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Research Article

Optimisation on the thermal insulation layer thickness in buildings with environmental analysis: an updated comprehensive study for Turkey's all provinces

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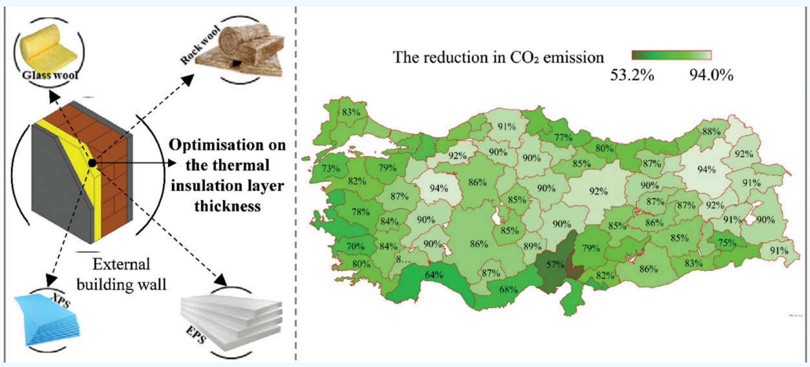
ABSTRACT

This study determines the optimum insulation layer thickness to be applied to external building walls considering the heating degree-day (HDD) method, then energy saving costs, payback periods, and carbon dioxide (CO_2) emissions are calculated accordingly. The optimisation analysis is performed for four different thermal insulation materials (glass wool, rock wool, extruded polystyrene, and expanded polystyrene). Natural gas is chosen as fuel for heating purposes, and horizontal perforated brick is preferred in the wall. One of the original features in this study is environmental analysis to determine the CO_2 emission for the insulated wall in Turkey provinces. Another feature is that it has the most up-to-date data about HDD values and fuel and insulation material costs. The worst and best insulation materials are obtained as rock wool and glass wool, respectively. The optimum insulation layer thickness for the best case is varied between 0.07 m and 0.23 m, depending on the HDD values of provinces. The annual total energy saving cost is in the range of 4.4–53.5 $/(m^{2}year), and the payback period is 0.11–0.38 years. Besides, the reduction in annual CO_2 emission is changed between 53.2% and 94% for the best case, compared to the uninsulated wall.



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INTRODUCTION

Energy demand and consumption escalate rapidly with increasing population all over the world. Countries that supply most of their energy through imports resort to more import policies to respond to energy requests. The increment of energy imports may cause energy bottlenecks in the future. From this point of view, technological developments to increase energy saving appear cheaper way than energy imports. The energy consumption of the building sector in Turkey, with 27%, is ahead of other sectors (transportation, industry, agriculture and forestry, commercial and public services), according to the statistical data in [1]. Most of the consumed energy in buildings is used in space-heating systems for Turkey [2]. Improving the building envelope by adding thermal insulation material has become an effective method to reduce heating and cooling demands [3]. A law accepted in Turkey aims to use energy effectively, reduce energy costs, and protect energy resources and the environment [4]. An energy identity certificate regarding thermal insulation material has been made compulsory with the energy performance regulation for buildings [5].

Diminishing the energy demands in the buildings can be procured by minimising heat losses [6]. The vast majority of heat is lost from the external building wall due to inadequate insulation thicknesses, thereby leading to energy waste [7]. Therefore, increasing the insulation layer thickness reduces heat losses from the wall significantly, thereby cutting back on expenses required for thermal comfort in buildings [8]. However, the insulation thickness must be neither too high nor too low to use energy virtually [9]. A building wall with low insulation thickness allows heat to pass from inside to outside or outside to inside, leading to an adverse impact on thermal comfort, energy savings, and air pollution [10]. A building wall with thick insulation material reduces the heat loss and subsequent heating load and fuel cost, but each increment in insulation thickness causes a gradual increase in investment costs for insulation [7, 10]. The optimum insulation layer thickness varies depending mainly on the degree-day values, the fuel types, and the insulation materials [11, 12].

Contemporary studies involving the optimisation analysis of the thermal insulation layer thickness have been primarily focused on the efficient use of energy in buildings [13, 14]. Besides determining the optimum thicknesses, some studies consider the cost [15, 16] and environmental [17–19] analyses. It is vital to choose a thermal insulation material with an appropriate layer thickness according to different climatic conditions to ensure maximum energy saving [20]. Although there are many similar studies for different countries, the literature review is limited to Turkey's findings. Turkey's climate zones are divided into four main climate types by an older Turkish Standard [21]. A significant number of studies are done with just one city regardless of the climatic region in Turkey. For example, in Malatya [10], Denizli [15,18,22], Erzurum [17], İstanbul [20], Bilecik [23], Bursa [24], İzmir and Ankara [25], Diyarbakır [26]. Moreover, some studies are carried out by selecting only one [27–36] or more [11–13, 37–39] cities from each climatic zone; furthermore, by merely opting for cold towns [9, 14] in Turkey. In most of them, different parameters (types of bricks, insulation materials, and fuels) are investigated by economic and environmental analysis to find the ideal configuration. Some of the notable works are detailed below.

Çomaklı and Yüksel[9] conducted the life-cycle cost analysis to determine the optimum insulation layer thickness for Erzurum, Kars, and Erzincan, the coldest provinces of Turkey. The authors used stropor as insulation material and coal as fuel in their review. They calculated that the optimum insulation layer thicknesses are 0.105 m, 0.107 m, and 0.085 m for Erzurum, Kars, and Erzincan, respectively. They also noted that energy-saving costs achieve up to 12.7 $\$/(m^2year)$, and the maximum payback period is 1.58 years. Moreover, the same authors [17] investigated the environmental effect of fuel oil on the external building wall containing stropor in Erzurum, Turkey. The authors specified that the reduction in carbon dioxide (CO_2) emission is about 27%.

Bolattürk[13] carried out the life-cycle cost analysis for sixteen different cities of Turkey (İskenderun, Adana, Antalya, Aydın, Manisa, Trabzon, İstanbul, Mardin, Uşak, Isparta, Eskişehir, Nevşehir, Erzincan, Hakkâri, Ağrı, and Ardahan), five different fuel types (coal, natural gas, fuel oil, liquefied petroleum gas (LPG), electricity), insulation material (polystyrene) to determine the optimum insulation layer thickness, energy saving costs and payback periods. The author indicated that the optimum insulation layer thicknesses range from 0.024 m to 0.172 m, the improvements in energy saving costs change between 22% and 79%, and the payback periods vary from 1.3 to 4.5 years, depending on parameters. The researcher suggested that the best suitable type of fuel is natural gas for all climatic conditions when examined for atmospheric contamination. In another study by Bolattürk [40], the optimisation analysis for polystyrene layer thickness is performed by considering both heating and cooling demands for seven different cities in Turkey (Adana, Antalya, Aydın, Hatay, İskenderun, İzmir, and Mersin). The author used the P1-P2 economic model to calculate the optimum insulation layer thickness. The author concluded that the heating degree-day has a more significant effect than the cooling degree-day on the determination of optimum insulation layer thicknesses for Turkey's climatic conditions.

Dombaycı et al. [15] conducted the life-cycle cost analysis of the optimisation of insulation layer thickness using two different insulation materials (expanded polystyrene and rock wool) and five different fuel types (coal, natural gas, fuel oil, LPG, and electricity). The authors stated that the best insulation material is expanded polystyrene, and the ideal fuel type is coal for Denizli, Turkey. They also reported that the optimum insulation layer thicknesses vary between 0.032 m and 0.259 m, the energy-saving costs range from 4.6 \$/(m^{2}year) to 102.9 \$/(m^{2}year), the payback periods change from 1.15 to 3.03 years. Also, Dombaycı[18] investigated the environmental impact of optimum insulation layer thickness for the best insulation material (expanded polystyrene) and fuel type (coal) and found that the reduction in CO_2 emission is 41.5%. Then, Dombaycı et al. [32] examined the optimum insulation layer thickness with economic and environmental analysis for Aydın, Samsun, Eskişehir, Ardahan, which are located in four different climate zones of Turkey. The authors selected expanded polystyrene and polyurethane as insulation materials, coal and natural gas as fuel types. They identified that the optimum insulation layer thickness is in the range of 0.025–0.137 m, the energy-saving cost is 11.8–96 \$/(m^{2}year), the reduction in CO_2 emission is 64.2-83.3%. A thermoeconomic analysis considering exergy is utilised to calculate the optimum insulation layer thickness for İzmir, Trabzon, Ankara, Kars in Turkey by Dombaycı et al. [41]. They reported that the exergy reduction varies from 27% to 56.6% for expanded polystyrene and from 22% to 51% for polyurethane.

Akyüz[26] calculated optimum insulation thickness, energy saving, cost-saving, payback period, and greenhouse gas emission for the city of Diyarbakir in Turkey. He employed natural gas, coal, and fuel oil as an energy sources, and utilised expanded polystyrene as insulation material. The optimum insulation thickness, payback period, and the annual prevented environmental impact for natural gas, coal and fuel oil was found to be 0.057 m, 0.066 m, and 0.089 m, 2.85, 3.57 years and 2.05 years and 17.45 kgCO_2/m^2, 51.28 kgCO_2/m^2 and 26.7 kgCO_2/m^2, respectively. Akyüz[35] determined the economic and environmental impact of thermal insulation for building walls in the cities of İzmir, İstanbul, Ankara, and Erzurum in Turkey. He employed expanded polystyrene, glass wool rock wool, and extruded polystyrene as insulation material and natural gas as an energy source. He found that payback periods for all scenarios have the lowest and highest value for RW and XPS, respectively. He concluded that thermal insulation is more effective in colder climates in terms of economic and annual avoided environmental impact.

Ustaoğlu et al. [38] conducted an experimental study to determine the thermal properties of lightweight concrete with different vermiculite content. They also do an analytical simulations to evaluate the energy consumption on a real building application for a variety of fuels and different climatic regions of Turkey. The proposed concrete can provide a significant reduction in energy consumption and reduce the carbon emission associated with the lower energy needs of buildings. They found that the payback period ranged from 1.4 years to 9 years, depending on the fuel.

Altun et al. [39] examined the effectiveness of insulation of an uninsulated building in two different processes according to TS 825: short-term (savings in annual heating energy need, additional insulation costs and additional greenhouse gas emission) and life cycle (life cycle cost and greenhouse gas emission). In addition, the payback periods of the additional investment in terms of costs and greenhouse gases were also analysed. Analysis has shown that insulations made according to the standard provide improvements up to 75% in annual heating energy need, 70% in life cycle cost, and 73% in life cycle greenhouse gas emission. The results reported that effective shell insulation greatly improved building energy performance and also significantly reduced building lifecycle costs and greenhouse gas emissions.

Şahin et al. [22] presented a comparative study, taking into account the different insulation materials and CO_2 emissions, in determining the most economical combination between the optimum insulation thicknesses in different fuel types for the city of Denizli in Turkey. They observed that the optimum insulation thickness, which makes the cost minimum, varies between 0.012 and 0.031 m for heating in the winter months and 0.009–0.022 m for cooling in the summer months. They concluded that while glass wool is suitable as insulation material with a difference of 22–24%, polyurethane with a difference of 10–34% would be more suitable in terms of low CO_2 emission.

Akan et al. [37] produced three different composite materials in different proportions from the mixtures of natural and waste materials and used them to determine the outer wall thickness of the buildings in twelve cities selected from four different climatic zones of Turkey. They determined that the annual energy requirement per unit surface area of the exterior walls of insulated buildings is 11.213–965.715 kJ/m^2. They also observed that insulation costs ranged from 22.841 \$/m^2 to 114.841 \$/m^2, and the payback period ranged from 2.5 to 6.5 years.The large-scale studies have been performed by Kürekçi et al. [11] and Kürekçi [12] for all provincial centres in Turkey. These studies estimated the optimum insulation layer thickness and carried out the economic analysis, but no effort is devoted to identifying environmental impacts. Furthermore, it is worth mentioning from the papers in [11, 12] that heating and cooling degree-day values are not up to date, even the insulation material and fuel costs.

The determination of optimum insulation layer thickness incorporated into the external building wall is still a live subject [42]. Many studies have indicated that the optimum thicknesses depend on different parameters such as heating and cooling degree-day values in cities, the types of bricks, insulation materials, and fuels [13]. It is also noted that the optimum parameters depend on the costs of insulation material and fuel, the rates of interest, and inflation [25]. Nevertheless, the research covering updated costs and rates is not available in the literature to calculate the optimum insulation layer thickness with economic and environmental analyses. To fill this void, this study used the most up-to-date data, which are heating degree-day values for all cities in Turkey, insulation material and fuel costs, interest, and inflation rates, and provided more realistic results. Besides, the reduction in CO_2 emission by optimum insulation layer thickness for Turkey's provinces is examined for the first time in this study. Commonly recommended brick (horizontal perforated brick) and fuel (natural gas) types are used in calculations. The aim is to apply the life-cycle cost analysis to minimise energy-saving cost and insulation cost, then the environmental analysis to reduce CO_2 emission. Four different insulation materials (glass wool, rock wool, extruded polystyrene, and expanded polystyrene) are viewed in terms of optimum layer thickness for all cities. Later, the energy saving costs, the payback periods, and the reduction in CO_2 emissions are determined considering the optimum values. This study is expected to assist the readers in constructing future buildings in Turkey's all provinces.

METHODOLOGY

An insulated external building wall is considered a composite structure consisting of internal plaster, brick, thermal insulation material, and external plaster. The wall without any thermal insulation material is called the uninsulated wall, while the wall with thermal insulation material is named the insulated wall. The uninsulated and insulated walls are schematically depicted in Figures 1a, 1b, respectively. Horizontal perforated brick is used in the external building walls because it is the most preferred brick type in Turkey [21, 43]. It stands out with less weight than other brick types; thus, it does not impose an extra burden on the building [44]. An essential property of horizontal perforated brick is that it provides indoor heat regulation with its high heat storage feature.

A comprehensive list of thermophysical properties of wall components and insulation types is shown in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook [45]. The thermophysical properties of the external building wall components are listed in Table 1. The thermal insulation materials mentioned in Table 1 are frequently applied in buildings in Turkey and do not harm the atmosphere and the ozone layer. The costs of thermal insulation materials, given in Table 1, are formed by averaging the annual costs, shown in Figure 2. Local currencies of all products included in this study are converted into dollars at the annual exchange rate [46].

Since the external building wall has more surface area, the heat loss amount is further than through windows, floors, and ceilings [12]. Thus, insulation application on the external wall has become a critical requirement to reduce the heat loss and fuel consumption of buildings [48]. Therefore, this study assumes that heat loss occurs only through the external wall. Heat loss per unit domain of the uninsulated or insulated wall is calculated as in Eq.(1) [48].

$$q = U\left(T_b - T_o\right) \tag{1}$$

The overall heat transfer coefficient of the uninsulated or insulated wall (U) is determined by Eq.(2) [49].

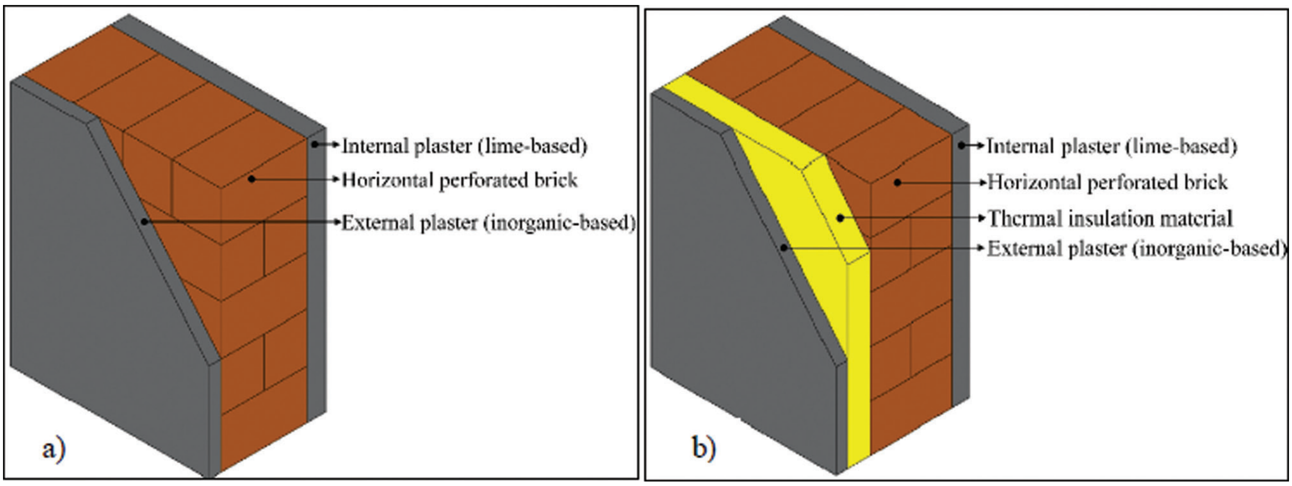

Figure 1. Schematic diagrams of a) the uninsulated wall and, b) the insulated wall.

Table 1. Thermophysical properties of the external building wall components [43,44,47]

Building wall components	x(m)	k(W/(m°C))	R((m2°C)/W)
Internal plaster (lime-based)	0.020	1.000	0.020
Horizontal perforated brick	0.135	0.331	0.408
External plaster (inorganic-based)	0.010	0.350	0.029
Thermal insulation materials	**Standard No.**	$k(W/(m°C))$	**Cy** ($\$/m^3$)
Glass wool (GW)	TS-EN-13162	0.040	25.193
Rock wool (RW)	TS-EN-13162	0.040	131.193
Extruded polystyrene (XPS)	TS-EN-13164	0.031	93.921
Expanded polystyrene (EPS)	TS-EN-13163	0.039	42.919

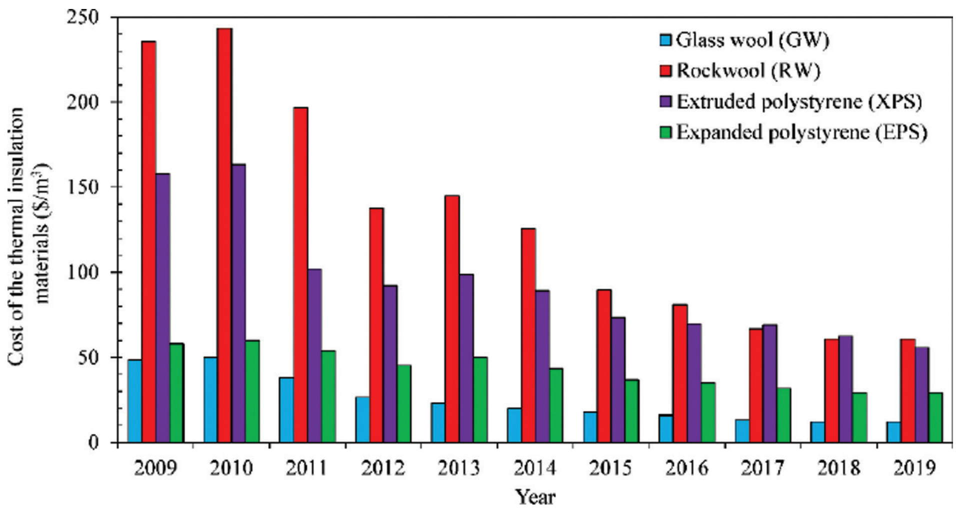

Figure 2. Cost of the thermal insulation materials with annual data from 2009 to 2019 [47].

$$U = \frac{1}{R_i + R_w + R_{ins} + R_o} = \frac{1}{R_{wt} + R_{ins}} = \frac{1}{R_{wt} + \dfrac{x_{ins}}{k}} \quad (2)$$

R_i (0.13 (m^{2}C)/W) and R_o (0.04 (m^{2}°C)/W) are the indoor and outdoor heat transfer resistances, respectively. R_w is the heat transfer resistance of the uninsulated wall, R_{wt} is the total heat transfer resistance of the uninsulated wall, and R_{ins} is the heat transfer resistance thermal insulation material [48]. Also, x_{ins} and k are the thermal insulation layer thickness and the thermal conductivity, respectively. When x_{ins} is zero meters, U corresponds to the overall heat transfer coefficient of the uninsulated wall. Depending on heating the degree-day method, the annual heat loss per unit domain of the uninsulated or insulated wall is calculated by Eq.(3) [48].

$$q_H = 86400\text{HDD}U \quad (3)$$

HDD refers to the heating degree-day value, which is used to estimate the heating energy demand [42]. It is calculated based on a base temperature (T_b), which can be defined as an equilibrium point between a heat resource and heat loss of the wall [49]. This study assumes that the base temperature is less than or equal to 15°C. It means no need for heating at the outdoor air temperature (T_o) above 15°C [49]. HDD can be expressed as in Eq.(4), and the "+" sign here shows that only positive results have been collected for a year.

$$HDD = \sum_{1}^{365} \left(T_b - T_o\right)^{+} \quad (4)$$

Turkey is divided into five climate zones based on a new revision in a Turkish Standard [43]. Figure 3 shows the map of all Turkey cities allocated to the five climate zones as heating degree-day values. These heating degree-day values are obtained by averaging the data of the last decade (2009–2019) in this study. In Figure 3, the first climate zone corresponds to the least HDD and the hottest cities, while the fifth climate zone is to the highest HDD and the coldest cities.

The comparison of HDDs of the last decade with the average values is shown in Figure 4(a-d) for all cities in

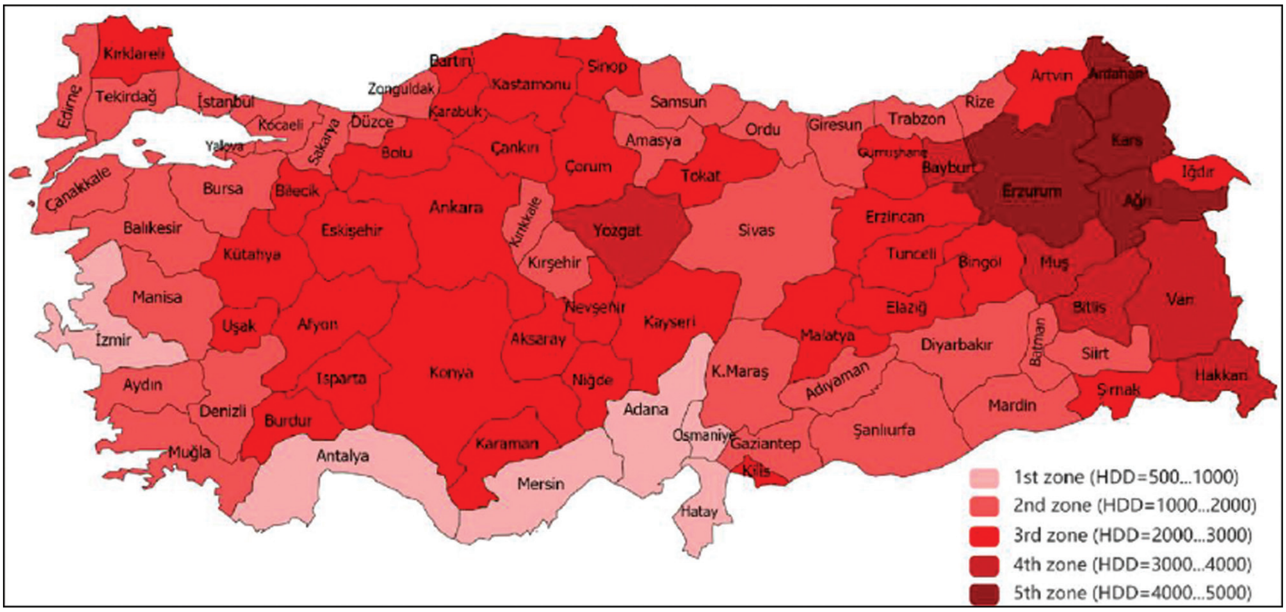

Figure 3. Schematic view of the cities of Turkey for each climate zone [49].

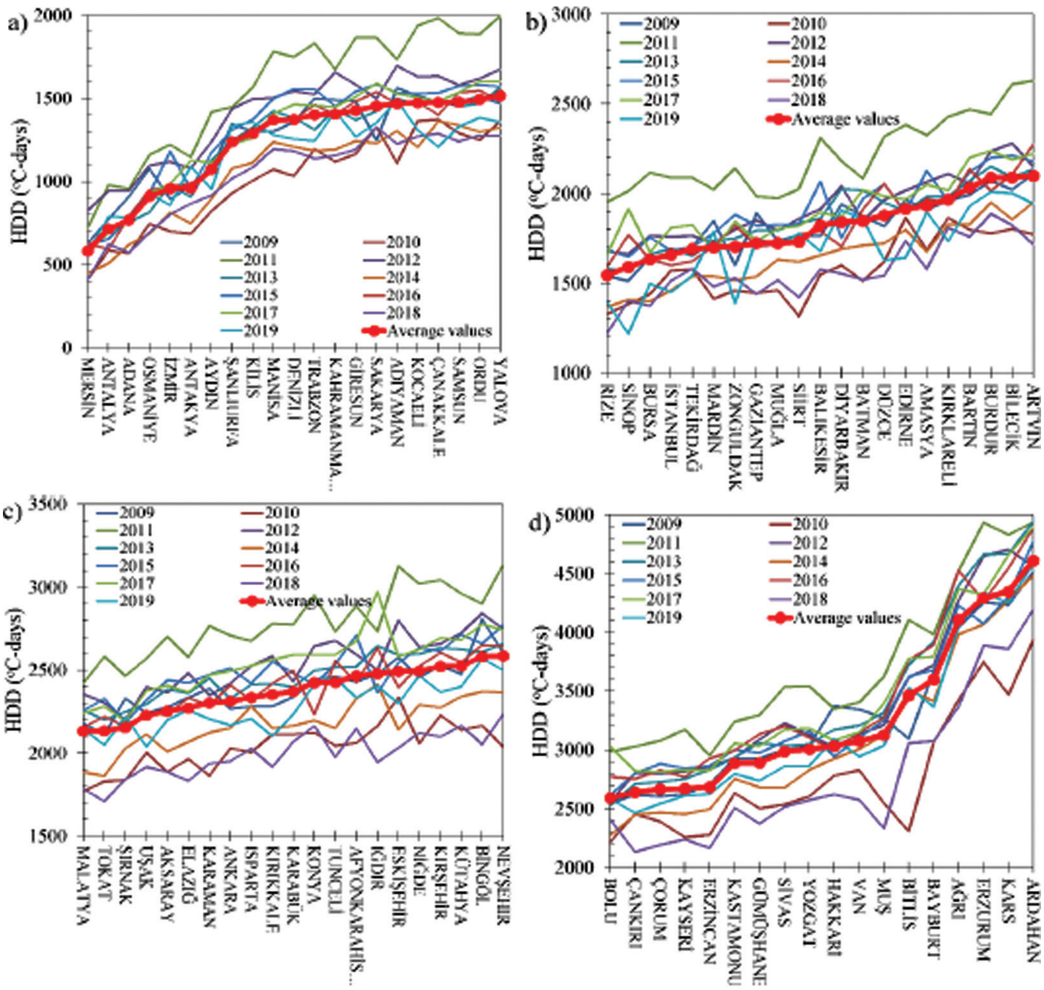

Figure 4. Comparison of HDDs of the last decade with the average values [49].

Turkey [49]. To provide a simple review, the HDDs are grouped at certain intervals and are shown in Figure 4(a–d) for all cities. The average values of the last decade are considered in all calculations of this study. In Figure 4(a–d), the highest annual heating demand reveals in Ardahan (4610°C-days). The minimum annual heating demand is identified to be in Mersin (583°C-days).

In the light of these HDD values, the annual heating energy demands of the uninsulated wall (E_H) and the insulated wall ($E_{H,ins}$) are calculated by Eq.(5) and Eq.(6), respectively [48].

$$E_H = \frac{86400\text{HDD}}{R_{wt}\eta} \tag{5}$$

$$E_{H,ins} = \frac{86400\text{HDD}}{\left(R_{wt} + R_{ins}\right)\eta} \tag{6}$$

Where $\eta = 0.90$ is the efficiency of the boiler [50]. Thermal insulation applications are necessary to reduce the heat loss from the building walls and increase energy saving. The most critical parameter for thermal insulation is the economic analysis to find the proper insulation layer thickness. Thus, the annual heating energy costis determined by Eq.(7) for the uninsulated wall (C_{AH}) and Eq.(8) for the insulated wall ($C_{A,H,ins}$) [48].

$$C_{A,H} = \frac{E_H C_{fuel}}{\text{LHV}} \tag{7}$$

$$C_{A,H,ins} = \frac{E_{H,ins} C_{fuel}}{\text{LHV}} \tag{8}$$

Where, LHV = 34518 kJ/m^3 is the lower heating value of natural gas [50]. Investigations in this paper are performed with natural gas as an energy source for the heating system in Figure 5. Because the natural gas combustion process works almost perfectly, very few waste products are released into the atmosphere as pollutants. Since it does not contain contaminating factors such as SO_2, ash particles, and unburned gases, natural gas is the least damaging fossil fuel to nature. Also, it is suggested that the best suitable type of fuel is natural gas for Turkey's climatic conditions by a study [13]. Therefore, it is demanded as the most suitable option in Turkey for domestic heating. C_{fuel} = 0.367 \$/m^3 is the cost of natural gas, and it is obtained by the average of the annual costs of natural gas, shown in Figure 6 [50].

In the present paper, the life-cycle cost method is used to determine the optimum insulation layer thickness, considering its economic dimensions. The life-cycle cost method is an extremely comprehensive method used to determine the annual total costs of the building walls in the pre-assessment periods [51]. This method covers the costs of thermal insulation materials and fuels, and it considers the effects of interest and inflation. The new methods are developed based on the life-cycle cost method. It appears as a method used frequently in the literature and in real life [16]. The annual total energy saving costs for heating demand are estimated based on the lifetime (N =10 years) and Present Worth Factor (PWF). PWF is calculated with the interest (i) and inflation (f) rates as follows:

$$r = \begin{cases} \dfrac{i-f}{1+f}, & \text{if } i > f \\ \\ \dfrac{f-i}{1+i}, & \text{if } f > i \end{cases} \tag{9}$$

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

where, r is the actual interest rate. Here, the interest (i = 12.4%), inflation (f = 9.7%), actual interest rates (r = 0.025) and Present Worth Factor (PWF = 8.759) are determined by taking the average of the last decade, as shown in Figure 7 [52].

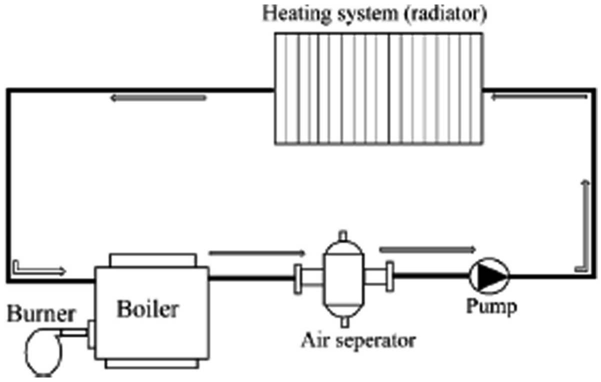

Figure 5. Schematic diagram of natural gas heating system.

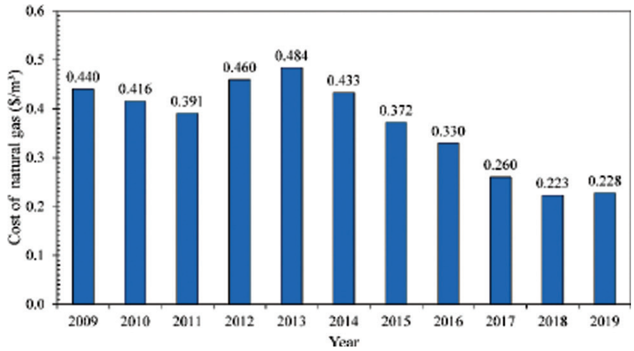

Figure 6. Cost of natural gas with annual data from 2009 to 2019 [50].

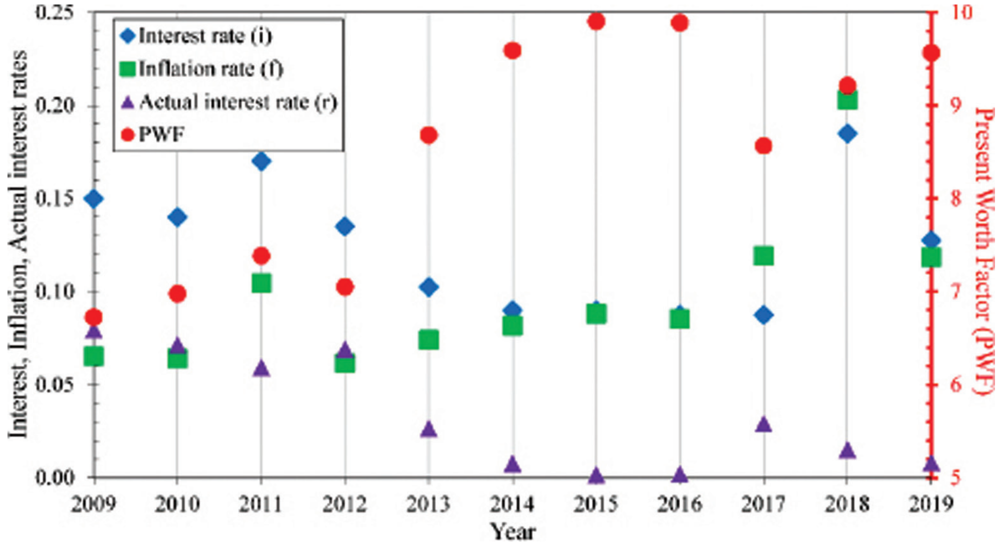

Figure 7. Interest, inflation, actual interest rates, and PWF with annual data from 2009 to 2019 [52].

Subsequently, regarding the life-cycle cost analysis, the annual total heating energy costs of the uninsulated wall (C_H) and the insulated wall ($C_{T,H}$) are calculated by Eq.(11) and Eq.(12), respectively [48].

$$C_H = C_{A,H}\text{PWF} \tag{11}$$

$$C_{T,H} = C_{A,H,ins}\text{PWF} + C_y x_{ins} \tag{12}$$

After that, the optimum insulation thickness ($x_{opt,H}$) reducing the annual total heating energy saving cost is calculated with Eq.(13) [48].

$$x_{opt,H} = \left(\frac{86400\text{HDD}C_{fuel}\text{PWF}k}{\text{LHV}C_y\eta}\right)^{1/2} - kR_{wt} \tag{13}$$

A_H represents the annual total heating energy saving cost, and it is calculated by Eq.(14). Payback period (PP_H) is calculated by Eq.(15) [48].

$$A_H = C_H - C_{T,H} \tag{14}$$

$$PP_H = \frac{C_y x_{ins}}{A_H} \tag{15}$$

Besides the life-cycle cost analysis, the reduction in CO_2 emission is calculated in this study to investigate the environmental effects caused by fuel consumption. The natural gas combustion reaction equation is as follows:

$$C_{1.05}H_4O_{0.034}N_{0.022} + 2.033(O_2 + 3.76N_2) \rightarrow 1.05CO_2 + 2H_2O + 7.65508N_2 \tag{16}$$

It is assumed to be complete combustion to facilitate the calculation process. For the heating demand per year, the annual total CO_2 emission is calculated by Eq. (17) for the uninsulated wall (M_{CO_2}) and Eq.(18) for the insulated wall ($M_{CO_2,ins}$) [48].

$$M_{CO_2} = \frac{86400\text{HDD}44g\rho_{fuel}}{R_{wt}M\ \eta\text{LHV}} \tag{17}$$

$$M_{CO_2,ins} = \frac{86400\text{HDD}44g\rho_{fuel}}{M\ \eta\text{LHV}}\left(\frac{k}{kR_{wt} + x_{ins}}\right) \tag{18}$$

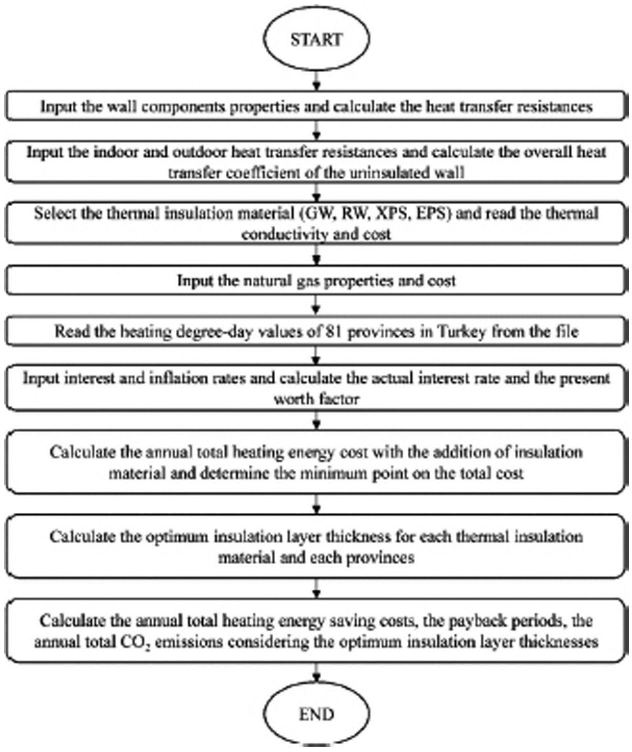

Figure 8. Flow chart for solution procedure.

The reduction in CO_2 emission is calculated by subtracting the annual total CO_2 emissions of the uninsulated wall and the insulated wall and then dividing the annual total CO_2 emission of the uninsulated wall. ρ_{fuel} is the density of natural gas equal to 0.79 kg/m³[53]. The molecular weight of natural gas (M) is calculated by Eq.(19).

$$M = 12g + y + 16z + 14t \tag{19}$$

The general chemical formula of natural gas is $C_gH_yO_zN_t$ and g, y, z, t, are given in Eq.(16). All calculations are analysed by considering the flow chart shown in Figure 8.

RESULTS AND DISCUSSION

The optimum insulation layer thicknesses, energy saving costs, payback periods, and CO_2 emissions are calculated with the average heating degree-day (HDD) values of Turkey's all provinces for the last ten years (from 2009 to 2019). The optimisation analysis is carried out for four different thermal insulation materials (glass wool-GW, rock wool-RW, extruded polystyrene-XPS, and expanded polystyrene-EPS). The thermal insulation material types are widely used in Turkey. Natural gas is used for heating purposes because it is the most used fuel type in Turkey. The life-cycle cost method preferred by researchers in the literature is used for economic analysis. Furthermore, a CO_2 emission analysis is done to investigate the environmental effects caused by fuel consumption. All cases in the research paper are calculated by using a custom-made code considering the flow chart in Figure 8. Coding and optimising in other auxiliary programs such as Excel take much longer than Fortran. Therefore, Fortran software has been preferred to save time in this study. The obtained far-reaching findings are detailed below.

The results produced for four different insulation materials (GW, RW, XPS, EPS) with HDD values of Ardahan, Turkey are shown in Figure 9(a-d) to demonstrate the

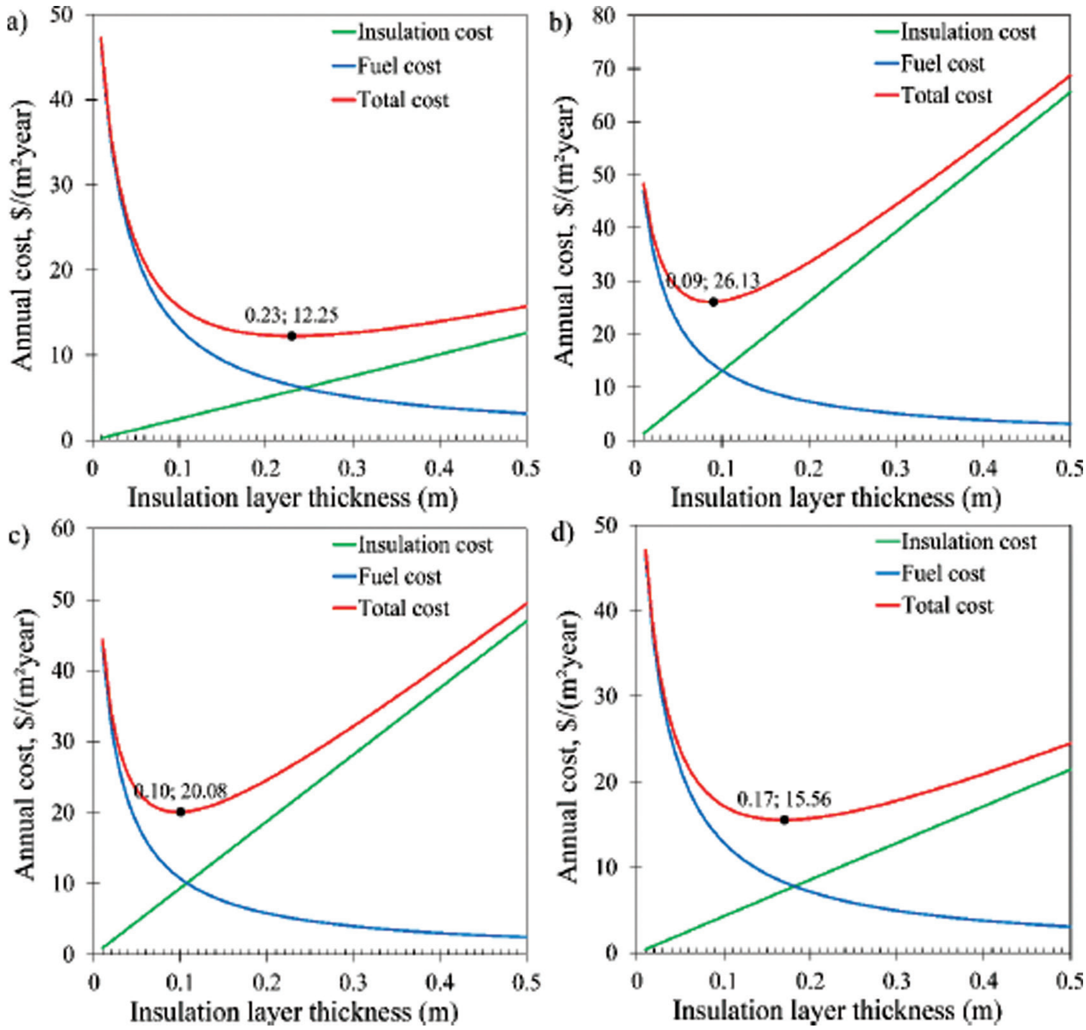

Figure 9. Effect of different insulation layer thicknesses on the annual costs of insulation, fuel, and total for Ardahan, Turkey a) GW, b) RW, c) XPS, d) EPS.

effect of different insulation layer thicknesses on the annual costs of insulation, fuel, and total. As can be seen in Figure 9(a-d), there are two significant parameters that affect the annual total heating energy cost of the insulated wall, which is defined as the sum of the insulation and fuel costs. The heat loss decreases as thermal insulation layer thickness increases in external walls. Therefore, the heating demand reduces, and the annual total energy saving cost decreases. However, if thermal insulation layer thickness is too much, the insulation cost continues to increase. In this case, the annual total heating energy cost of the insulated wall begins to rise after a certain point due to the extra insulation cost. The point where the annual total heating energy cost is minimum gives the optimum insulation layer thickness. These points where the annual total heating energy cost is minimum ($C_{T,H}$ =12.25, 26.13, 20.08, and 15.56 \$/(m^{2}year)), are expressed as the optimum insulation layer thickness ($x_{opt,H}$ = 0.23, 0.09, 0.10, and 0.17 m) for the situations in Figure 9(a-d), respectively.

The results produced with Ardahan's HDD values in the case of using natural gas as an energy source are shown in Figure 10(a-c) to indicate the effect of different insulation layer thicknesses (GW, RW, XPS, EPS) on the annual total heating energy saving cost (A_H), the payback period (PP_H), the annual total CO_2 emission ($M_{CO_2,ins}$). The annual total heating energy saving cost, calculated by the difference between the annual total heating energy costs of uninsulated (C_H) and insulated ($C_{T,H}$) walls, is given in Figure 10a for different insulation layer thicknesses. The annual total heating energy saving cost increases with increasing insulation layer thickness; it attains a peak and then begins to decrease. For example, the maximum annual total heating energy saving cost (A_H = 53.50 \$/(m^{2}year)) is obtained with 0.23 m insulation layer thickness for GW. As the insulation layer thickness increases, the payback period (PP_H) always tends to rise (Figure 10b). Nevertheless, the trend of payback period increments after reaching the optimum insulation thickness because of increasing insulation cost and decreasing the annual total heating energy saving cost. For Ardahan, the payback period varies between 0.11 years ($x_{opt,H}$ = 0.23 m for GW) and 0.30 years ($x_{opt,H}$ = 0.09 m for RW) considering the thermal insulation material type and the optimum insulation layer thickness. The annual total CO_2 emission ($M_{CO_2,ins}$), shown in Figure 10c, reduces with increasing

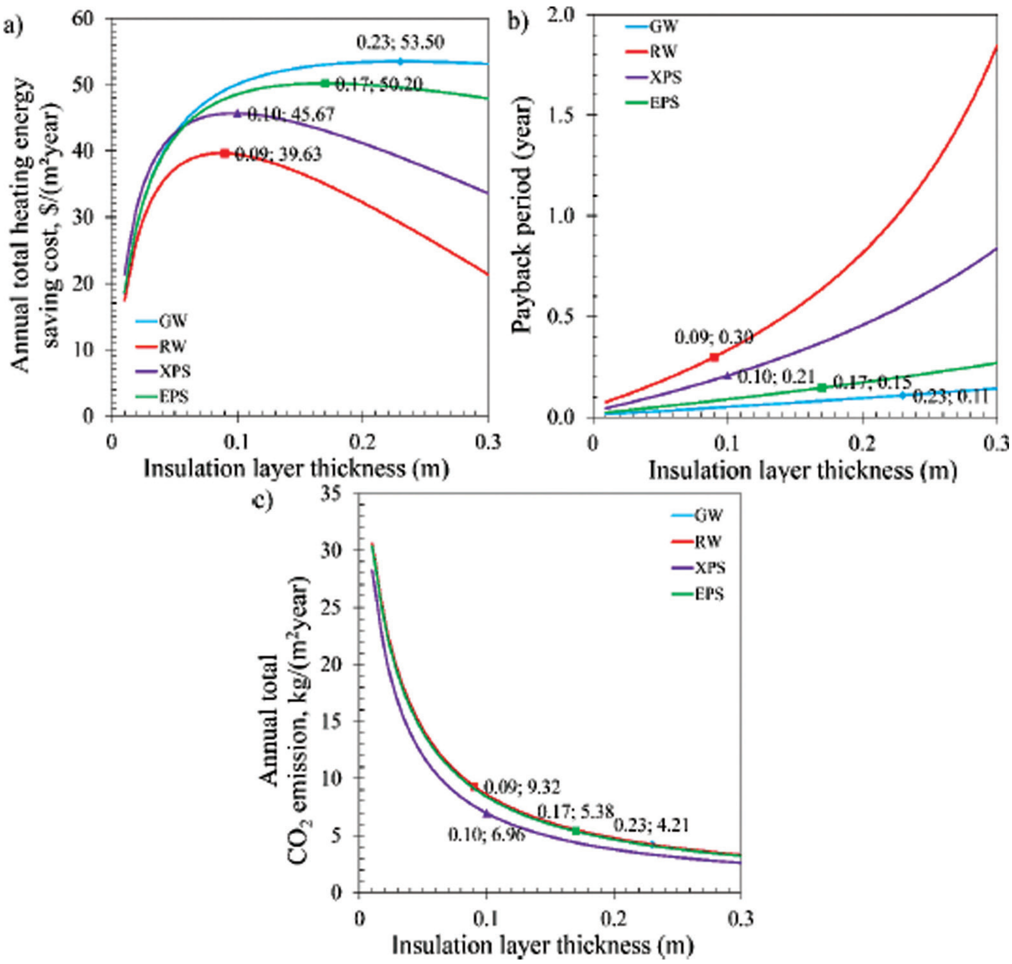

Figure 10. Effect of different insulation layer thicknesses on a) A_H, b) PP_H, c) $M_{CO_2,ins}$ for Ardahan, Turkey.

Table 2. Comparison of parameters between the present study and two studies in the literature

Parameters	The present study	Kürekçi[12]	Dombaycı et al. [32]
R_{wt}	0.627 (m²°C)/W	0.503 (m²°C)/W	¬
k	0.039 W/(m°C)	0.039 W/(m°C)	0.039 W/(m°C)
C_y	43 \$/m³	120 \$/m³	120 \$/m³
HDD	4610 °C-days	5137 °C-days	5845 °C-days
η	0.90	0.90	0.93
LHV	34518 kJ/m³	34485 kJ/m³	48570 kJ/kg
C_{fuel}	0.367 \$/m³	0.385 \$/m³	0.55 \$/kg
i	12.4%	8.25%	¬
f	9.7%	7.91%	¬
N	10 years	10 years	¬
PWF	8.759	9.83	9.83
Results			
$x_{opt,H}$	0.17 m	0.113 m	0.1193 m
A_H	50.2 \$/(m²year)	¬	73.35 \$/(m²year)
PP_H	0.15 years	¬	¬
$M_{CO2,ins}$	5.38 kg/(m²year)	¬	¬
Reduction in CO_2 emission	92.33%	¬	69%

insulation layer thickness. After the optimum value, the variation of the annual total CO_2 emission decreases despite the increment of insulation layer thickness, and its curve becomes an approximately horizontal form.

Table 2 shows the comparison of results between the present study and two studies in the literature. EPS as a thermal insulation material, Ardahan as a province, and natural gas as a fuel type are selected in Table 2. Since the input parameters differ in all studies, the results obtained by equations in the methodology section are different from each other.

The calculations are repeated with thermal insulation materials for all cities in Turkey to determine the optimum insulation layer thickness. Figure 11(a-d) illustrates the variation of optimum insulation layer thicknesses ($x_{opt,H}$) with increasing HDD values in Turkey's all provinces for different insulation materials such as GW, RW, XPS, and EPS. For example, Mersin province has the lowest HDD (583 °C-days) in Figure 11a, while Ardahan province has the highest HDD (4610 °C-days) in Figure 11d. The optimum insulation thickness is lower in hotter cities (HDD is low) and higher in colder cities (HDD is high). Briefly, it can be stated that the required thermal insulation layer thickness increases as the heating demand increases. The optimum insulation layer thickness is in the range of 0.07–0.23 m for glass wool, 0.01–0.09 m for rock wool, 0.02–0.1 m for extruded polystyrene, and 0.04–0.17 m for expanded polystyrene. While the optimum insulation layer thicknesses are the least level with RW, which is the most expensive thermal insulation material, they are the highest level with GW, which is the cheapest thermal insulation material. Besides, the optimum insulation layer thickness is a maximum of 0.23 m for GW. When the optimum insulation layer thicknesses that respond to heating demand are examined, they decrease in order of GW, EPS, XPS, and RW due to the increment of thermal insulation costs.

Figure 12(a-d) shows the variation of annual total heating energy saving costs (A_H) with increasing HDD values in Turkey's all provinces. These values are determined by the optimum insulation layer thickness for different insulation materials such as GW, RW, XPS, and EPS. The annual total heating energy saving costs of using RW, XPS, EPS, and GW are ranged from 1.15, 2.35, 3.46, and 4.36 \$/(m²year) (in Mersin) to 39.64, 45.68, 50.20, and 53.50 \$/(m²year) (in Ardahan), respectively. Preferring wall structure with RW is disadvantageous in terms of energy-saving costs because of the thin optimum insulation layer thicknesses and the high insulation material prices. The annual total heating energy saving cost varies between 1.15 \$/(m²year) and 39.64 \$/(m²year) for the worst case. The most advantageous situation is GW with the thick optimum insulation layer thicknesses and the low insulation material prices. The annual total heating energy saving cost varies between 4.36 \$/(m²year) and 53.5 \$/(m²year) for the best case.

The variations of payback periods (PP_H) with increasing HDD values in Turkey's cities are plotted in Figure 13(a-d). The payback periods are determined by the optimum insulation layer thickness for different insulation materials (GW, RW, XPS, and EPS). The payback periods are inversely proportional to the annual total heating energy

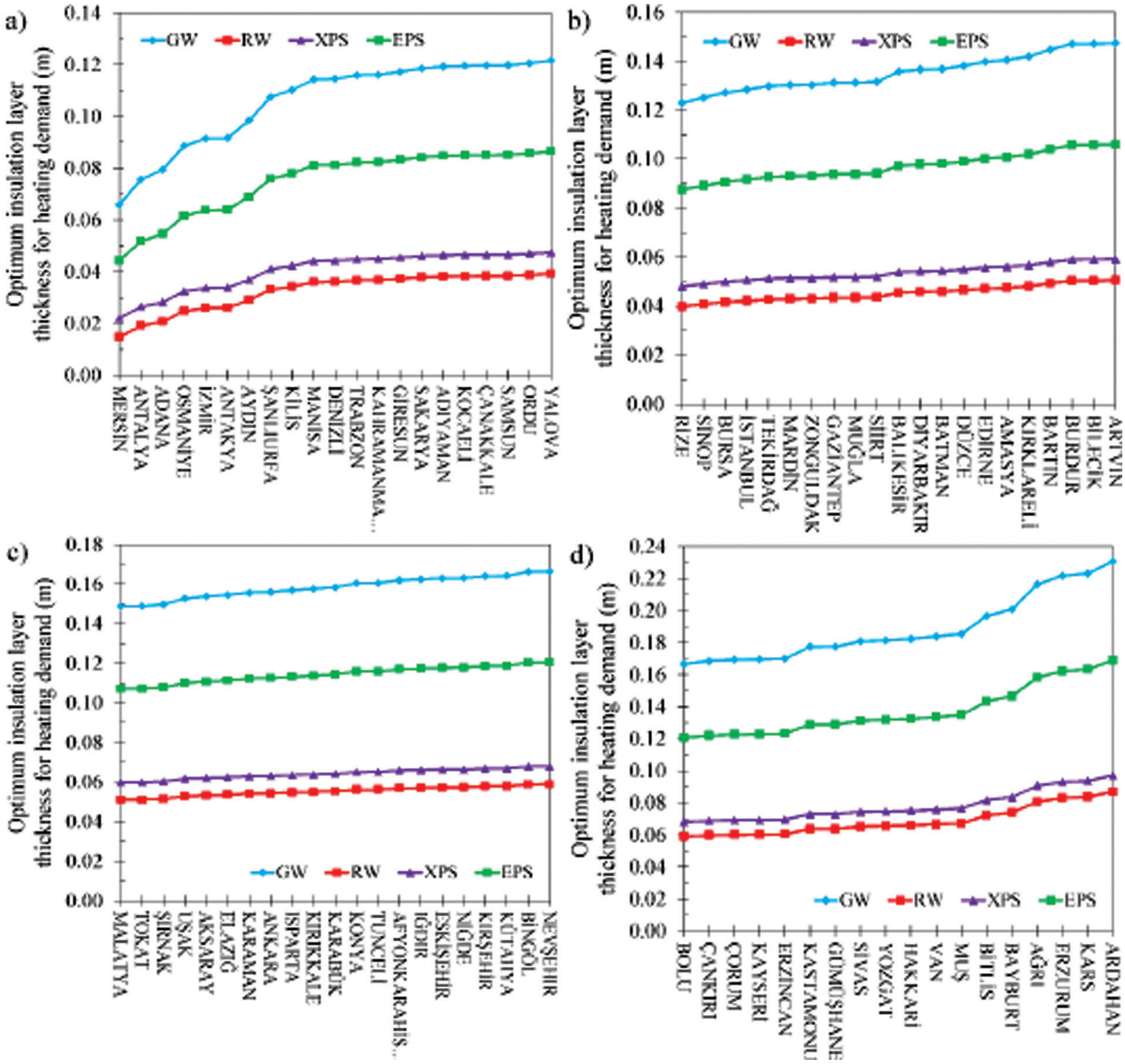

Figure 11. The variation of optimum insulation layer thicknesses ($x_{opt,H}$) with increasing HDDs in Turkey's all provinces.

saving costs. In this case, the payback periods decrease with increasing the annual total heating energy saving costs. As can be seen from Figure 13(a-d), the payback period does not regularly decrease and fluctuates, in contrast to the continuous increase in cost. Because there is no proportionality between the insulation cost and the annual total heating energy saving costs. The highest payback period (1.69 years) is realised with the use of RW in Eskişehir, while the lowest payback period (0.11 years) is with the use of GW in Kilis. The most advantageous thermal insulation material is GW, and its payback period ranges from 0.11 to 0.38 years for all cities, depending on the optimum insulation layer thicknesses.

The variation of the annual total CO_2 emission is calculated by the optimum insulation layer thicknesses for building heated by natural gas. Figure 14(a-d) indicates the variation of the annual total CO_2 emission ($M_{CO_2,ins}$) with increasing HDD values in Turkey's cities. The obtained results are presented in Figure 14(a-d) for different thermal insulation materials (GW, RW, XPS, and EPS). An observation like the annual total heating energy saving costs can be accomplished to the annual total CO_2 emission, so CO_2 emissions increase with rising optimum insulation layer thicknesses. The fluctuations in the annual total CO_2 emission change similarly to the payback period curves due to the lack of a linear ratio between HDD values and optimum insulation layer thickness. By using RW, the lowest CO_2 emission (3.40 kg/(m^{2}year)) takes place in Eskişehir, while the highest CO_2 emission (9.57 kg/(m^{2}year)) is in Kilis. The minimum CO_2 emissions are 1.92 kg/(m^{2}year) (EPS) and

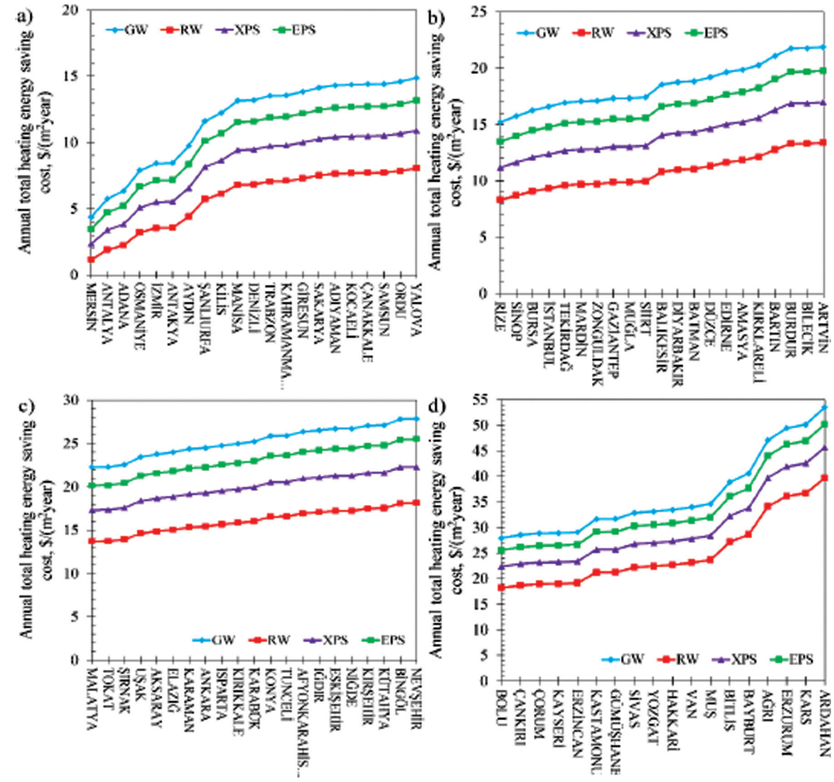

Figure 12. The variation of the annual total heating energy saving costs (A_H) with increasing HDDs in Turkey's all provinces.

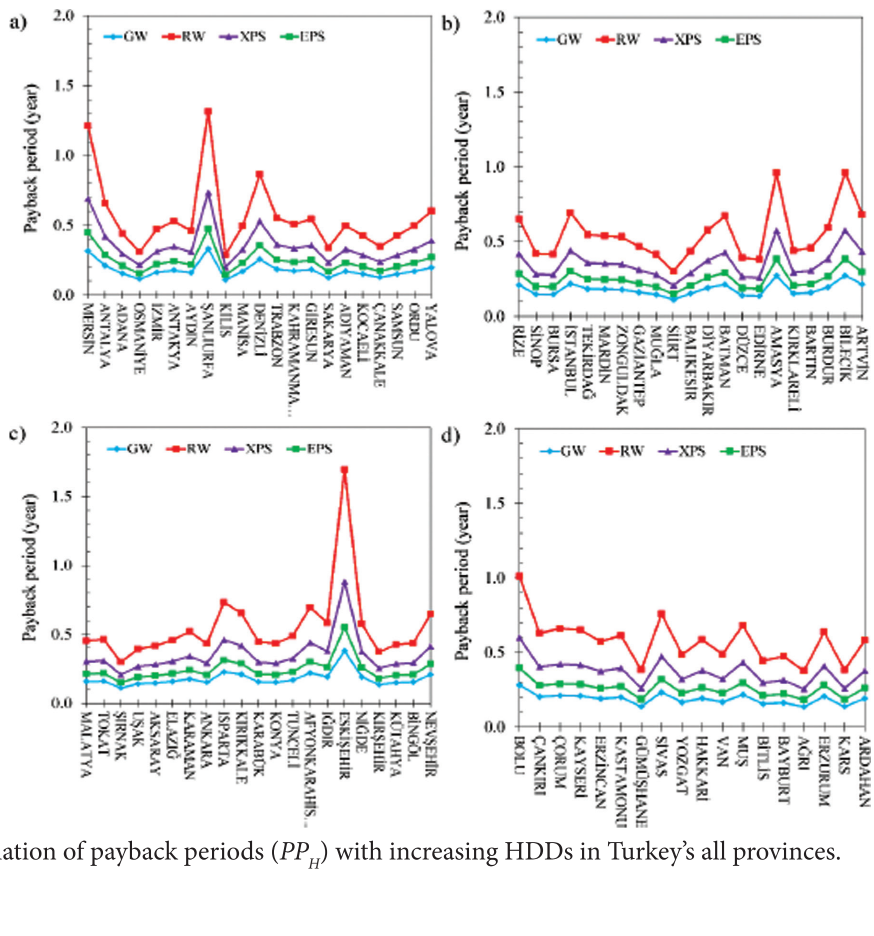

Figure 13. The variation of payback periods (PP_H) with increasing HDDs in Turkey's all provinces.

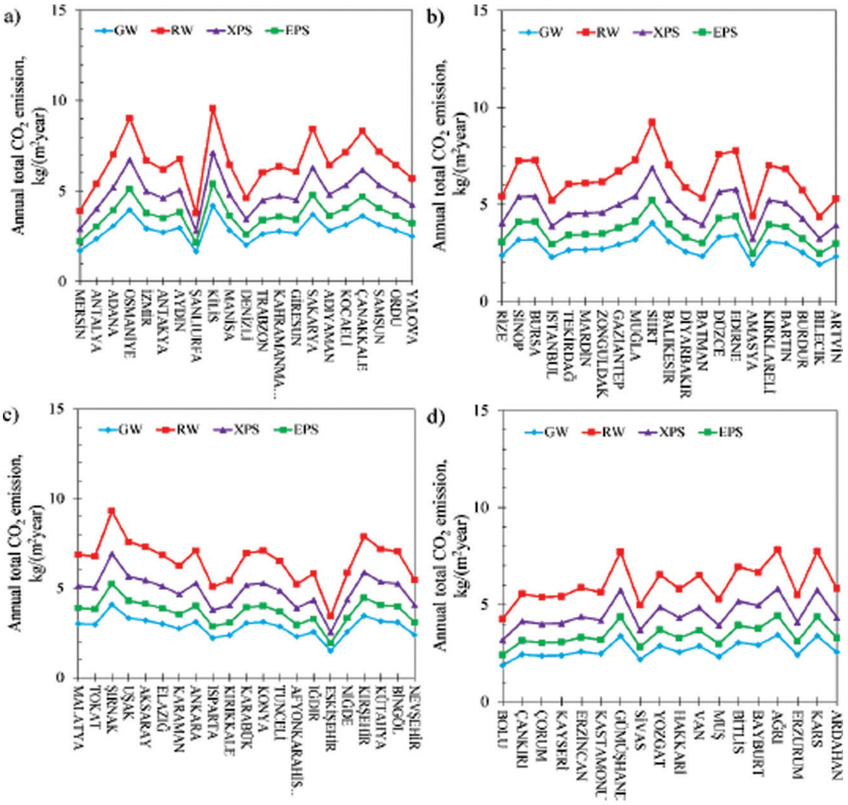

Figure 14. The variation of the annual total CO_2 emission ($M_{CO_2,ins}$) with increasing HDDs in Turkey's all provinces.

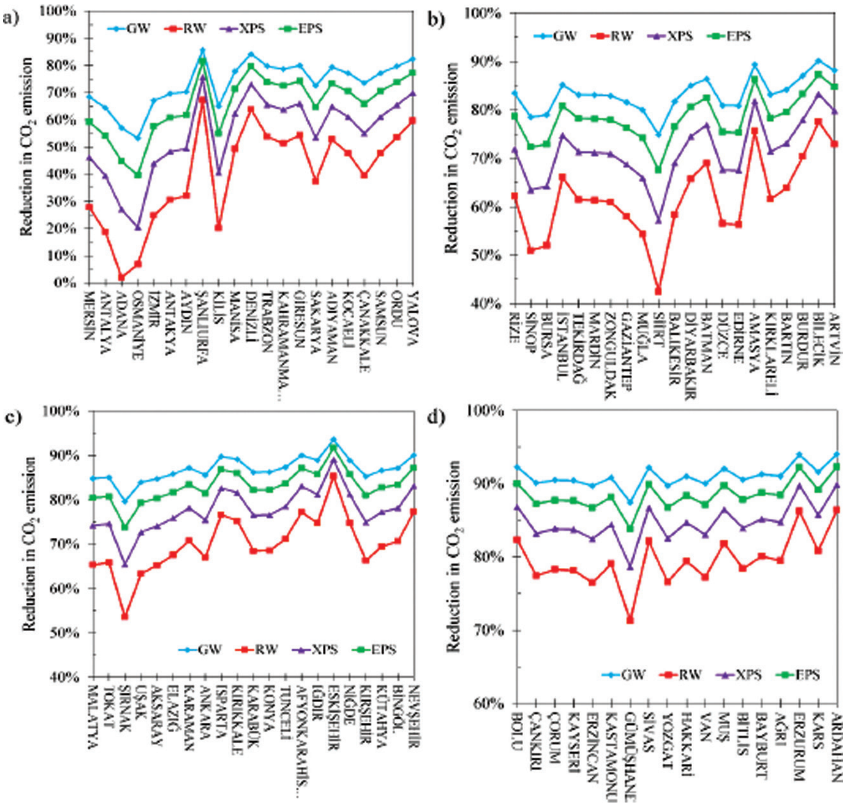

Figure 15. The variation of the reduction in CO_2 emission with increasing HDDs in Turkey's all provinces.

2.54 kg/(m^{2}year) (XPS) in Eskişehir, while the maximum CO_2 emissions are 5.41 kg/(m^{2}year) (EPS) and 7.13 kg/(m^{2}year) (XPS) in Kilis. The annual total CO_2 emission varies from 1.49 kg/(m^{2}year) (in Eskişehir) to 4.19 kg/(m^{2}year) (in Kilis) for the best wall configuration with GW.

The study's primary goal is to identify the annual total CO_2 emission for an insulated wall compared to the uninsulated wall depending on the fuel type used in buildings for Turkey's all provinces. Adhering to this goal, the variation of the reduction in CO_2 emission is calculated by the optimum insulation layer thicknesses. Figure 15(a-d) shows the reduction in CO_2 emission with increasing HDD values in Turkey's cities. The reduction in CO_2 emission increases in the order of RW, XPS, EPS, and GW for insulation materials. Compared to the uninsulated wall, the reduction in CO_2 emission varies from 1.97% (in Adana), 20.43%, 36.67% and 53.19% (in Osmaniye) to 86.41%, 89.88%, 92.33% and 94.05% (in Ardahan) for RW, XPS, EPS and GW, respectively.

CONCLUSIONS

The present study examines the effect of thermal insulation material types (glass wool, rock wool, extruded polystyrene, and expanded polystyrene) and their optimum layer thicknesses on energy-saving costs and payback periods in heated buildings with natural gas. Specifically, this study aims to determine the reduction in carbon dioxide (CO_2) emission of the insulated wall compared to the uninsulated wall in Turkey's provinces. To these aims, the life-cycle cost analysis is done by using the most actual data, such as heating degree-day (HDD) values, insulation material, and fuel costs, interest, and inflation rates. The attained noticeable results in this study are presented, which is as follows:

- As HDD values changes between the lowest (583°C-days in Mersin) and the highest (4610°C-days in Ardahan), the optimum insulation layer thickness increases in the range of 0.07–0.23 m for glass wool, 0.01–0.09 m for rock wool, 0.02–0.1 m for extruded polystyrene, and 0.04–0.17 m for expanded polystyrene.
- The best and worst case is the building wall, which contains glass wool, the cheapest thermal insulation material, and rock wool, the expensive material.
- Regarding optimum insulation layer thicknesses of glass wool, the annual total energy saving cost changes between 4.36 \$/(m^{2}year) in Mersin and 53.5 \$/(m^{2}year) in Ardahan.
- The payback period increases with the increase in the insulation material thickness and cost; on the contrary, it decreases with the increase in the annual energy saving cost. When the optimum insulation layer thicknesses of glass wool are 0.16 m in Eskişehir and 0.11 m in Kilis, the payback periods are maximum 0.38 and minimum 0.11 years, respectively.
- The reduction in CO_2 emission varies from 1.97% (in Adana), 20.43%, 36.67% and 53.19% (in Osmaniye) to 86.41%, 89.88%, 92.33% and 94.05% (in Ardahan) for rock wool, extruded polystyrene, expanded polystyrene and glass wool, respectively.

Consequently, this study will be a resource to serve the architects and engineers during the construction of future buildings in Turkey's provinces. The number of parameters can be increased with different fuel types, insulation materials, and wall component types to evaluate the environmental effects in future works. Moreover, the optimum insulation layer thicknesses can be determined by the thermoeconomic analysis.

NOMENCLATURE

A_H	Annual total heating energy saving cost, \$/(m^{2}year)
$C_{A,H}$	Annual heating energy cost for the uninsulated wall, \$/(m^{2}year)
$C_{A,H,ins}$	Annual heating energy cost for the insulated wall, \$/(m^{2}year)
C_{fuel}	Cost of the fuel, \$/m^3
C_H	Annual total heating energy cost of the uninsulated wall, \$/(m^{2}year)
$C_{T,H}$	Annual total heating energy cost of the insulated wall, \$/(m^{2}year)
C_y	Cost of the thermal insulation material, \$/m^3
E_H	Annual heating energy demand of the uninsulated wall, J/(m^{2}year)
$E_{H,ins}$	Annual heating energy demand of the insulated wall, J/(m^{2}year)
f	Inflation rate, %
HDD	Heating degree-day value, °C-days
i	Interest rate, %
k	Thermal conductivity, W/(m°C)
LHV	Lower heating value of natural gas, kJ/m^3
M	Molecular weight of natural gas, kg/mol
M_{CO_2}	Annual total CO_2 emission for the uninsulated wall, kg/(m^{2}year)
$M_{CO_2,ins}$	Annual total CO_2 emission for the insulated wall, kg/(m^{2}year)
N	Lifetime, year
PP_H	Payback period for heating demand, year
PWF	Present Worth Factor
r	Actual interest rate
R	Heat transfer resistance, (m^2°C)/W
R_i	Indoor heat transfer resistance, (m^2°C)/W
R_{ins}	Heat transfer resistance of thermal insulation material, (m^2°C)/W

R_o	Outdoor heat transfer resistance, (m^2°C)/W
R_w	Heat transfer resistance of the uninsulated wall, (m^2°C)/W
R_{wt}	Total heat transfer resistance of the uninsulated wall, (m^2°C)/W
T_b	Base temperature, °C
T_o	Outdoor air temperature, °C
U	Overall heat transfer coefficient of the uninsulated or insulated wall, W/(m^2°C)
q	Heat loss per unit domain of the uninsulated or insulated wall, W/m^2
q_H	Annual heat loss per unit domain of the uninsulated or insulated wall, J/(m^{2}year)
x	Layer thickness of each wall component, m
x_{ins}	Thermal insulation layer thickness, m
$x_{opt,H}$	Optimum insulation layer thickness for heating demand, m
η	Efficiency of the boiler
ρ_{fuel}	Density of natural gas, kg/m^3

AUTHORSHIP CONTRIBUTIONS

Cenker Aktemur: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Writing - review & editing, Formal analysis, Supervision. Feyza Bilgin: Conceptualization, Methodology, Software, Investigation, Writing - review & editing, Visualization, Formal analysis. Sezer Tunçkol: Writing - review & editing.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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