	0.076	0.106	0.000	0.106	0.141	0.000	0.141	0.136	0.000	0.136	0.055	0.000	0.055
Zonguldak	2020	50	0.055	0.000	0.055	0.077	0.000	0.078	0.104	0.000	0.105	0.100	0.000	0.101	0.039	0.000	0.040
Aksaray	2626	131	0.065	0.000	0.066	0.091	0.000	0.092	0.121	0.005	0.123	0.117	0.005	0.119	0.047	0.000	0.048
Bayburt	4149	8	0.085	0.000	0.085	0.119	0.000	0.119	0.157	0.000	0.157	0.152	0.000	0.152	0.062	0.000	0.062
Karaman	2698	119	0.066	0.000	0.067	0.092	0.000	0.094	0.123	0.004	0.125	0.118	0.003	0.120	0.047	0.000	0.048
Kirikkale	2609	128	0.064	0.000	0.066	0.090	0.000	0.092	0.121	0.005	0.123	0.116	0.004	0.118	0.046	0.000	0.047
Batman	1823	763	0.051	0.019	0.060	0.072	0.029	0.084	0.097	0.042	0.113	0.094	0.040	0.108	0.037	0.014	0.043
Şirnak	2065	184	0.056	0.002	0.058	0.078	0.004	0.081	0.105	0.010	0.109	0.101	0.009	0.105	0.040	0.001	0.041
Bartin	2226	44	0.058	0.000	0.059	0.082	0.000	0.082	0.110	0.000	0.111	0.106	0.000	0.106	0.042	0.000	0.042
Ardahan	5137	0.3	0.097	0.000	0.097	0.134	0.000	0.134	0.177	0.000	0.177	0.171	0.000	0.171	0.070	0.000	0.070
Iğdir	2764	276	0.067	0.005	0.069	0.093	0.009	0.097	0.125	0.017	0.129	0.120	0.016	0.125	0.048	0.003	0.050
Yalova	1843	123	0.052	0.000	0.053	0.073	0.000	0.075	0.098	0.005	0.101	0.094	0.004	0.097	0.037	0.000	0.038
Karabük	2145	85	0.057	0.000	0.058	0.080	0.000	0.081	0.107	0.000	0.109	0.103	0.000	0.105	0.041	0.000	0.042
Kilis	1554	689	0.046	0.018	0.055	0.065	0.026	0.077	0.088	0.039	0.103	0.085	0.037	0.099	0.033	0.012	0.039
Osmaniye	1103	584	0.036	0.015	0.045	0.052	0.023	0.063	0.071	0.034	0.086	0.068	0.032	0.083	0.026	0.010	0.032
Düzce	2065	35	0.056	0.000	0.056	0.078	0.000	0.079	0.105	0.000	0.106	0.101	0.000	0.102	0.040	0.000	0.040

Table 8
Optimum insulation thickness by insulant types for fuel-oil fuel in all provinces.

Fuel-oil																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Adana	874	796	0.039	0.020	0.050	0.056	0.030	0.070	0.077	0.043	0.095	0.073	0.041	0.092	0.028	0.014	0.036
Adiyaman	1695	824	0.061	0.021	0.069	0.085	0.030	0.097	0.115	0.044	0.129	0.110	0.042	0.124	0.044	0.015	0.050
Afyon	2828	58	0.083	0.000	0.084	0.116	0.000	0.117	0.154	0.000	0.155	0.148	0.000	0.149	0.060	0.000	0.061
Ağri	4423	35	0.108	0.000	0.108	0.150	0.000	0.150	0.197	0.000	0.198	0.190	0.000	0.191	0.078	0.000	0.079
Amasya	2210	159	0.072	0.000	0.073	0.100	0.002	0.102	0.134	0.008	0.136	0.129	0.007	0.131	0.052	0.000	0.053
Ankara	2677	109	0.081	0.000	0.081	0.112	0.000	0.114	0.149	0.003	0.151	0.144	0.002	0.145	0.058	0.000	0.059
Antalya	1083	562	0.046	0.014	0.053	0.064	0.022	0.074	0.087	0.033	0.100	0.084	0.031	0.096	0.033	0.010	0.038
Artvin	2429	58	0.076	0.000	0.076	0.106	0.000	0.107	0.141	0.000	0.142	0.136	0.000	0.137	0.055	0.000	0.055
Aydin	1213	601	0.049	0.016	0.056	0.069	0.023	0.079	0.094	0.035	0.106	0.090	0.033	0.102	0.035	0.011	0.041
Balikesir	1914	226	0.066	0.003	0.068	0.092	0.007	0.095	0.123	0.013	0.127	0.118	0.012	0.122	0.047	0.002	0.049
Bilecik	2397	101	0.075	0.000	0.076	0.105	0.000	0.107	0.140	0.002	0.142	0.135	0.002	0.136	0.055	0.000	0.055
Bingöl	2838	361	0.083	0.009	0.086	0.116	0.014	0.120	0.154	0.022	0.159	0.149	0.021	0.153	0.060	0.006	0.063
Bitlis	3311	105	0.091	0.000	0.092	0.127	0.000	0.128	0.168	0.003	0.169	0.162	0.002	0.163	0.066	0.000	0.067
Bolu	2821	22	0.083	0.000	0.083	0.116	0.000	0.116	0.154	0.000	0.154	0.148	0.000	0.148	0.060	0.000	0.060
Burdur	2351	183	0.075	0.002	0.076	0.104	0.004	0.106	0.138	0.010	0.141	0.133	0.009	0.136	0.054	0.000	0.055
Bursa	1920	177	0.066	0.001	0.068	0.092	0.004	0.095	0.123	0.010	0.126	0.119	0.009	0.122	0.048	0.000	0.049
Çanakkale	1789	249	0.063	0.004	0.066	0.088	0.008	0.092	0.118	0.015	0.123	0.114	0.014	0.118	0.045	0.003	0.047
Çankiri	2864	76	0.084	0.000	0.084	0.117	0.000	0.118	0.155	0.000	0.156	0.149	0.000	0.150	0.061	0.000	0.061
Çorum	2958	24	0.085	0.000	0.086	0.119	0.000	0.119	0.158	0.000	0.158	0.152	0.000	0.152	0.062	0.000	0.062
Denizli	1627	469	0.059	0.012	0.064	0.083	0.018	0.090	0.112	0.028	0.120	0.108	0.027	0.116	0.043	0.008	0.046
Diyarbakir	2142	640	0.070	0.017	0.076	0.099	0.024	0.106	0.131	0.036	0.141	0.126	0.035	0.136	0.051	0.011	0.055
Edirne	2224	195	0.072	0.002	0.074	0.101	0.005	0.103	0.134	0.011	0.137	0.129	0.010	0.132	0.052	0.001	0.053
Elaziğ	2653	337	0.080	0.008	0.083	0.112	0.012	0.116	0.148	0.021	0.153	0.143	0.020	0.148	0.058	0.005	0.060
Erzincan	3047	130	0.087	0.000	0.088	0.121	0.000	0.123	0.160	0.005	0.162	0.155	0.005	0.156	0.063	0.000	0.064
Erzurum	4827	7	0.114	0.000	0.114	0.158	0.000	0.158	0.207	0.000	0.207	0.200	0.000	0.200	0.082	0.000	0.082
Eskişehir	3049	27	0.087	0.000	0.087	0.121	0.000	0.122	0.160	0.000	0.161	0.155	0.000	0.155	0.063	0.000	0.063
Gaziantep	2009	521	0.068	0.013	0.073	0.095	0.020	0.102	0.126	0.031	0.135	0.122	0.029	0.130	0.049	0.009	0.052
Giresun	1765	108	0.062	0.000	0.064	0.088	0.000	0.089	0.117	0.003	0.119	0.113	0.002	0.115	0.045	0.000	0.046
Gümüşhane	3234	40	0.090	0.000	0.090	0.126	0.000	0.126	0.166	0.000	0.166	0.160	0.000	0.160	0.065	0.000	0.066
Hakkari	3470	184	0.094	0.002	0.095	0.131	0.004	0.133	0.173	0.010	0.175	0.166	0.009	0.169	0.068	0.001	0.069
Hatay	1119	614	0.047	0.016	0.054	0.066	0.024	0.076	0.089	0.035	0.102	0.086	0.033	0.099	0.033	0.011	0.039
Isparta	2607	88	0.079	0.000	0.080	0.111	0.000	0.112	0.147	0.001	0.148	0.142	0.000	0.143	0.057	0.000	0.058
İçel	852	585	0.039	0.015	0.047	0.055	0.023	0.066	0.075	0.034	0.090	0.072	0.032	0.086	0.028	0.010	0.034
İstanbul	1865	159	0.065	0.000	0.066	0.091	0.002	0.093	0.121	0.008	0.124	0.117	0.007	0.119	0.047	0.000	0.048
İzmir	1118	559	0.047	0.014	0.053	0.066	0.022	0.075	0.089	0.033	0.101	0.086	0.031	0.097	0.033	0.010	0.038
Kars	4772	2	0.113	0.000	0.113	0.157	0.000	0.157	0.206	0.000	0.206	0.199	0.000	0.199	0.082	0.000	0.082

Table 8 (*Continued*)

Fuel-oil																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Kastamonu	3112	23	0.088	0.000	0.088	0.123	0.000	0.123	0.162	0.000	0.163	0.157	0.000	0.157	0.064	0.000	0.064
Kayseri	3113	38	0.088	0.000	0.088	0.123	0.000	0.123	0.162	0.000	0.163	0.157	0.000	0.157	0.064	0.000	0.064
Kiriklareli	2274	185	0.073	0.002	0.075	0.102	0.004	0.104	0.136	0.010	0.139	0.131	0.009	0.134	0.053	0.001	0.054
Kirşehir	2857	85	0.084	0.000	0.084	0.117	0.000	0.118	0.155	0.000	0.156	0.149	0.000	0.150	0.061	0.000	0.061
Kocaeli	1786	204	0.063	0.003	0.065	0.088	0.005	0.091	0.118	0.012	0.122	0.114	0.011	0.117	0.045	0.001	0.047
Konya	2836	101	0.083	0.000	0.084	0.116	0.000	0.117	0.154	0.002	0.155	0.149	0.002	0.150	0.060	0.000	0.061
Kütahya	2880	35	0.084	0.000	0.084	0.117	0.000	0.118	0.155	0.000	0.156	0.150	0.000	0.150	0.061	0.000	0.061
Malatya	2461	407	0.077	0.010	0.080	0.107	0.016	0.112	0.142	0.025	0.148	0.137	0.024	0.143	0.055	0.007	0.058
Manisa	1535	570	0.057	0.015	0.063	0.080	0.022	0.089	0.108	0.033	0.119	0.104	0.032	0.114	0.041	0.010	0.046
K. Maraş	1653	649	0.060	0.017	0.067	0.084	0.025	0.093	0.113	0.037	0.125	0.109	0.035	0.120	0.043	0.012	0.048
Mardin	2004	755	0.068	0.019	0.075	0.095	0.028	0.104	0.126	0.041	0.139	0.122	0.039	0.134	0.049	0.013	0.054
Muğla	1879	369	0.065	0.009	0.069	0.091	0.014	0.096	0.122	0.023	0.128	0.117	0.021	0.123	0.047	0.006	0.050
Muş	3563	208	0.095	0.003	0.097	0.133	0.006	0.135	0.175	0.012	0.178	0.169	0.011	0.171	0.069	0.001	0.070
Nevşehir	3033	47	0.087	0.000	0.087	0.121	0.000	0.121	0.160	0.000	0.161	0.154	0.000	0.155	0.063	0.000	0.063
Niğde	2856	63	0.084	0.000	0.084	0.117	0.000	0.118	0.155	0.000	0.156	0.149	0.000	0.150	0.061	0.000	0.061
Ordu	1804	119	0.063	0.000	0.065	0.089	0.000	0.090	0.119	0.004	0.121	0.114	0.003	0.116	0.046	0.000	0.047
Rize	1820	81	0.064	0.000	0.065	0.089	0.000	0.090	0.119	0.000	0.121	0.115	0.000	0.116	0.046	0.000	0.047
Sakarya	1833	155	0.064	0.000	0.066	0.090	0.002	0.092	0.120	0.008	0.123	0.115	0.007	0.118	0.046	0.000	0.047
Samsun	1826	76	0.064	0.000	0.065	0.089	0.000	0.091	0.120	0.000	0.121	0.115	0.000	0.116	0.046	0.000	0.047
Siirt	1958	747	0.067	0.019	0.074	0.093	0.028	0.103	0.125	0.041	0.137	0.120	0.039	0.132	0.048	0.013	0.053
Sinop	1879	92	0.065	0.000	0.066	0.091	0.000	0.092	0.122	0.001	0.123	0.117	0.001	0.119	0.047	0.000	0.048
Sivas	3444	27	0.093	0.000	0.094	0.130	0.000	0.130	0.172	0.000	0.172	0.166	0.000	0.166	0.068	0.000	0.068
Tekirdağ	2032	112	0.068	0.000	0.069	0.095	0.000	0.097	0.127	0.004	0.129	0.123	0.003	0.124	0.049	0.000	0.050
Tokat	2399	97	0.075	0.000	0.076	0.105	0.000	0.107	0.140	0.002	0.142	0.135	0.001	0.136	0.055	0.000	0.055
Trabzon	1724	91	0.062	0.000	0.063	0.086	0.000	0.088	0.116	0.001	0.117	0.111	0.001	0.113	0.044	0.000	0.045
Tunceli	2716	353	0.081	0.008	0.084	0.113	0.013	0.117	0.150	0.022	0.155	0.145	0.021	0.150	0.059	0.005	0.061
Şanliurfa	1503	940	0.056	0.023	0.066	0.079	0.034	0.093	0.107	0.048	0.124	0.103	0.046	0.119	0.041	0.016	0.048
Uşak	2414	127	0.076	0.000	0.077	0.106	0.000	0.107	0.141	0.005	0.143	0.135	0.004	0.137	0.055	0.000	0.056
Van	3476	32	0.094	0.000	0.094	0.131	0.000	0.131	0.173	0.000	0.173	0.167	0.000	0.167	0.068	0.000	0.068
Yozgat	3422	20	0.093	0.000	0.093	0.130	0.000	0.130	0.171	0.000	0.171	0.165	0.000	0.165	0.068	0.000	0.068
Zonguldak	2020	50	0.068	0.000	0.068	0.095	0.000	0.096	0.127	0.000	0.128	0.122	0.000	0.123	0.049	0.000	0.049
Aksaray	2626	131	0.080	0.000	0.081	0.111	0.000	0.113	0.147	0.005	0.149	0.142	0.005	0.144	0.058	0.000	0.058
Bayburt	4149	8	0.104	0.000	0.104	0.145	0.000	0.145	0.191	0.000	0.191	0.184	0.000	0.184	0.076	0.000	0.076
Karaman	2698	119	0.081	0.000	0.082	0.113	0.000	0.114	0.150	0.004	0.151	0.144	0.003	0.146	0.059	0.000	0.059
Kirikkale	2609	128	0.079	0.000	0.080	0.111	0.000	0.112	0.147	0.005	0.149	0.142	0.004	0.143	0.057	0.000	0.058
Batman	1823	763	0.064	0.019	0.071	0.089	0.029	0.100	0.120	0.042	0.133	0.115	0.040	0.128	0.046	0.014	0.051
Şirnak	2065	184	0.069	0.002	0.071	0.096	0.004	0.099	0.128	0.010	0.132	0.124	0.009	0.127	0.050	0.001	0.051
Bartin	2226	44	0.072	0.000	0.072	0.101	0.000	0.101	0.134	0.000	0.135	0.129	0.000	0.130	0.052	0.000	0.052
Ardahan	5137	0.3	0.118	0.000	0.118	0.163	0.000	0.163	0.214	0.000	0.214	0.207	0.000	0.207	0.085	0.000	0.085
Iğdir	2764	276	0.082	0.005	0.084	0.115	0.009	0.118	0.152	0.017	0.156	0.146	0.016	0.150	0.059	0.003	0.061
Yalova	1843	123	0.064	0.000	0.065	0.090	0.000	0.092	0.120	0.005	0.122	0.116	0.004	0.118	0.046	0.000	0.047
Karabük	2145	85	0.070	0.000	0.071	0.099	0.000	0.100	0.131	0.000	0.133	0.127	0.000	0.128	0.051	0.000	0.052
Kilis	1554	689	0.058	0.018	0.065	0.081	0.026	0.091	0.109	0.039	0.121	0.105	0.037	0.117	0.042	0.012	0.047
Osmaniye	1103	584	0.046	0.015	0.053	0.065	0.023	0.075	0.088	0.034	0.101	0.085	0.032	0.097	0.033	0.010	0.038
Düzce	2065	35	0.069	0.000	0.069	0.096	0.000	0.097	0.128	0.000	0.129	0.124	0.000	0.124	0.050	0.000	0.050

required insulation thickness increases so long as the unit prices of the fuels increase. The thickest required insulation materials were calculated for LPG, due to the fact that it is more expensive than the other fuels,

Optimum insulation thickness for different fuel types has been calculated with Eqs. (20)–(22). For heating, cooling, and both heating and cooling, optimum insulation thicknesses are provided in Tables 6–9 for natural gas, coal, fuel-oil and LPG, respectively. Following data is given in the tables with respect to all provincial centers of Turkey: heating degree-day values, cooling degrees-day values, required optimum insulation thickness for buildings that are heated but not cooled (x_{optH}), required optimum insulation thickness for buildings that are cooled but not heated (x_{optH}), required optimum insulation thickness for buildings that are both heated and cooled ($x_{optH,C}$).

By means of calculations made, required optimum insulation thicknesses according to heating degree-day values and type of insulant are provided in Fig. 3. As heating degree-day values increase, required insulation thickness increases.

Fig. 4 shows required optimum insulation thicknesses according to cooling degree-day values and type of insulant. Just like in heating, as degree-day values increase in cooling, required insulation thickness increases too.

Calculations were made for 81 provinces in Turkey. Instead of showing variations of optimum insulation thicknesses for all provinces, variations of insulation thicknesses for 5 provinces chosen from 5 regions according to heating degree-day values set out at TS 825 standard [6] will be provided. Variations in the province chosen will serve as a guide for other provinces.

For five chosen provinces, variations of required optimum insulation thicknesses by type of insulant used in external walls are provided in Fig. 5 for buildings heated only and Fig. 6 for buildings both heated and cooled. When required insulation thicknesses are examined, thicknesses decrease in the order of glass wool, rock wool, EPS, XPS and polyurethane.

Fig. 7 shows required optimum insulation thicknesses by fuels in 5 chosen provinces in the event of heating only. Whereas Fig. 8 shows optimum insulation thicknesses needed to be used in external walls of buildings both heated and cooled.

Fig. 9 shows variation of total net saving ($A_{year,H}$) value with thickness of insulant to be used by fuels individually for 5 provinces chosen, in the event EPS insulant is used at buildings heated only. As thickness of insulant used increases, total net saving amount

Table 9
Optimum insulation thickness by insulant types for LPG fuel in all provinces.

LPG																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Adana	874	796	0.062	0.020	0.070	0.087	0.030	0.098	0.117	0.043	0.131	0.113	0.041	0.126	0.045	0.014	0.051
Adiyaman	1695	824	0.093	0.021	0.099	0.129	0.030	0.138	0.171	0.044	0.181	0.165	0.042	0.175	0.067	0.015	0.072
Afyon	2828	58	0.125	0.000	0.125	0.173	0.000	0.173	0.226	0.000	0.227	0.219	0.000	0.219	0.091	0.000	0.091
Ağri	4423	35	0.160	0.000	0.160	0.221	0.000	0.221	0.288	0.000	0.289	0.278	0.000	0.279	0.116	0.000	0.116
Amasya	2210	159	0.108	0.000	0.109	0.151	0.002	0.152	0.198	0.008	0.200	0.191	0.007	0.193	0.079	0.000	0.079
Ankara	2677	109	0.121	0.000	0.121	0.168	0.000	0.169	0.220	0.003	0.221	0.212	0.002	0.213	0.088	0.000	0.088
Antalya	1083	562	0.071	0.014	0.076	0.099	0.022	0.106	0.132	0.033	0.141	0.128	0.031	0.136	0.051	0.010	0.055
Artvin	2429	58	0.114	0.000	0.115	0.159	0.000	0.159	0.208	0.000	0.209	0.201	0.000	0.202	0.083	0.000	0.083
Aydin	1213	601	0.076	0.016	0.081	0.106	0.023	0.113	0.141	0.035	0.150	0.136	0.033	0.145	0.055	0.011	0.059
Balikesir	1914	226	0.100	0.003	0.101	0.139	0.007	0.141	0.183	0.013	0.185	0.176	0.012	0.179	0.072	0.002	0.073
Bilecik	2397	101	0.113	0.000	0.114	0.158	0.000	0.158	0.207	0.002	0.208	0.200	0.002	0.201	0.082	0.000	0.083
Bingöl	2838	361	0.125	0.009	0.127	0.173	0.014	0.176	0.227	0.022	0.231	0.219	0.021	0.223	0.091	0.006	0.092
Bitlis	3311	105	0.136	0.000	0.137	0.189	0.000	0.189	0.247	0.003	0.248	0.238	0.002	0.239	0.099	0.000	0.099
Bolu	2821	22	0.124	0.000	0.124	0.173	0.000	0.173	0.226	0.000	0.226	0.218	0.000	0.219	0.090	0.000	0.090
Burdur	2351	183	0.112	0.002	0.113	0.156	0.004	0.157	0.205	0.010	0.207	0.198	0.009	0.200	0.081	0.000	0.082
Bursa	1920	177	0.100	0.001	0.101	0.139	0.004	0.141	0.183	0.010	0.185	0.177	0.009	0.179	0.072	0.000	0.073
Çanakkale	1789	249	0.096	0.004	0.098	0.133	0.008	0.136	0.176	0.015	0.179	0.170	0.014	0.173	0.070	0.003	0.071
Çankiri	2864	76	0.125	0.000	0.126	0.174	0.000	0.175	0.228	0.000	0.229	0.220	0.000	0.221	0.091	0.000	0.091
Çorum	2958	24	0.128	0.000	0.128	0.177	0.000	0.177	0.232	0.000	0.232	0.224	0.000	0.224	0.093	0.000	0.093
Denizli	1627	469	0.091	0.012	0.094	0.126	0.018	0.131	0.167	0.028	0.173	0.161	0.027	0.167	0.066	0.008	0.068
Diyarbakir	2142	640	0.106	0.017	0.111	0.148	0.024	0.154	0.194	0.036	0.202	0.188	0.035	0.195	0.077	0.011	0.080
Edirne	2224	195	0.109	0.002	0.110	0.151	0.005	0.153	0.199	0.011	0.201	0.192	0.010	0.194	0.079	0.001	0.080
Elaziğ	2653	337	0.120	0.008	0.122	0.167	0.012	0.170	0.219	0.021	0.222	0.211	0.020	0.215	0.087	0.005	0.089
Erzincan	3047	130	0.130	0.000	0.131	0.180	0.000	0.181	0.236	0.005	0.237	0.228	0.005	0.229	0.094	0.000	0.095
Erzurum	4827	7	0.167	0.000	0.168	0.232	0.000	0.232	0.302	0.000	0.302	0.292	0.000	0.292	0.122	0.000	0.122
Eskişehir	3049	27	0.130	0.000	0.130	0.180	0.000	0.180	0.236	0.000	0.236	0.228	0.000	0.228	0.094	0.000	0.095
Gaziantep	2009	521	0.103	0.013	0.106	0.143	0.020	0.147	0.188	0.031	0.194	0.181	0.029	0.187	0.074	0.009	0.077
Giresun	1765	108	0.095	0.000	0.096	0.132	0.000	0.134	0.175	0.003	0.176	0.168	0.002	0.170	0.069	0.000	0.070
Gümüşhane	3234	40	0.134	0.000	0.134	0.186	0.000	0.187	0.244	0.000	0.244	0.235	0.000	0.236	0.098	0.000	0.098
Hakkari	3470	184	0.140	0.002	0.141	0.194	0.004	0.195	0.253	0.010	0.255	0.244	0.009	0.246	0.102	0.001	0.102
Hatay	1119	614	0.073	0.016	0.078	0.101	0.024	0.109	0.135	0.035	0.145	0.130	0.033	0.139	0.052	0.011	0.056
Isparta	2607	88	0.119	0.000	0.119	0.165	0.000	0.166	0.217	0.001	0.218	0.209	0.000	0.210	0.086	0.000	0.087
İçel	852	585	0.061	0.015	0.067	0.086	0.023	0.094	0.115	0.034	0.126	0.111	0.032	0.121	0.044	0.010	0.049
İstanbul	1865	159	0.098	0.000	0.099	0.137	0.002	0.138	0.180	0.008	0.182	0.174	0.007	0.176	0.071	0.000	0.072
İzmir	1118	559	0.073	0.014	0.077	0.101	0.022	0.108	0.135	0.033	0.144	0.130	0.031	0.138	0.052	0.010	0.056
Kars	4772	2	0.166	0.000	0.166	0.230	0.000	0.230	0.300	0.000	0.300	0.290	0.000	0.290	0.121	0.000	0.121
Kastamonu	3112	23	0.131	0.000	0.132	0.182	0.000	0.182	0.239	0.000	0.239	0.230	0.000	0.231	0.096	0.000	0.096
Kayseri	3113	38	0.131	0.000	0.132	0.182	0.000	0.183	0.239	0.000	0.239	0.230	0.000	0.231	0.096	0.000	0.096
Kiriklareli	2274	185	0.110	0.002	0.111	0.153	0.004	0.155	0.201	0.010	0.203	0.194	0.009	0.196	0.080	0.001	0.081
Kirşehir	2857	85	0.125	0.000	0.126	0.174	0.000	0.175	0.228	0.000	0.229	0.220	0.000	0.221	0.091	0.000	0.091
Kocaeli	1786	204	0.096	0.003	0.097	0.133	0.005	0.135	0.176	0.012	0.178	0.170	0.011	0.172	0.069	0.001	0.071
Konya	2836	101	0.125	0.000	0.125	0.173	0.000	0.174	0.227	0.002	0.228	0.219	0.002	0.220	0.091	0.000	0.091
Kütahya	2880	35	0.126	0.000	0.126	0.175	0.000	0.175	0.229	0.000	0.229	0.221	0.000	0.221	0.091	0.000	0.092
Malatya	2461	407	0.115	0.010	0.118	0.160	0.016	0.163	0.210	0.025	0.214	0.203	0.024	0.207	0.084	0.007	0.085
Manisa	1535	570	0.088	0.015	0.092	0.122	0.022	0.128	0.162	0.033	0.169	0.156	0.032	0.163	0.064	0.010	0.067
K. Maraş	1653	649	0.092	0.017	0.096	0.128	0.025	0.134	0.168	0.037	0.177	0.162	0.035	0.171	0.066	0.012	0.070
Mardin	2004	755	0.102	0.019	0.107	0.142	0.028	0.149	0.187	0.041	0.196	0.181	0.039	0.189	0.074	0.013	0.078
Muğla	1879	369	0.099	0.009	0.101	0.137	0.014	0.141	0.181	0.023	0.185	0.174	0.021	0.179	0.072	0.006	0.073
Muş	3563	208	0.142	0.003	0.143	0.196	0.006	0.198	0.257	0.012	0.259	0.248	0.011	0.250	0.103	0.001	0.104
Nevşehir	3033	47	0.130	0.000	0.130	0.180	0.000	0.180	0.235	0.000	0.236	0.227	0.000	0.228	0.094	0.000	0.094
Niğde	2856	63	0.125	0.000	0.126	0.174	0.000	0.174	0.228	0.000	0.228	0.220	0.000	0.220	0.091	0.000	0.091
Ordu	1804	119	0.096	0.000	0.097	0.134	0.000	0.135	0.177	0.004	0.178	0.171	0.003	0.172	0.070	0.000	0.070
Rize	1820	81	0.097	0.000	0.097	0.135	0.000	0.136	0.178	0.000	0.179	0.171	0.000	0.172	0.070	0.000	0.071
Sakarya	1833	155	0.097	0.000	0.098	0.135	0.002	0.137	0.178	0.008	0.180	0.172	0.007	0.174	0.071	0.000	0.071
Samsun	1826	76	0.097	0.000	0.098	0.135	0.000	0.136	0.178	0.000	0.179	0.172	0.000	0.173	0.070	0.000	0.071
Siirt	1958	747	0.101	0.019	0.106	0.141	0.028	0.147	0.185	0.041	0.194	0.179	0.039	0.187	0.073	0.013	0.077
Sinop	1879	92	0.099	0.000	0.099	0.137	0.000	0.138	0.181	0.001	0.182	0.174	0.001	0.176	0.072	0.000	0.072
Sivas	3444	27	0.139	0.000	0.139	0.193	0.000	0.193	0.252	0.000	0.252	0.243	0.000	0.244	0.101	0.000	0.101
Tekirdağ	2032	112	0.103	0.000	0.104	0.144	0.000	0.145	0.189	0.004	0.190	0.182	0.003	0.184	0.075	0.000	0.075
Tokat	2399	97	0.113	0.000	0.114	0.158	0.000	0.158	0.207	0.002	0.208	0.200	0.001	0.201	0.082	0.000	0.083
Trabzon	1724	91	0.094	0.000	0.094	0.131	0.000	0.132	0.172	0.001	0.174	0.166	0.001	0.167	0.068	0.000	0.069
Tunceli	2716	353	0.122	0.008	0.124	0.169	0.013	0.172	0.222	0.022	0.225	0.214	0.021	0.217	0.088	0.005	0.090
Şanliurfa	1503	940	0.087	0.023	0.094	0.121	0.034	0.131	0.160	0.048	0.172	0.154	0.046	0.166	0.063	0.016	0.068
Uşak	2414	127	0.114	0.000	0.115	0.158	0.000	0.159	0.208	0.005	0.209	0.200	0.004	0.202	0.083	0.000	0.083
Van	3476	32	0.140	0.000	0.140	0.194	0.000	0.194	0.253	0.000	0.254	0.245	0.000	0.245	0.102	0.000	0.102
Yozgat	3422	20	0.139	0.000	0.139	0.192	0.000	0.192	0.251	0.000	0.251	0.243	0.000	0.243	0.101	0.000	0.101
Zonguldak	2020	50	0.103	0.000	0.103	0.143	0.000	0.144	0.188	0.000	0.189	0.182	0.000	0.182	0.075	0.000	0.075
Aksaray	2626	131	0.119	0.000	0.120	0.166	0.000	0.167	0.217	0.005	0.219	0.210	0.005	0.211	0.087	0.000	0.087
Bayburt	4149	8	0.154	0.000	0.154	0.214	0.000	0.214	0.279	0.000	0.279	0.269	0.000	0.269	0.112	0.000	0.112
Karaman	2698	119	0.121	0.000	0.122	0.168	0.000	0.169	0.221	0.004	0.222	0.213	0.003	0.214	0.088	0.000	0.089
Kirikkale	2609	128	0.119	0.000	0.120	0.165	0.000	0.166	0.217	0.005	0.218	0.209	0.004	0.211	0.086	0.000	0.087
Batman	1823	763	0.097	0.019	0.102	0.135	0.029	0.142	0.178	0.042	0.187	0.172	0.040	0.181	0.070	0.014	0.074

Table 9 (*Continued*)

LPG																	
City	HDD	CDD	XPS			EPS			Glass wool			Rock wool			Polyurethane		
			$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$	$X_{opt,H}$	$X_{opt,C}$	$X_{opt,H,C}$
Şirnak	2065	184	0.104	0.002	0.105	0.145	0.004	0.147	0.191	0.010	0.193	0.184	0.009	0.186	0.076	0.001	0.076
Bartin	2226	44	0.109	0.000	0.109	0.151	0.000	0.152	0.199	0.000	0.199	0.192	0.000	0.192	0.079	0.000	0.079
Ardahan	5137	0.3	0.173	0.000	0.173	0.240	0.000	0.240	0.312	0.000	0.312	0.302	0.000	0.302	0.126	0.000	0.126
Iğdir	2764	276	0.123	0.005	0.125	0.171	0.009	0.173	0.224	0.017	0.226	0.216	0.016	0.219	0.089	0.003	0.091
Yalova	1843	123	0.098	0.000	0.098	0.136	0.000	0.137	0.179	0.005	0.180	0.173	0.004	0.174	0.071	0.000	0.071
Karabük	2145	85	0.106	0.000	0.107	0.148	0.000	0.149	0.195	0.000	0.196	0.188	0.000	0.189	0.077	0.000	0.078
Kilis	1554	689	0.088	0.018	0.093	0.123	0.026	0.130	0.163	0.039	0.172	0.157	0.037	0.166	0.064	0.012	0.068
Osmaniye	1103	584	0.072	0.015	0.077	0.101	0.023	0.108	0.134	0.034	0.143	0.129	0.032	0.138	0.052	0.010	0.056
Düzce	2065	35	0.104	0.000	0.104	0.145	0.000	0.145	0.191	0.000	0.191	0.184	0.000	0.184	0.076	0.000	0.076

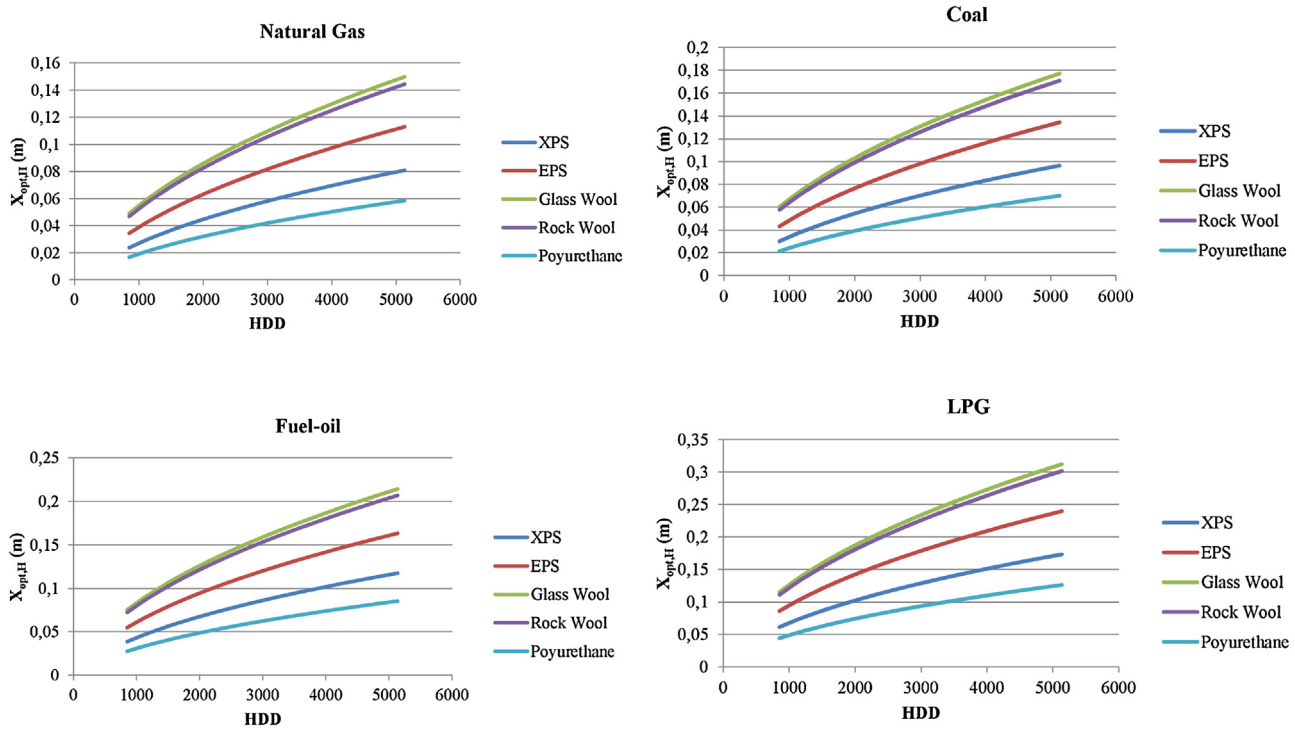


Fig. 3. Optimum insulation thickness needed to be used according to heating degree-day values at external walls of buildings heated only.

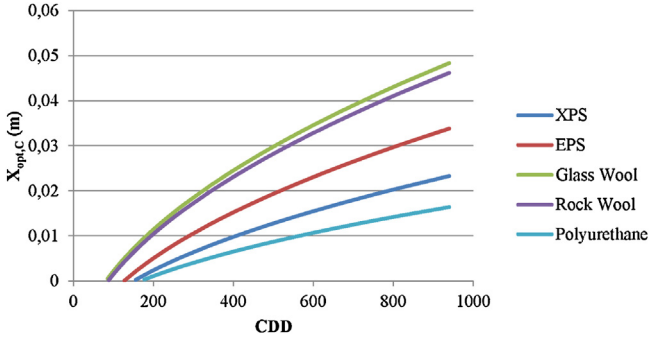


Fig. 4. Optimum insulation thickness needed to be used according to cooling degree-day values at external walls of buildings cooled only.

increases, then variation decreases despite increase of insulation thickness and the curve takes a horizontal form. When net saving amount is compared for same insulant thickness, the highest is LPG, and then fuel-oil, coal and natural gas respectively. This ranking occurs due to the fact that while natural gas is more affordable in Turkey in comparison with other fuels, LPG is the most expensive in comparison with other fuels chosen.

For the provinces chosen, Fig. 10 shows variation of EPS insulant thickness to be used individually for four fuels and total net saving ($A_{year,H}$) value in the event of utilization of EPS insulant. When net saving amount is compared for same insulation thickness, Erzurum province is highest, and then Sivas, Ankara, Istanbul and İzmir respectively. It is observed that heating degree-day values of the provinces decrease accordingly.

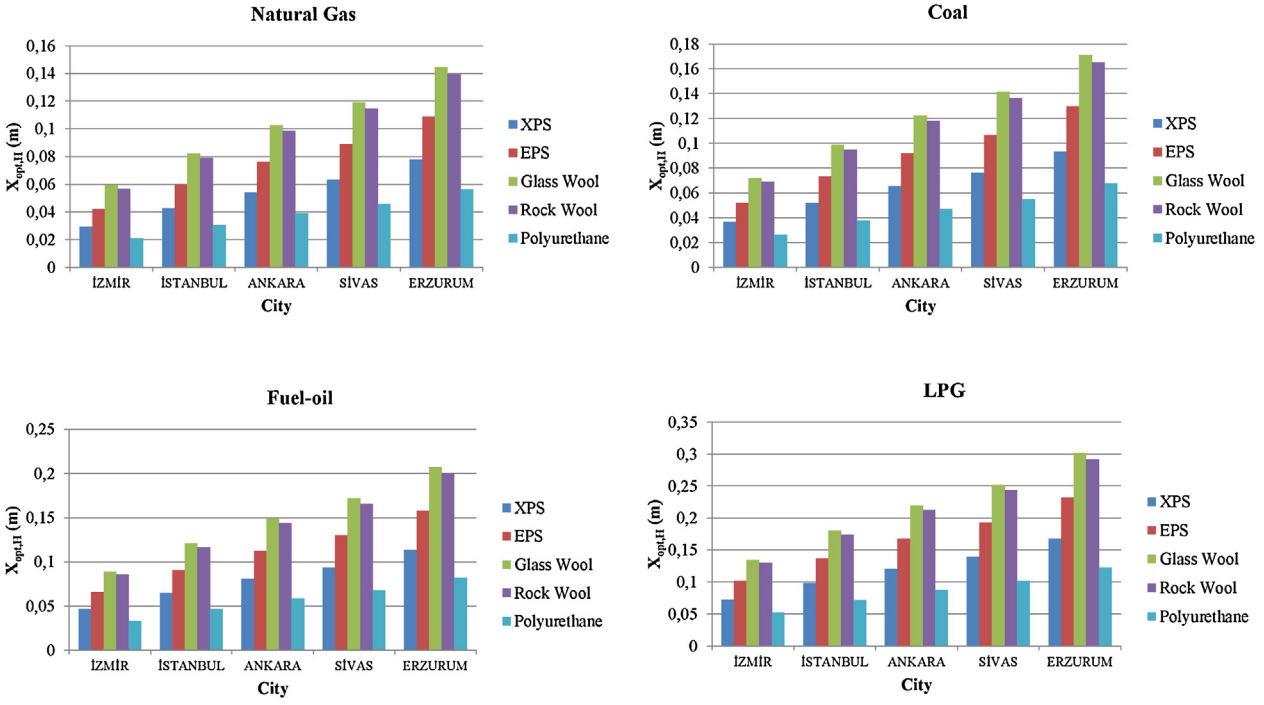


Fig. 5. Optimum thicknesses of insulants to be used by fuels at buildings heated only for sample cities chosen.

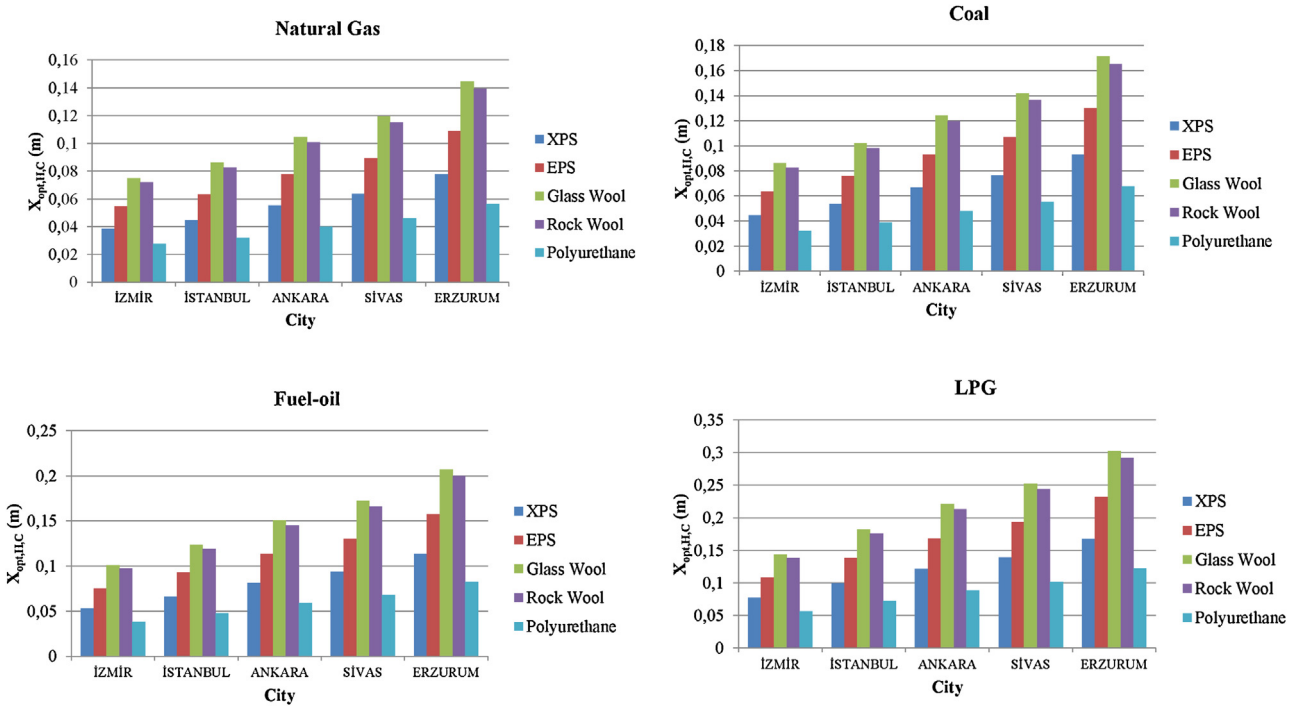


Fig. 6. Optimum thicknesses of insulants to be used by fuels at buildings both heated and cooled for sample cities chosen.

Table 10
Optimum insulation thickness at external walls of buildings heated only, net saving amount and payback period in the event EPS insulant is used for 5 provinces chosen.

City	Natural gas			Coal			Fuel-oil			LPG		
	$X_{opt,H}$ (m)	$A_{year,H}$ ($/m^2)	pp_H (year)	$X_{opt,H}$ (m)	$A_{year,H}$ ($/m^2)	pp_H (year)	$X_{opt,H}$ (m)	$A_{year,H}$ ($/m^2)	pp_H (year)	$X_{opt,H}$ (m)	$A_{year,H}$ ($/m^2)	pp_H (year)
Izmir	0.042	1.625	3.118	0.052	2.336	2.684	0.066	3.490	2.260	0.101	7.634	1.594
Istanbul	0.060	2.996	2.414	0.073	4.228	2.078	0.091	6.214	1.750	0.137	13.291	1.234
Ankara	0.076	4.532	2.015	0.092	6.338	1.734	0.112	9.240	1.461	0.168	19.531	1.030
Sivas	0.089	6.008	1.777	0.107	8.360	1.529	0.130	12.132	1.288	0.193	25.475	0.908
Erzurum	0.109	8.709	1.501	0.130	12.053	1.292	0.158	17.403	1.088	0.232	36.270	0.767

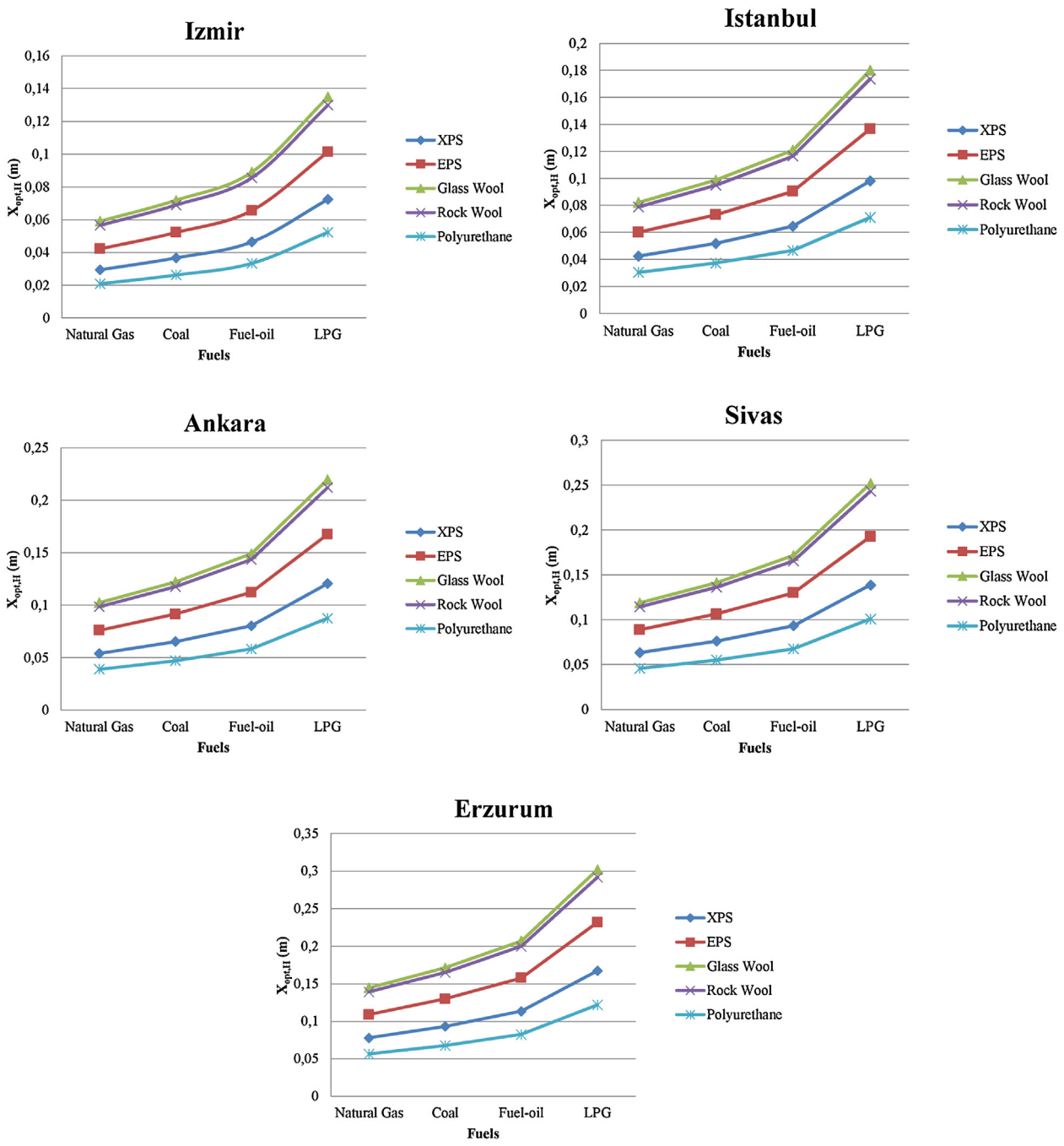


Fig. 7. Variations of optimum thickness of insulant to be chosen by fuel used in buildings only heated at 5 provinces chosen.

Table 11
Optimum insulation thickness at external walls of buildings both heated and cooled, net saving amount and payback period in the event EPS insulant is used for 5 provinces chosen.

City	Natural gas			Coal			Fuel-oil			LPG		
	$X_{opt,H,C}$ (m)	$A_{year,H,C}$ ($/m^2)	$pp_{H,C}$ (year)	$X_{opt,H,C}$ (m)	$A_{year,H,C}$ ($/m^2)	$pp_{H,C}$ (year)	$X_{opt,H,C}$ (m)	$A_{year,H,C}$ ($/m^2)	$pp_{H,C}$ (year)	$X_{opt,H,C}$ (m)	$A_{year,H,C}$ ($/m^2)	$pp_{H,C}$ (year)
Izmir	0.055	2.530	2.595	0.063	3.260	2.328	0.075	4.432	2.035	0.108	8.608	1.509
Istanbul	0.063	3.260	2.328	0.076	4.497	2.022	0.093	6.489	1.716	0.138	13.573	1.222
Ankara	0.078	4.717	1.980	0.093	6.526	1.712	0.114	9.431	1.447	0.169	19.726	1.025
Sivas	0.089	6.055	1.771	0.107	8.407	1.525	0.130	12.180	1.285	0.193	25.524	0.907
Erzurum	0.109	8.722	1.500	0.130	12.065	1.291	0.158	17.415	1.087	0.232	36.282	0.767

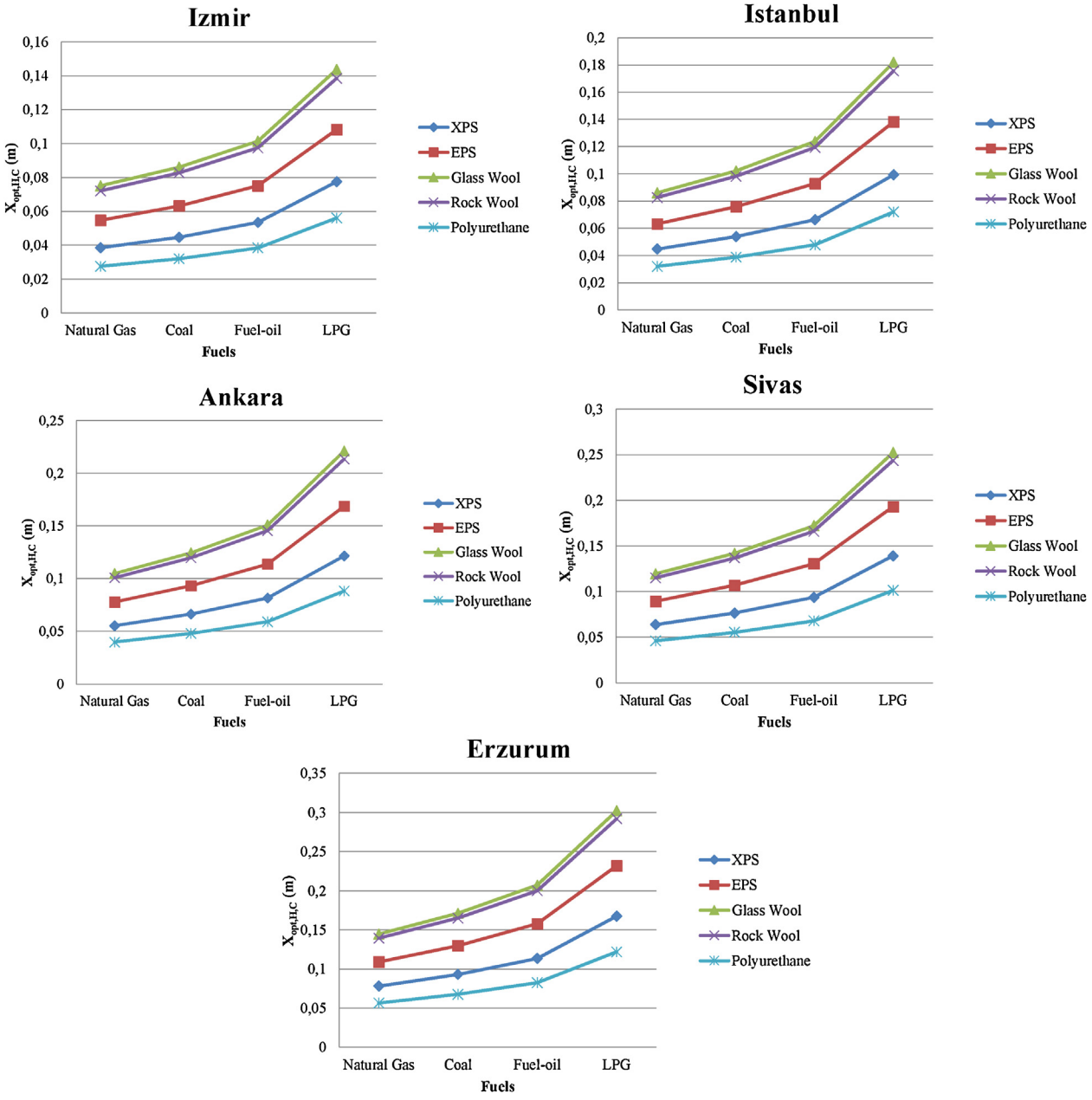


Fig. 8. Variations of optimum thickness of insulant to be chosen by fuel used in the event of both heating and cooling at 5 provinces chosen.

Table 10 shows annual energy gain and payback periods for 5 chosen provinces, in the event EPS insulant is used at optimum thickness in external walls of buildings heated only. The difference between Table 10 and Table 11 is annual energy gain and payback periods in consideration of optimum insulation thicknesses calculated by taking into account buildings both heated and cooled. When the two tables are reviewed, required insulation thickness for buildings heated and cooled is more than required insulation thickness for buildings heated only. In addition to this, energy gain at unit area increases and payback periods decrease. If this variation is examined by fuel, annual energy gain for Istanbul province is calculated as 8.83, 6.37, 4.41 and 2.12% for natural gas, coal, fuel-oil and LPG, respectively. As fuel price increases, percentile variation amount decreases. When variation in payback periods is examined, it is calculated as 3.58, 2.69, 1.93 and 0.97% by same province and same fuel ranking.

4. Conclusion

As energy sources of Turkey are limited and foreign-dependent, conservation and efficient use of energy, particularly in the housing sector which sees intensive energy consumption and high heat losses, gains more significance day by day.

In this study, required optimum insulation thicknesses for buildings heated only, cooled only and both heated and cooled were calculated. Calculations took into account five individual insulants and four individual fuel types. Calculations made were repeated for all provinces in Turkey. Conclusions obtained as a result of calculations made:

As heating degree-day values and cooling degree-day values increase, required optimum insulation thickness increases.

The insulant with the thinnest optimum insulation thickness for the same region and same fuel is polyurethane. XPS, EPS, rock wool and glass wool follow polyurethane respectively.

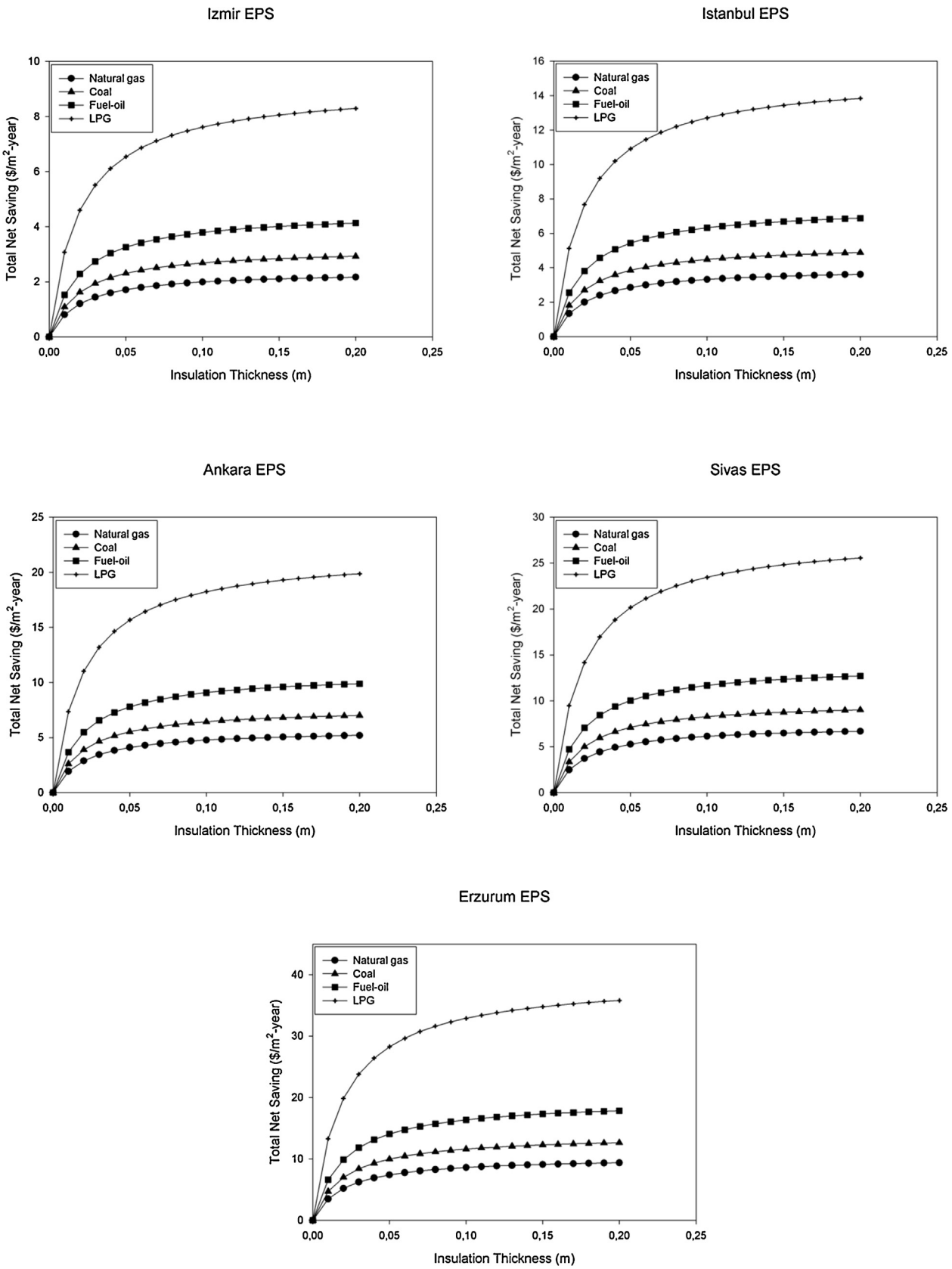


Fig. 9. Variation of EPS insulant thickness and total net saving ($A_{year,H}$) value by provinces.

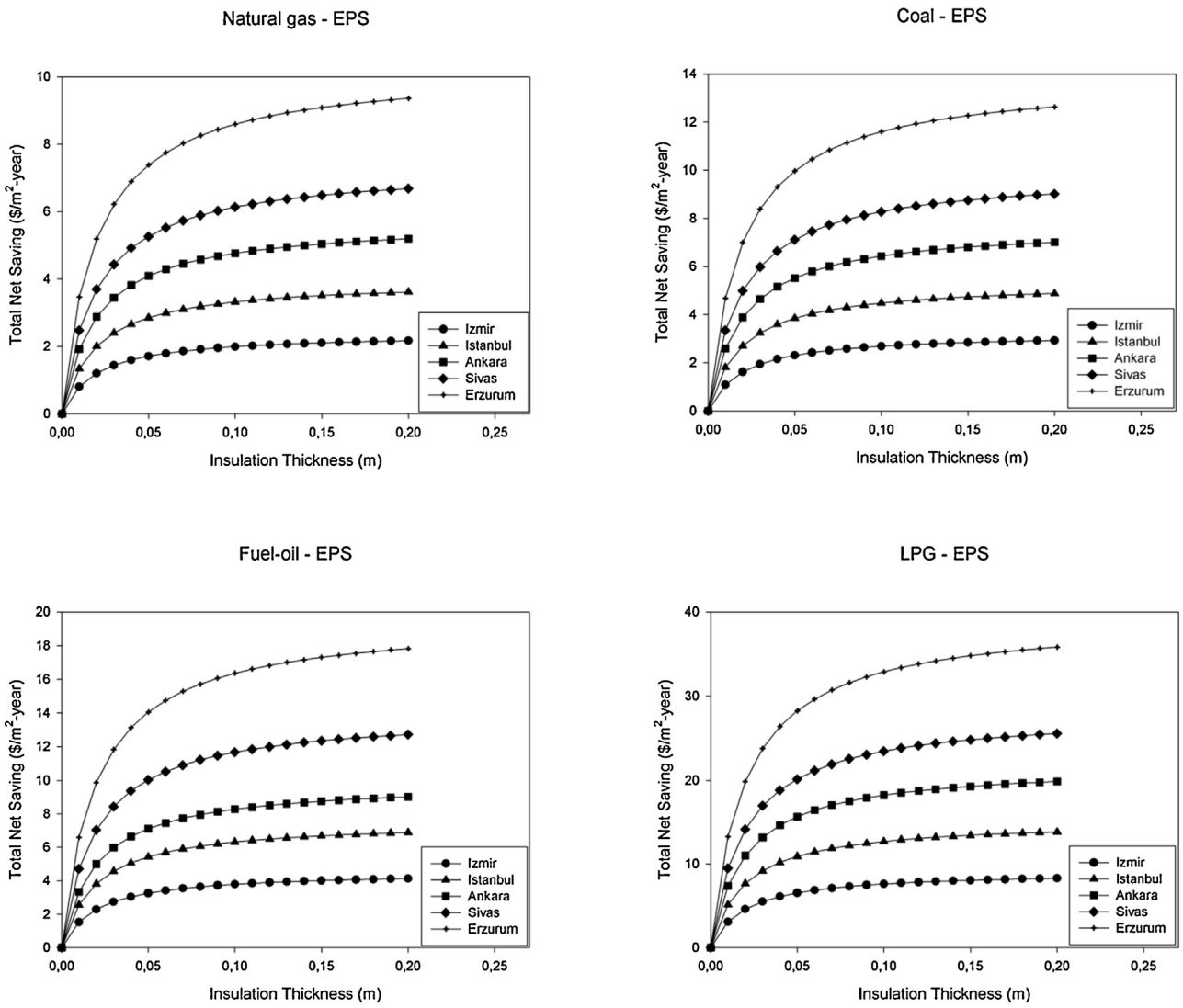


Fig. 10. Variation of EPS insulant thickness and total net saving ($A_{year,H}$) value by fuel.

Optimum insulation thickness needed to be used for buildings both heated and cooled is generally more in comparison with buildings heated only. This difference gets larger in warm provinces but may be the same in cold provinces.

Net saving amount is higher for buildings both heated and cooled in comparison with buildings heated only. Payback period is calculated as shorter for buildings both heated and cooled.

Net saving amount increases for natural gas, coal, fuel-oil and LPG respectively. Payback periods decrease with natural gas, coal, fuel-oil and LPG respectively. The ranking is due to current market prices for these fuels. Variation in fuel prices would also change the ranking.

Though variable according to the fuel used and the insulant selected, payback periods of insulations applied to buildings are usually very short. Investments in insulation shortly pay off and contribute to diminishing the dependency of this country in terms of fuel sources. In a time like today, when fuel and energy costs are drastically increasing, this situation becomes vitally important.

Considering the optimum insulation thickness calculated with respect to different fuel types, and environmental pollution caused by fuel wastes, natural gas has been found to be the optimum fuel among other types selected. Meanwhile, as optimum insulation thickness for natural gas is lower compared to other fuels, the initial investment cost will be lower as well.

References

[1] O. Acikgoz, A novel evaluation regarding the influence of surface emissivity on radiative and total heat transfer coefficients in radiant heating systems by means of theoretical and numerical methods, Energy Build. 102 (2015) 105–116.
[2] A. Aytaç, U.T. Aksoy, Enerji Tasarrufu İçin Dış Duvarlarda Optimum Yalıtım Kalınlığı ve Isıtma Maliyeti İlişkisi, J. Gazi Univ. Fac. Eng. Archit. 21 (2006) 753–758.
[3] R.G. Oğulata, Sectoral energy consumption in Turkey, Renew. Sustainable Energy Rev. 6 (2002) 471–480.
[4] K. Kaygusuz, A. Kaygusuz, Energy and sustainable development part II: enviromental impacts of energy use, Energy Sources 26 (2004) 1071–1082.
[5] A. Demirbaş, Energy balances, energy sources energy policy, future developments in Turkey, Energy Convers. Manage. 42 (2001) 1239–1258.
[6] TS 825, Binalarda Isı Yalıtım Kuralları, Turkish Standards Institute, 1998.
[7] N. Sisman, E. Kahya, N. Aras, H. Aras, Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regionse, Energy Policy 35 (2007) 5151–5155.
[8] H. Bulut, O. Büyükalaca, T. Yılmaz, Türkiye İçin Isıtma ve Soğutma Derece-Gün Bölgeleri, in: 16. Isı Bilimi ve Tekniği Kongresi, 30 May–2 June, Kayseri, 2007.
[9] M. Bayram, B. Yeşilata, Isıtma ve Soğutma Derece Gün Sayılarının Entegrasyonu, in: IX. Ulusal Tesisat Mühendisliği Kongresi ve Sergisi, May 6–9, Izmir, 2009.

[10] A. Dombaycı, M. Gölcü, Y. Pancar, Optimization of insulation thickness for external walls using different energy-sources, Appl. Energy 83 (2006) 921–928.
[11] K. Çomaklı, B. Yüksel, Optimum insulation thickness of external walls for energy saving, Appl. Therm. Eng. 23 (2003) 473–479.
[12] A. Bolattürk, Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, Appl. Therm. Eng. 26 (2006) 1301–1309.
[13] A. Bolattürk, Optimum insulation thickness for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey, Build. Environ. 43 (2008) 1055–1064.
[14] O. Kaynaklı, A study on residential heating energy requirement and optimum insulation thickness, Renew. Energy 33 (2008) 1164–1172.
[15] M. Özel, K. Pıhtılı, Determination of optimum insulation thickness by using heating and cooling degree-day values, Sigma Eng. Sci. J. 26 (2008) 191–197.
[16] A. Uçar, F. Balo, Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey, Appl. Energy 86 (2009) 730–736.
[17] A. Hasan, Optimizing insulation thickness for buildings using life cycle cost, Appl. Energy 63 (1999) 115–124.
[18] N.A. Kurekci, Ö. Agra, Ö. Emanet, Determination of optimum insulation thickness for different climatic zones of Turkey, in: ASME International Mechanical Engineering Congress and Exposition, November 13–19, Lake Buena Vista, FL, USA, 2009.
[19] N.A. Kurekci, A.T. Bardakcı, H. Cubuk, Ö. Emanet, Tırkiyenin Tım Ölleri Öüin Optimum Yalİtİm Kalİnlİçİnİn Belirlenmesi, Install. Tech. 131 (2012) 5–21.
[20] X. Liu, Y. Chen, H. Ge, P. Fazio, G. Chen, Determination of optimum insulation thickness of exterior wall with moisture transfer in hot summer and cold winter zone of China, Proc. Eng. 121 (2015) 1008–1015.
[21] M.K. Nematchoua, C.R.R. Raminosoa, R. Mamiharijaona, T. Rene, J.A. Orosa, W. Elvis, P. Meukam, Study of the economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate: case of Cameroon, Renew. Sustainable Energy Rev. 50 (2015) 1192–1202.
[22] M. Ozel, Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate, Energy Convers. Manage. 66 (2013) 106–114.
[23] D.B. Ozkan, C. Onan, Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey, Appl. Energy 88 (2011) 1331–1342.
[24] C. Onan, Determination of the thermal insulation for the model building approach and the global effects in Turkey, Adv. Mech. Eng. 2014 (2014) 1–12.
[25] I. Axaopolos, P. Axaopolos, G. Panayiotou, S. Kalogirou, J. Gelegenis, Optimal economic thickness of various insulation materials for different orientations of external walls considering the wind characteristics, Energy 90 (2015) 939–952.
[26] O. Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications, Renew. Sustainable Energy Rev. 16 (2012) 415–425.
[27] Prices of fuel, 2015. www.igdas.com.tr.