Journal of Cleaner Production 435 (2024) 140376

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An integrated assessment of the financial and environmental impacts of exterior building insulation application

A.S. Canbolat

Hybrid and Electric Vehicle Technology Program, Vocational School of Gemlik Asim Kocabiyik, Bursa Uludag University, Bursa, Turkey

ARTICLE INFO

Handling Editor: Jing Meng

Keywords:
CO_2 emissions
Life-cycle cost analysis
Thermal insulation
Solar radiation
Multi-objective optimization

ABSTRACT

In the literature, optimum thermal insulation thickness on building's exterior was examined by many researchers. Optimum insulation thickness was generally studied with the aim of minimizing the total cost, and suitable values were determined within this scope. In this study, it has also considered the amount of CO_2 released into the atmosphere due to the fuels used in building heating and cooling processes, as well as insulation materials, in addition to the total cost. This study has been focused on optimization of the determination of the ideal insulation thickness of buildings by simultaneously minimizing the total cost and CO_2 emission, using the knee point approach. In this context, a multi-objective optimization study has been conducted for thermal insulation applied to buildings located in different climatic zones considering the solar radiation. A comprehensive analysis has been carried out to determine the impact of the heating source type (natural gas, electricity, fuel oil), insulation material (expanded polystyrene, extruded polystyrene, mineral wool, polyurethane foam), climatic zone (I, II, III, IV) and the purpose of the building's use (summer house, winter house or all-season house) on the optimum insulation thickness. The degree-day approach has been used to calculate annual energy consumption, and accordingly the life-cycle cost (LCC) method has been used in economic analysis. The optimum insulation thicknesses have been calculated with two separate objectives: one to minimize only the total cost and the other to minimize only the CO_2 emissions. It has been found that when the primary goal of insulation application is to minimize CO_2 emissions, the calculated optimum insulation thicknesses are consistently higher compared to situations where the main goal is minimizing total cost. Furthermore, for various climatic zones and different purpose of the building's use, an ideal insulation thicknesses that simultaneously minimizes both the cost and CO_2 emissions have been identified. In this research, the equations providing environmentally optimum insulation thicknesses to minimize CO_2 emissions have been derived and presented to researchers. Finally, the conclusion is drawn that the knee point approach can be applied in insulation scenarios where two objective functions need simultaneous optimization.

1. Introduction

Due to the global increase in population, rapid technological advancements, and improved living standards, there has been a corresponding rise in energy consumption and greenhouse gas emissions. In addition to the increasing energy consumption, the rising energy unit prices caused by rapid economic recovery following the epidemic, also cause a great challenge around the world ("International Energy Agency," 2022). As a result of all these developments, the issues of energy saving and, accordingly, reducing the carbon footprint have gained great importance. Approximately 40% of the total energy consumption and 35% of the greenhouse gas emission take place in residential and service buildings (Axaopoulos et al., 2015; Robert and Kummert, 2012). In this context, installing insulation is the most practical and effortless method to conserve heat energy in buildings, as most of the heat transfer takes place through the building exterior. The application of insulation not only helps save energy, but also plays an important role in reducing the overall carbon footprint by reducing the energy consumption required for heating and cooling. In the early studies in the literature, the focus was solely on determining insulation thickness by considering the total cost as the objective function. However, in recent years, with sustainability, carbon footprint, and similar topics gaining prominence, the environmental effects of insulation applications have also started to be considered in studies. In a study by Kurekci (2016), an analysis was conducted to determine the ideal insulation thicknesses for Türkiye's 81 cities. Analyzes were carried out for different fuels which were fuel oil,

E-mail address: ascanbolat@uludag.edu.tr.

https://doi.org/10.1016/j.jclepro.2023.140376
Received 23 September 2023; Received in revised form 6 December 2023; Accepted 23 December 2023
Available online 30 December 2023

natural gas, coal, and LPG. Moreover, this optimization study examined various insulation materials, including rock wool, extruded polystyrene, polyurethane, glass wool, and expanded polystyrene. Akan (2021) also conducted a study on optimal thermal insulation thickness for all cities in Türkiye by using whole-life cost analysis. Extruded polystyrene, polyurethane foam, rock wool, and expanded polystyrene were chosen for the insulation material due to their frequent use. In order to heat the building natural gas was selected, while electricity was selected for the cooling process. In the study, a regression model was created using MATLAB in order to quickly determine the optimum insulation thickness, and it was observed that close values were obtained compared to theoretical results. In the study handled by Altun (2022), to determine most proper facade parameters, including window types and insulation thickness, it was conducted a dynamic modeling analysis of the thermal and financial aspects of an area. The outcomes of the investigation highlighted the significance of design criteria on energy efficiency and economy, including glazing type, window area, orientation, and insulation thickness. Canbolat et al. (2019) conducted an in-depth statistical examination to identify the ideal insulation thickness considering various parameters such as present worth factor, insulation cost, fuel cost, electricity cost, heating system's efficiency, coefficient of cooling system performance, and heating-cooling degree day, using the Taguchi and ANOVA methods. The most influential parameters on establishing the ideal insulation thickness were revealed to be heating degree-days, insulation cost, and the present worth factor. A statistical study using a similar approach on optimum thermal insulation thickness was also performed by Arslanoglu (Arslanoglu and Yigit, 2017). In the study, a statistical optimization study was carried out by considering only the heating demands, accordingly, heating degree-day, wall type, insulation type, fuel type, and lifetime were selected as design parameters. It was concluded that the daily average temperature, and consequently, the heating degree-days, is the most influential parameter on the insulation applications. Kaynakli (2011) performed an investigation into the various factors influencing on identification of the ideal insulation thickness. The factors encompassed considerations such as cooling and heating loads, energy expenses, discount and inflation rates, lifetime, and the physical properties of insulation material. The study employed a whole-life cost analysis methodology to determine the most appropriate thickness.

In recent years, there has been a growing emphasis on environmentally friendly approaches in the heating and cooling processes of buildings, aiming to reduce carbon emissions and mitigate global warming. Doi (Doi (2022) investigated impacts of roof treatments, roads, and other components on the passive cooling technologies in residential areas to reduced energy consumption and carbon emissions. Harsito et al. (2022) experimentally and numerically examined the effect of exergy solar panels on photovoltaic performance by adding a thermoelectric system. They determined that the intensity of sunlight hitting the photovoltaic surface directly impacts the panel's temperature, subsequently influencing energy efficiency. Nistratov et al. (2022) devised a method for regenerating and reusing carbon and glass fibers obtained from non-recyclable remnants of carbon plastics. It was found that developed method can produce 2.3 tons per hour of reinforced building materials that contribute positively to both the environment and the economy. In this context, environmental effects have started to be taken into account in the investigations related to insulation applications. Acikkalp et al. (Açıkkalp and Kandemir, 2019) determined different optimum insulation thicknesses considering not only economic but also environmental effects. In their analysis, they preferred glass wool and rock wool as insulation material. According to the results of the study, while the ideal insulation thickness was lower in the analysis made by taking into account only economic concerns, the ideal insulation thickness was higher when only environmental effects were considered. Dombayci et al. (2020) enterprised to determine the most suitable insulation thickness that would reduce CO_2 emissions by using exergy destruction equations. They selected natural gas as fuel, rock wool and glass wool as insulation material. Based on the results of the study, they determined the ideal insulation thickness as 18 cm for rock wool, and 40 cm for glass wool. Carreras et al. (2015) conducted a multi-objective optimization by minimizing the total cost and energy-related carbon footprint using a software which called EnergyPlus. According to outcomes of their study, 23 cm insulation thickness was found to be the most suitable one for the city Lleida located in Spain. Axaopoulos et al. (2019a) determined the environmentally ideal insulation thickness for the city Athens located in Greece by using CO_2 emission factors. They obtained insulation thickness ranging from 11.2 cm to 23.4 cm, which varied depending on the wall types, insulation materials, and wall orientations. Yuan et al. (2017) contributed to the literature about thermal insulation applications by determining optimum insulation thickness and CO_2 emissions for various climatic zones utilizing up-to-date data. According to outcomes of the study conducted for China, climatic regions that are extremely hot and extremely cold, are much more suitable for applying thermal insulation regarding energy saving and reducing CO_2 emission. Huang et al. (2020) determined the optimum insulation thickness, which gives the minimum total cost, for different fuel types and insulation materials using life cycle cost analysis. They compared a new aerogel super-insulation material with the other conventional materials such as foamed polyurethane, extruded polystyrene, expanded polystyrene, and glass fibers. Additionally, they calculated the amount of CO_2 emitted into the atmosphere for each case and LPG was found the best fuel type ecologically.

As indicated by the studies presented above, numerous studies have been carried out in recent years, examining various parameters, and employing diverse methodologies to determine the ideal insulation thickness. Due to many factors such as sudden increases in energy prices, incentives to reduce the use of fossil fuels, and the desire to reduce greenhouse gases, energy conservation in buildings will remain on the agenda in the upcoming period and will remain up-to-date.

In addition, in the literature the knee point approach has been used for multi-objective optimization of many engineering problems. Duan et al. (2014) used knee point approach to investigate the impacts of the thickness and radius on crashworthiness of composite tape sinusoidal specimen, in which specific energy absorption and the peak impact load were considered as factor in the multi-objective optimization. In order to determine the optimal tube design profiles Tran et al. (2014) obtained the knee points from the pareto solutions space in the process of multi-objective crashworthiness optimization. Li et al. (2015) utilized the knee point approach when designing optimization for improving the crash behavior of aluminum foam-filled columns. It is concluded that the literature lacks studies that have utilized the knee point approach in addressing insulation optimization problems. In the present study, knee point approach, which is frequently used in other engineering areas such as crashworthiness design problems, structure optimizations, has been applied to thermal insulation optimization for the first time.

Consequently, even though there have been studies in the field of insulation thickness applications, it has not been encountered in the literature with a study conducted a multiple optimization that minimizes both total cost and CO_2 emissions evaluating together considering solar radiation. Optimum insulation thicknesses that minimize both objective functions (Cost and CO_2) simultaneously, have been calculated for 4 provinces located in different climate zones. A new equation that gives the environmentally optimum insulation thickness that minimizes the amount of CO_2 released into the atmosphere has been derived. With these aspects, this study differs from other studies related to insulation applications. In addition, ideal insulation thicknesses have been obtained for 3 different scenarios of seasonal usages: building cooled but not heated (summer house), heated but not cooled (winter house), and both cooled and heated (all-season house). Analyses are carried out for various heating sources (natural gas, electricity, fuel oil) and insulation material (EPS, XPS, MW, PUR). Annual energy cost saving, carbon saving, payback period, saving rate and carbon saving rate are determined for numerous cases.

2. Mathematical model

2.1. Degree-day approach

The annual energy consumption can be determined using a variety of approaches. In the literature most researchers use degree-days method to estimate the energy consumption under steady state conditions (Alsayed and Tayeh, 2019; Aydin and Biyikoğlu, 2021; Bolattürk, 2006; Büyükalaca et al., 2001; Minne et al., 2015; Yu et al., 2009). For the static conditions, the degree-hours method, which is a method similar to the degree-days method, can also be used while calculating the energy consumption (Bolattürk, 2008; Kaynakli, 2008). Besides these methods, annual energy consumption in buildings can be calculated with different approaches. For the dynamic conditions, analytical methods taking into account the transient behavior of the building system have been used by some researchers (Daouas, 2011; Daouas et al., 2010). Numerical models based on an implicit finite difference method can be used for dynamic transient conditions (Ozel, 2012a). Furthermore, annual energy consumption can also be predicted with energy simulation softwares such as EnergyPlus (Djuric et al., 2007; Masoso and Grobler, 2008), Visual DOE (Iqbal and Al-Homoud, 2007; Radhi, 2009). However, the degree-day approach is the most commonly used method to obtain the annual energy consumption of a building in academic studies due to its practicality, ease of use, reliability, free of charge, and ability to yield accurate results. Because of these reasons, this method has been used in this study. In order to utilize this method, first of all, heating degree days (*HDD*) and cooling degree days (*CDD*) values must be calculated. *HDD* and *CDD* are the terms used to measure the coldness or hotness of a region in a season, respectively. The sum of the differences between the average temperature of the relevant day (T_0) and the reference temperature (T_r) gives the *HDD* and *CDD* values. If the calculated difference is positive, it indicates that energy needs to be expended for cooling the building, whereas if it's negative, it means energy should be allocated for heating the building. A zero-temperature differential implies that there is no need for either heating or cooling. The annual total *HDD* and *CDD* values for the cooling and heating seasons can be calculated by Eqs. (1) and (2).

$$HDD = \sum_{d=1}^{365} (T_r - T_0) \quad for\ T_r > T_0 \tag{1}$$

$$CDD = \sum_{d=1}^{365} (T_0 - T_r) \quad for\ T_0 > T_r \tag{2}$$

2.2. Solar radiation calculations

In order to obtain more realistic *HDD* and *CDD* values, a new term that includes the solar radiation effect called T_{sol} is calculated instead of the average daily temperature (T_0) in these equations. Solar air temperature (T_{sol}) which is associated with both solar radiative flux and the ambient outside air temperature, can be calculated using the following equation (Al-Khawaja, 2004; Cengel, 2002).

$$T_{sol} = \frac{\alpha_s \dot{q}_s}{h_0} + T_0 - \frac{\varepsilon\sigma\left(T_0{}^4 - T_{sky}{}^4\right)}{h_0} \tag{3}$$

In this equation, first term represents the heat from solar exposure impact on the opaque surface, second one is average daily temperature, and the last term denotes a correction factor for heat transfer via radiation between the surface and its surroundings In Eq. (3), α_s is the surface's solar absorption rate, h_0 is combined radiation and convection coefficient of exterior surface, $\dot{q}_s$ is the solar irradiance reaching the surface, σ is the Stefan Boltzmann constant, ε is radiative emission coefficient of surface, and T_{sky} is sky and surrounding surface temperature.

The solar irradiance reaching the surface ($\dot{q}_s$) needs to be determined by the summation of diffuse, direct, and reflected solar radiations. It can be calculated using the following equation (Duffie and Beckman, 1991). Here, ρ is reflectance of the ground and it is assumed to be 0.2 (Yiğit and Atmaca, 2010).

$$\dot{q}_s = \dot{q}_{h,d}\left(\frac{1+\cos\beta}{2}\right) + \dot{q}_h\left(1 - \frac{\dot{q}_{h,d}}{\dot{q}_h}\right)R_b + \dot{q}_h\rho\left(\frac{1-\cos\beta}{2}\right) \tag{4}$$

In order to determine the solar irradiance reaching the surface, some terms have to be calculated. The average daily diffuse radiation for the horizontal surface ($\dot{q}_{h,d}$) which is one of the terms, can be calculated using the Eq. (5) (Tiris et al., 1995). In this equation, k_T which represents clearness index, can be found by Eq. (6).

$$\dot{q}_{h,d} = 0.703\dot{q}_h - k_T\dot{q}_h(0.414 + 0.428k_T) \tag{5}$$

$$k_T = \dot{q}_h / \dot{q}_{0,h} \tag{6}$$

Here, while $\dot{q}_h$ is the monthly mean daily global solar radiation, $\dot{q}_{0,h}$ denotes the monthly mean daily extraterrestrial radiation. Clearness index varies depending on the relative sunshine duration, declination angle (δ), latitude angle ($\varnothing$), and altitude of the location (Kilic and Ozturk, 1983).

The incidence's angle of direct solar irradiance (θ) based on other angles such as declination (δ), latitude ($\varnothing$), and azimuth (γ) angle, for the vertical surfaces is given below.

$$\cos\theta = \cos\delta\ \sin\varnothing\cos\gamma\ \cos\omega - \sin\delta\ \cos\varnothing\cos\gamma + \cos\delta\ \sin\gamma\ \sin\omega \tag{7}$$

The angle of incidence of solar radiation, which is called zenith angle (θ_z), can be calculated for the horizontal surfaces using Eq. (8).

$$\cos\theta_z = \sin\delta\ \sin\varnothing + \cos\delta\ \cos\varnothing\cos\omega \tag{8}$$

R_b values can be calculated by dividing the azimuth angle by zenith angle as shown in Eq (9).

$$R_b = \cos\theta / \cos\theta_z \tag{9}$$

Consequently, the solar irradiance reaching the surface ($\dot{q}_s$), and consequently solar air temperature (T_{sol}) can be calculated using the terms described in detail above.

2.3. Annual heating and cooling transmission load

After calculating the *HDD* and *CDD* values considering solar radiation, the heat loss/gain from the outer walls should be calculated in order to determine the annual energy need of the building. The wall structure considered in the analysis consists of 2 cm internal plaster (k = 0.87 W/mK), 20 cm hollow brick (k = 0.45 W/mK), insulation material (k = 0.03 W/mK), and 3 cm external plaster (k = 0.87 W/mK), as shown in Fig. 1. In this study, while different sources are used for heating, it is assumed that air conditioning is used for cooling, and this results in electricity consumption.

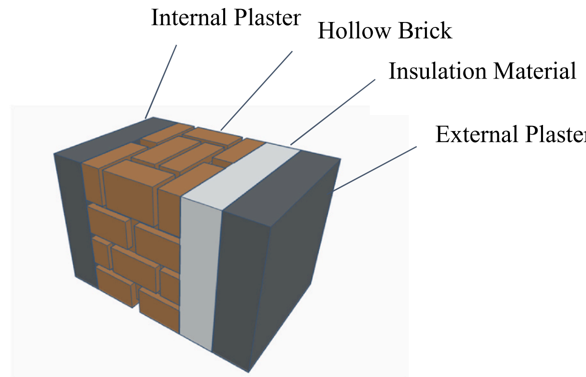

Fig. 1. Wall structure of buildings.

Table 1
Parameters used in the calculations.

Financial parameter	Value
Interest rate, *i*	20%
Inflation rate, *g*	17%
Actual interest rate, *r*	0.0256
Lifetime, *N*	10
Present worth factor, *PWF*	8.7

The heat transfer coefficients for the inside (h_i) and outside (h_o) are taken close to real values by the researchers (Kaynakli, 2013; Ozel, 2012b, 2012a; Ozel and Pihtili, 2007). In this study, the inside (h_i) and outside (h_o) heat transfer coefficients are assumed as 8.3 W/m^2K and 28.4 W/m^2K, respectively (Kaynakli and Kaynakli, 2016). The value of 28.4 W/m^2K has been determined by calculating the average of the outside heat transfer coefficient in summer and winter conditions in the study of Kaynakli (Kaynakli and Kaynakli, 2016). The annual heating energy demand ($E_{A,H}$) can be found by taking the annual heat loss in unit area and dividing it by the efficiency of the heating system (η).

$$E_{A,H} = \frac{86400\ HDD}{(R_i + R_o + R_w + R_{ins})\eta} \tag{10}$$

In this equation, while R_i represents inside air-film thermal resistance which can be determined as $1/h_i$, R_o denotes outside air-film thermal resistance which can be calculated as $1/h_o$. Besides, R_w is total thermal resistance of the wall without the insulation and R_{ins} expresses thermal resistance of the insulation layer.

The annual cooling energy demand ($E_{A,C}$) can be found by taking the annual heat gain in unit area and dividing it by the coefficient of cooling system performance (*COP*). The *COP* value is chosen as 2.5 based on studies in the literature (Jraida et al., 2017; Kon and Caner, 2022; Ozel, 2013).

$$E_{A,C} = \frac{86400\ CDD}{(R_i + R_o + R_w + R_{ins})COP} \tag{11}$$

Here, sum of the $R_i + R_o + R_w$ expressions can also be expressed as $R_{t,w}$, that is total wall's thermal resistance of the uninsulated wall.

2.4. Economic analysis and optimum insulation thickness based on total cost

When the literature is examined, it can be seen that life cycle cost (LCC) analysis has been used in many studies on optimum insulation thickness (Bektas Ekici et al., 2012; Guven, 2019; Kurekci, 2016; Minne et al., 2015; Su et al., 2016). Therefore, this study utilizes LCC analysis, a widely accepted method for evaluating the total costs related to heating and cooling over the entire lifetime of a building. The annual energy cost is calculated using a financial term called present worth factor (*PWF*), which varies depending on the building's lifespan (*N*), interest rate (*i*), and inflation rate (*g*) (see Table 1). The term *r* in the equations below represents the actual interest rate. Financial parameters have been chosen using published data from the Central Bank of Türkiye and the Turkish Statistical Institute ("Central Bank of Türkiye,", "Turkish Statistical Institute,").

$$r = (i - g)/(1 + g) \quad if \quad i > g \tag{12}$$

$$r = (g - i)/(1 + i) \quad if \quad i < g \tag{13}$$

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

$$PWF = N/(1 + i) \quad if \quad i = g \tag{15}$$

The lifetime (*N*) of the building is assumed to be 10 years (Kallioğlu et al., 2020; Ozel, 2011; Ucar and Balo, 2009).

Table 2
Prices, lower heating values, efficiencies, and emission factors of heating sources (Akan and Akan, 2022; Anastaselos et al., 2009; Axaopoulos et al., 2019b; Ucar and Balo, 2010).

Heating Source	Price, C_f	Lower heating value, H_u	Efficiency, η (%)	Emission factor, f_h ($kgCO_2/kWh$)
Natural Gas	0.327 USD/m^3	34.526×10^6 J/m^3	93	0.194
Electricity	0.1059 USD/kWh	3.599×10^6 J/kWh	99	0.588
Fuel Oil	0.734 USD/kg	40.594×10^6 J/kg	80	0.268

Table 3
Prices, physical properties, and emission factors of insulation materials (Anastaselos et al., 2009; Axaopoulos et al., 2019b).

Insulation Material	Price, C_{ins}(USD/m^3)	Density, ρ(kg/m^3)	Conductivity, k (W/mK)	Emission factor, f_{ins}($kgCO_2/kg$)
Expanded Polystyrene (EPS)	100	20	0.036	3.51
Extruded Polystyrene (XPS)	150	30	0.037	3.83
Mineral Wool (MW)	130	55	0.04	1.16
Polyurethane Foam (PUR)	200	40	0.036	4.47

The cost due to insulation application is obtained by multiplying the price of the insulation material (C_{ins}) and the insulation thickness (x). C_{inst} represents the installation costs and assumed as 8 USD/m^2 (Ozbek et al., 2022). The total heating ($C_{T,H}$), cooling ($C_{T,C}$), and annual ($C_{T,A}$) costs can be calculated using the Eq. (16) and (17), respectively.

$$C_{T,H} = C_{ins}x + C_{inst} + \frac{86400 HDD C_f PWF}{\left(R_{t,w} + \frac{x}{k}\right)H_u\eta} \tag{16}$$

$$C_{T,C} = C_{ins}x + C_{inst} + \frac{86400 CDD C_e PWF}{\left(R_{t,w} + \frac{x}{k}\right)COP} \tag{17}$$

$$C_{T,A} = C_{ins}x + C_{inst} + \frac{86400 HDD C_f PWF}{\left(R_{t,w} + \frac{x}{k}\right)H_u\eta} + \frac{86400 CDD C_e PWF}{\left(R_{t,w} + \frac{x}{k}\right)COP} \tag{18}$$

In these equations, C_f and C_e represent fuel cost and electricity cost, respectively. H_u is the lower heating value of the heating source and k is the thermal conductivity of the insulation material. Relevant values are presented in Table 2 and Table 3.

For cost optimization, firstly the total cost expressions given in Eq. (16) and (17) should be minimized. In this context, when the derivatives of the relevant equations are taken with respect to x and equalized to zero, insulation thicknesses that give optimum values in terms of cost are obtained. The ideal thicknesses in terms of cost for heating ($x_{cost,H}$), cooling ($x_{cost,C}$), and annual ($x_{cost,A}$), can be determined using the Eq. (19) and (20), respectively.

$$x_{cost,H} = \sqrt{\frac{86400 HDD C_f PWF k}{H_u \eta C_{ins}}} - R_{t,w}k \tag{19}$$

$$x_{cost,C} = \sqrt{\frac{86400 CDD C_e PWF k}{COP C_{ins}}} - R_{t,w}k \tag{20}$$

Table 4
Energy requirements of an uninsulated building for various heating sources.

	Natural Gas			Electricity			Fuel Oil		
	Heating (MJ/m^2)	Cooling (MJ/m^2)	Annual (MJ/m^2)	Heating (MJ/m^2)	Cooling (MJ/m^2)	Annual (MJ/m^2)	Heating (MJ/m^2)	Cooling (MJ/m^2)	Annual (MJ/m^2)
Zone I	76.6	58.4	134.9	71.9	58.4	130.3	89.0	58.4	147.4
Zone II	159.0	29.1	188.1	149.4	29.1	178.5	187.4	28.8	216.3
Zone III	286.9	23.6	310.5	269.5	23.6	293.1	333.5	23.6	357.1
Zone IV	362.6	12.8	375.5	340.7	12.8	353.5	421.6	12.8	434.4

$$x_{cost,A} = \sqrt{\frac{86400PWFk\left(C_f HDD/H_u\eta + C_e CDD/COP\right)}{C_{ins}}} - R_{t,w}k \tag{21}$$

The Energy Cost Savings (*ECS*) over the system's lifetime is established through a comparison of heating and cooling expenditures between insulated and non-insulated structures. *ECS* is calculated using the following equation.

$$ECS = \left[C_{energy,H} + C_{energy,C}\right]_{x=0} - \left[C_{energy,H} + C_{energy,C}\right]_{x=x_{ideal,A}} \tag{22}$$

The term, $x_{ideal,A}$, may vary as $x_{cost,A}$ or $x_{env,A}$ depending on the case examined. Here, $x_{env,A}$ represents the optimum insulation thickness in terms of environmental effects. The Savings Rate (*SR*) is calculated by dividing the energy cost savings by the annual total cost in uninsulated conditions, and it can be represented as follows:

$$SR = \frac{ECS}{\left[C_{T,A}\right]_{x=0}} \tag{23}$$

The payback period (*PP*) is calculated by dividing the initial insulation cost by the annual energy cost savings. This period signifies the time required to recover the initial investment and can be computed using the following equation.

$$PP = \frac{\left(C_{ins}\, x_{x=x_{ideal,A}} + C_{inst}\right)}{(ECS/N)} \tag{24}$$

2.5. CO_2 emission calculations and optimum insulation thickness based on CO_2

While insulation on building exterior walls reduces energy costs, it also reduces the amount of CO_2 released into the atmosphere, which is called *operational emissions*. However, the negative environmental effects of CO_2 generated during the production, transportation, and assembly processes of the insulation material, which is called *embodied emissions*, generally are not taken into account. In this study, while examining the environmental effects of insulation application, analyzes are carried out considering both operational and embodied emissions to obtain more realistic results.

Total CO_2 emissions (CE_T) due to the heating (CE_H), cooling (CE_C) and insulation process (CE_{ins}) are expressed in Eq. (25).

$$CE_T = CE_H + CE_C + CE_{ins} \tag{25}$$

The yearly CO_2 emissions from heating (CE_H), cooling (CE_C) and insulation process (CE_{ins}), can be determined using the Eq. (26) and (27), respectively.

$$CE_H = \frac{0.024\, HDDf_h}{\left(R_{t,w} + \frac{x}{k}\right)\eta} \tag{26}$$

$$CE_C = \frac{0.024\, CDDf_c}{\left(R_{t,w} + \frac{x}{k}\right)COP} \tag{27}$$

$$CE_{ins} = \frac{\rho x f_{ins}}{N} \tag{28}$$

In these equations, f_h, f_c, and f_{ins} represent the emission factors and presented in Tables 2 and 3. According to the information available in the literature, the emission factor for electricity has been taken as 0.588 $kgCO_2/kWh$ (Anastaselos et al., 2009; Axaopoulos et al., 2019b). The emission factor for generating thermal energy from fuel oil and natural gas are considered to be 0.268, and 0.194 $kgCO_2/kWh$, respectively (Akan and Akan, 2022; Anastaselos et al., 2009).

The total amount of CO_2 released into the atmosphere from a building which is used only heating season can be calculated using Eq. (29). Similarly, the equations calculating the total amount of CO_2 released to the atmosphere from the building used during the cooling season and from the building used throughout the year are given below in Eqs (30) and (31), respectively.

$$M_{CO_2,H} = \frac{0.024\, HDDf_h}{\left(R_{t,w} + \frac{x}{k}\right)\eta} + \frac{\rho x f_{ins}}{N} \tag{29}$$

$$M_{CO_2,C} = \frac{0.024\, CDDf_c}{\left(R_{t,w} + \frac{x}{k}\right)COP} + \frac{\rho x f_{ins}}{N} \tag{30}$$

$$M_{CO_2,A} = \frac{0.024\, HDDf_h}{\left(R_{t,w} + \frac{x}{k}\right)\eta} + \frac{0.024\, CDDf_c}{\left(R_{t,w} + \frac{x}{k}\right)COP} + \frac{\rho x f_{ins}}{N} \tag{31}$$

To obtain ideal thicknesses in terms of environmental effects, firstly the total amount of CO_2 expressions for different seasonal usage scenarios, given in Eq. (29) and (30), should be minimized. In this context, when the derivatives of the relevant equations are taken with respect to *x* and equalized to zero, insulation thicknesses that give optimum values in terms of environmental effects are obtained. These new derived equations calculate the environmentally optimum insulation thicknesses that minimize the amount of CO_2 released into the atmosphere. The ideal thicknesses in terms of environmental effects for heating ($x_{env,H}$), cooling ($x_{env,C}$) and annual ($x_{env,A}$), can be determined using the Eq. (32-33-34), respectively.

$$x_{env,H} = \frac{\sqrt{15}\ \sqrt{f_{ins}\, f_h\ \eta\ HDD\ k\ N\rho}}{25 f_{ins}\eta\rho} - kR_{t,w} \tag{32}$$

$$x_{env,C} = \frac{\sqrt{15}\ \sqrt{f_{ins}\, f_c\ CDD\ k\ N\ COP\ \rho}}{25 f_{ins} COP\rho} - kR_{t,w} \tag{33}$$

$$x_{env,A} = \frac{\sqrt{15}\ \sqrt{f_{ins} f_c\ CDD\,\eta^2\, kN\, COP\,\rho + f_{ins} f_h\,\eta\, HDD\, kN\, COP^2\rho}}{25 f_{ins}\eta COP\rho} - kR_{t,w} \tag{34}$$

A new term, the Carbon Saving (*CS*) over the system's lifetime is presented through a comparison of CO_2 releasing in case of heating and cooling between insulated and non-insulated structures. *CS* is calculated using the following equation.

$$CS = \left[C_{CO_2,H} + C_{CO_2,C}\right]_{x=0} - \left[C_{CO_2,H} + C_{CO_2,C}\right]_{x=x_{env,A}} \tag{35}$$

Another new term, the Carbon Savings Rate (*CSR*) is presented and it can be computed by dividing the Carbon Savings by the annual total amount of CO_2 in uninsulated conditions, and it can be represented as

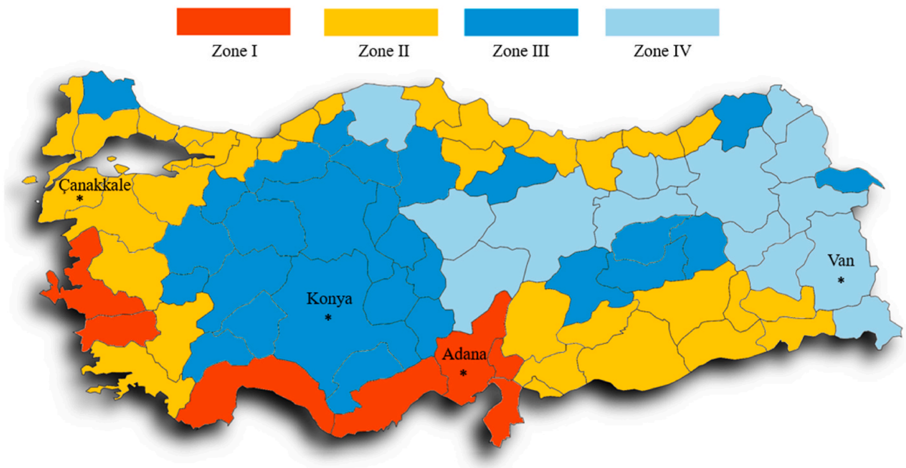

Fig. 2. Different climatic zones of Türkiye and selected cities for the study.

follows:

$$CSR = \frac{CS}{\left[M_{CO_2,A}\right]_{x=0}} \tag{36}$$

2.6. Knee point approach for multi-objective optimization

In this study, two different ideal insulation thicknesses are obtained for each building located in different climatic regions, minimizing the total cost and the amount of CO_2 released into the atmosphere. In addition, a multi-objective optimization study is carried out by making use of the knee point approach, by reducing both target functions (Cost and CO_2) into a single function. Consequently, a single insulation thickness is determined, which gives the most satisfactory solution that simultaneously minimizes both CO_2 and total cost.

It is seen in the literature that the knee point approach mentioned above is frequently used in many studies which include bicriteria optimization problems (Albak, 2021; Duan et al., 2014; Li et al., 2015; Tran et al., 2014). This approach is based on normalizing the values obtained in both target functions and then finding the minimum distance to the "utopia point". The utopia point symbolizes the perfect solutions for both objectives. In practice, achieving this 'utopia point' becomes unreachable due to conflicting objectives. Therefore, in this study, minimum distance selection method is utilized to determine the knee point value which can be formulated mathematically below (Duan et al., 2014; Peng et al., 2017).

$$\min D = \sqrt{\left(\sum_{\tau=1}^{n}\left(\frac{f_{c\tau}}{\min\left(f_{\tau}(x)\right)} - 1\right)^2\right)} \tag{37}$$

Here, n represents the number of the objective functions, $f_{c\tau}$ denotes the τ th objective value in the c th result, and D signifies the distance from knee point to the utopia point.

3. Results and discussion

In this study, four cities from different climatic zones are selected for the analysis to observe the influence of the climate on the optimum insulation applications. Among the selected cities, Adana, Çanakkale, Konya, and lastly Van are located in the 1st (Zone I), 2nd (Zone II), 3rd (Zone III), and 4th (Zone IV) degree day regions, respectively, as shown in Fig (2). Türkiye is categorized into four climatic regions, with Zone I representing the warmest climate and Zone IV representing the coldest climate according to Turkish Standards Institution (TS 825) (Thermal Insulation Requirements for Buildings, 2013).

In this study, solar radiation has been considered in calculations, correspondingly incoming solar radiation on vertical surfaces for cities situated in various climatic zones are presented in Fig. (3) on a monthly basis.

When examining the trend in the graph presented in Fig. (3), it becomes evident that solar radiation values on vertical surfaces are consistently higher in cities across all climate zones during the summer months, such as June, July, and August, while they exhibit lower values

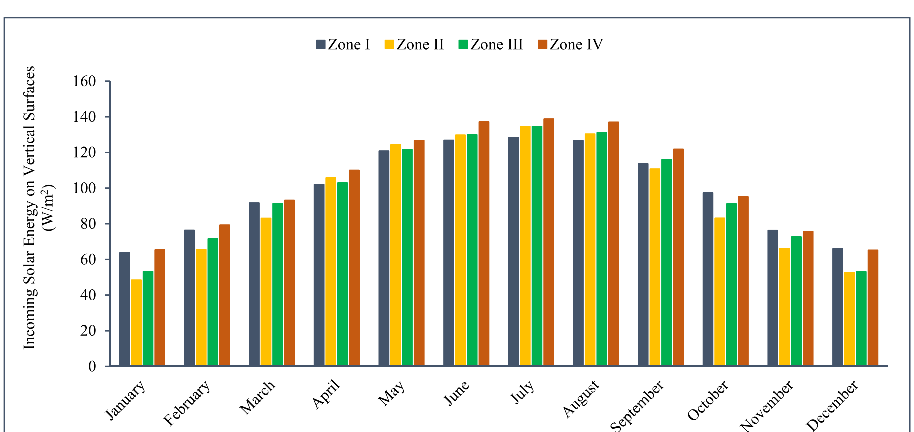

Fig. 3. Incoming solar radiation on vertical surfaces for each month.

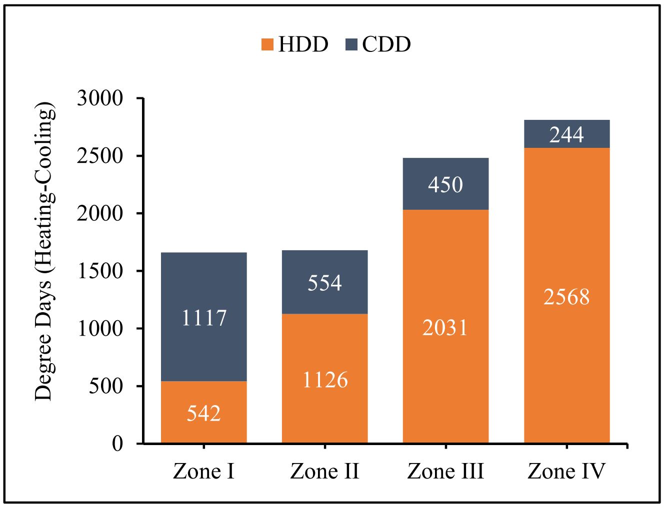

Fig. 4. Yearly average heating and cooling degree days for various locations.

during the winter months, such as December and January. When analyzing the graph in greater detail, it is apparent that, the city located in Zone IV experiences the highest solar radiation levels in all months except for October, November, and December. Although the lowest solar radiation levels are computed in the city located in Zone I during April, May, June, July, and August, conversely, this city experiences the highest solar radiation values in October, November, and December. The reason of these variations is not only by air temperature but also by the geographical and meteorological conditions of the area where the building is situated, including factors such as altitude, latitude angle, and relative sunshine duration.

CDD and *HDD* values of cities located in different climatic regions are determined by adding solar radiation effect to the calculations. As shown in Fig. (4), the cities with the highest *HDD* values, which are directly proportional to heating energy needs, are in the order of Zone 4, Zone 3, Zone 2, and Zone 1, respectively. On the contrary, the cities with the highest *CDD* value, which are directly related to cooling energy needs, are Zone 1, Zone 2, Zone 3, and Zone 4, respectively. It is clear from the graph that the total annual energy needs are ordered by magnitude as follows: Zone 4 > Zone 3 > Zone 2 > Zone 1.

In Figs. 5–8, graphs illustrating the total cost and the corresponding amount of CO_2 emissions, which vary with insulation thickness, are presented for cities in various climatic regions. Additionally, a graph has been created to achieve the most satisfactory solution by combining both financial and environmental objectives into a single function. Here, using the knee point approach, the ideal insulation thickness and the total cost and total CO_2 amounts in this thickness are determined. The analyses have been carried out and graphs have been generated for three different building usage scenarios, including summer houses, winter

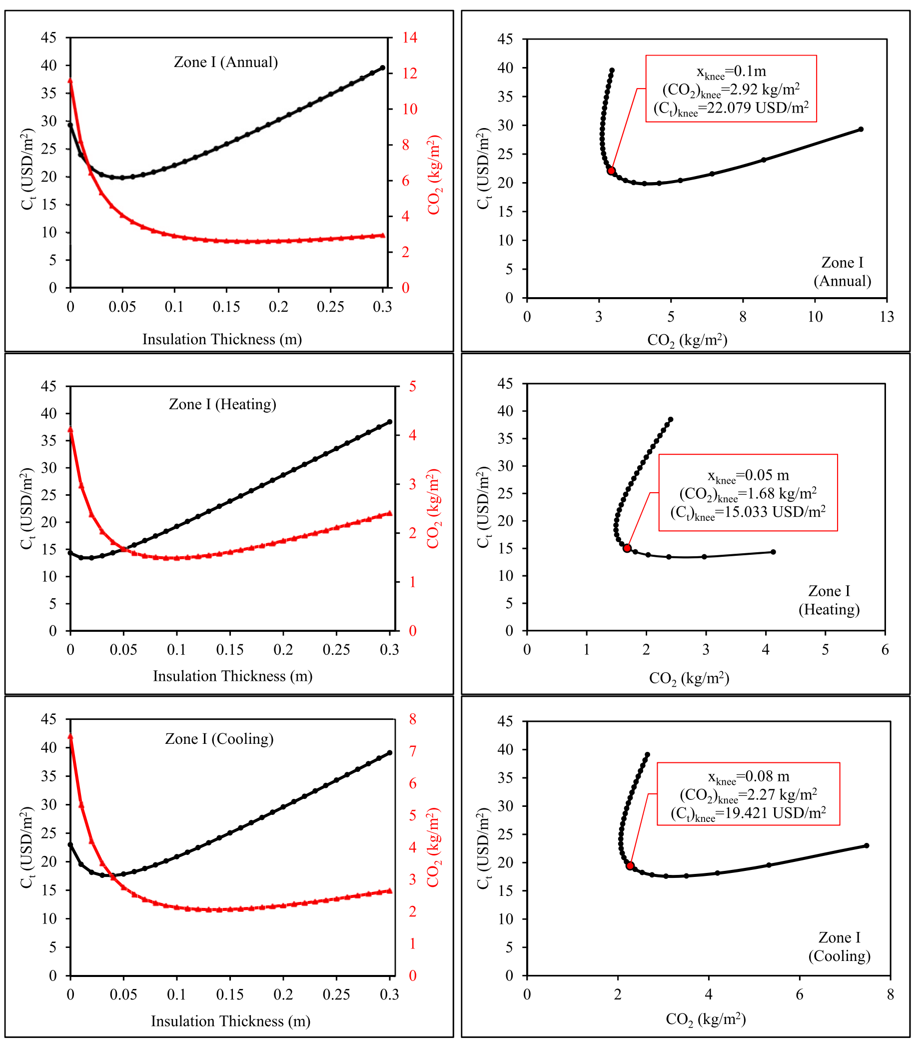

Fig. 5. Variation of CO_2 and total cost with insulation thickness **(a)** and optimum insulation thickness considering both CO_2 and total cost **(b)** for zone I.

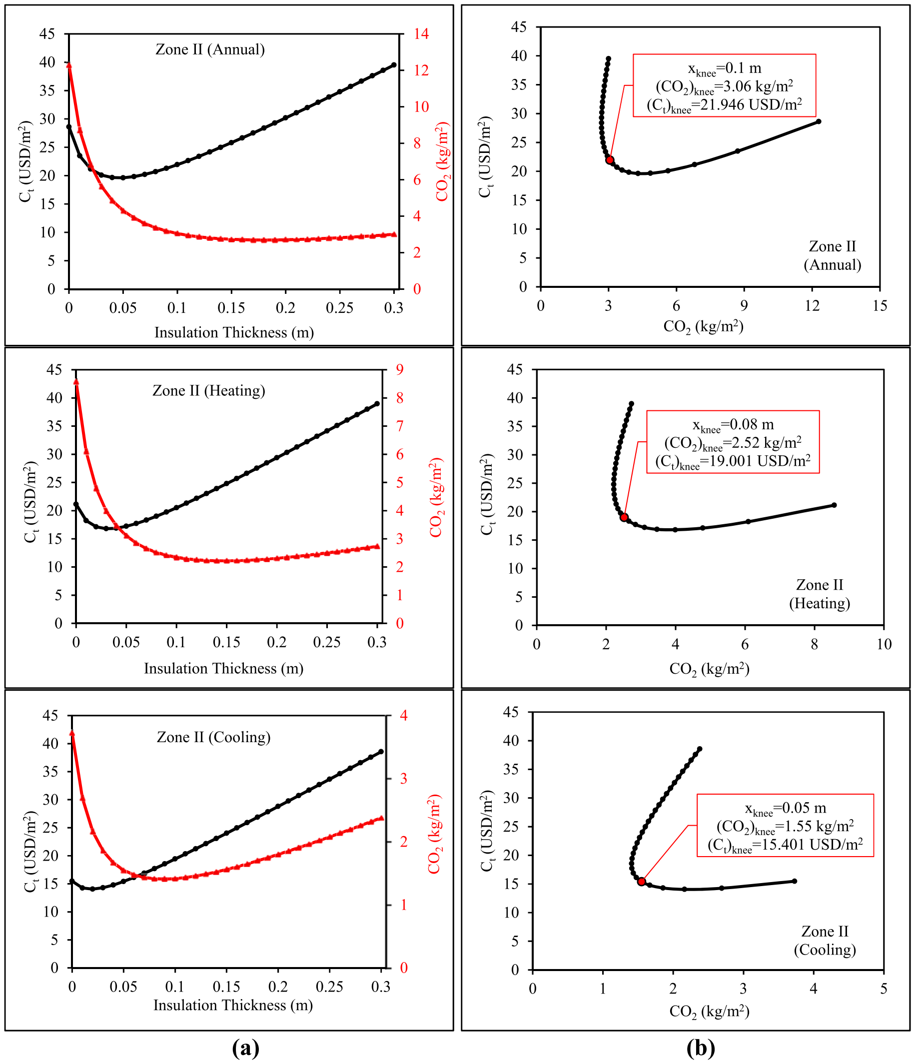

Fig. 6. Variation of CO_2 and total cost with insulation thickness **(a)** and optimum insulation thickness considering both CO_2 and total cost **(b)** for zone II.

houses, and all-season houses.

Variation of CO_2 and total cost with insulation thicknesses in a building located in Zone I are presented for annual, heating, and cooling energy needs (see Fig. (5)). Evidently, from the graphs, the insulation thickness that minimizes the total cost and the insulation thickness that minimizes the CO_2 released into the atmosphere are different from each other. For example, when the first graph in Fig. (5a) is examined (for an all-season house), it is determined that the insulation thickness that results in the lowest total cost is 4.7 cm, while the insulation thickness that leads to the lowest CO_2 emissions is 17.4 cm. Considering only environmental effects for all three scenarios (summer houses, winter houses, and all-season houses), it appears that higher insulation thicknesses are required compared to the financial optimization as seen in Fig. (5a). When the primary objective of the insulation application is to minimize CO_2 emissions, the calculated optimum insulation thickness is consistently higher compared to the scenario where the main goal is to minimize total costs. This difference arises due to the consideration of different parameters in the calculation of these values. Since there are extra parameters such as emission factors (f_h, f_c, and f_{ins}) and material density (ρ) in the calculation of the insulation thickness that minimizes CO_2 emissions, as a result of the combined effect of these parameters, it has been observed that the thickness that minimizes CO_2 emissions is more than the thickness that minimizes the cost. In addition, the difference in optimum insulation thicknesses that minimizes the cost for summer and winter seasons is due to a similar reason. For instance, in calculating optimum thickness for summer season, factors such as cooling degree day (*CDD*), electricity cost (C_e), and cooling system performance (*COP*). Play a crucial role, while for winter season, heating degree day (*HDD*), fuel cost (C_f), and heating source efficiency (η) replace these parameters. When insulating an all-season house with consideration for both environmental and financial factors, the optimal solution is achieved at a specific insulation thickness of 10 cm, as indicated by the knee point approach in Fig. (5b). Similarly, for winter house, and summer house this ideal insulation thicknesses are calculated as 5 cm and 8 cm, respectively.

Fig. (6) illustrates the impact of insulation thickness variation on CO_2 emissions and total costs for a building situated in Zone II with respect to its annual, heating, and cooling energy demands. In Zone II, similar to the conditions observed in Zone I, it becomes evident, when focusing solely on environmental impact, that higher insulation thicknesses are necessary, as illustrated in Fig. (6a). Fig. (6b) reveals that, when taking into account both environmental and financial purposes, the ideal insulation thicknesses are found to be 10 cm for an all-season house, 8 cm for a winter house, and 5 cm for a summer house.

In Fig. (7), graphs have been created with the same approach to illustrate various usage scenarios of a building located in Zone 3. In Fig. (7b), it becomes evident that when considering both environmental and financial factors simultaneously, the ideal insulation thickness varies: 13 cm for all-season houses, 12 cm for winter houses, and 5 cm for summer houses. When examining the optimal insulation thicknesses

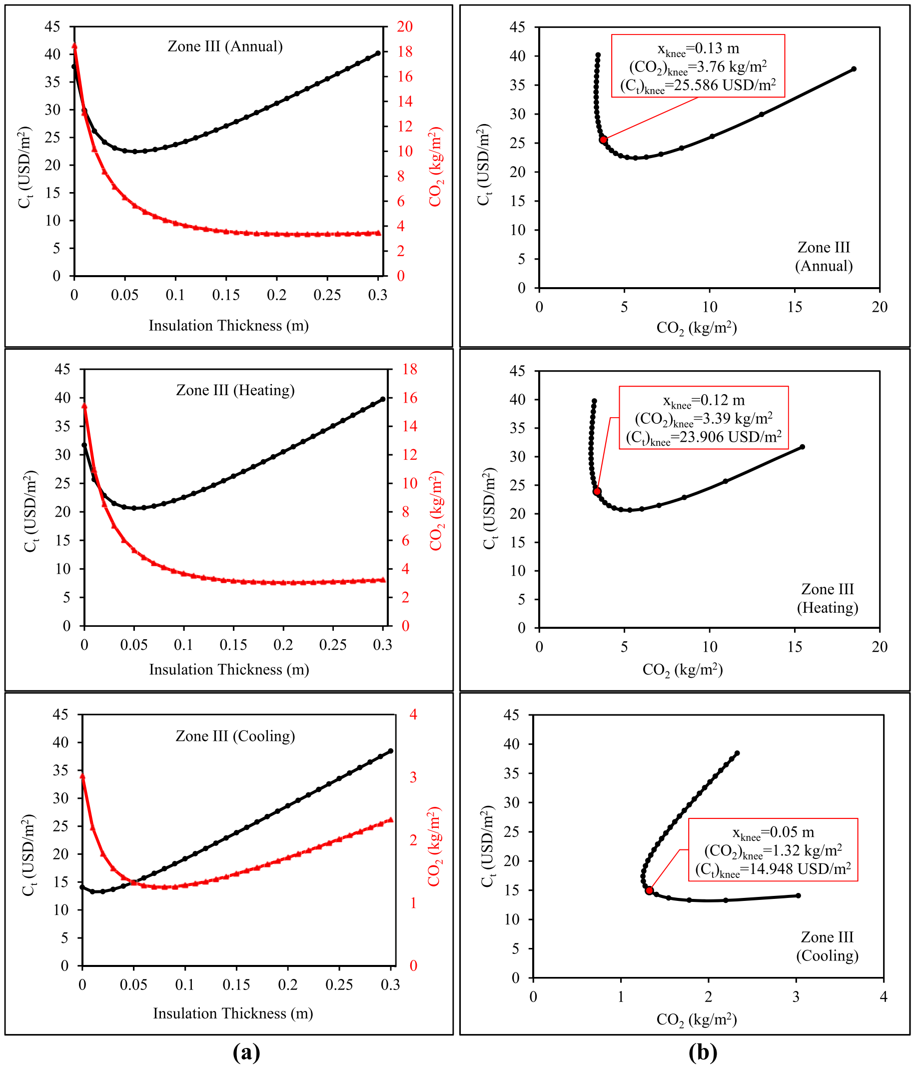

Fig. 7. Variation of CO_2 and total cost with insulation thickness **(a)** and optimum insulation thickness considering both CO_2 and total cost **(b)** for zone III.

for all three building usage scenarios in both Zone I and Zone II, it is consistently observed that the ideal thicknesses determined using the knee point method are closer with the insulation thickness that minimizes costs. For the first time, the ideal insulation thickness determined by the knee point method in the summer house scenario in Zone III is closer to the insulation thickness that minimizes CO_2 emissions.

Likewise, in Zone IV, the ideal insulation thickness determined by the knee point method in the summer house scenario is closer to the insulation thickness that minimizes CO_2 emissions. In all scenarios except these 2 cases, the ideal insulation thicknesses determined by the knee point method are closer to the insulation thickness that minimizes the total cost.

As illustrated in Fig. (8b), when considering both environmental and financial purposes, the ideal insulation thicknesses are determined to be 14 cm for an all-season house, 13 cm for a winter house, and 3 cm for a summer house.

Since it is assumed that natural gas is used as the heating source in these analyses, "Natural Gas" section in Table 5 can be referred for a more detailed understanding of the differences in optimum insulation thicknesses obtained in Figs. 5–8. For an all-season house and winter house scenarios, as it is moved from hot climate to cold climate regions (From Zone I to Zone IV), it is seen that the difference between the optimum insulation thickness in terms of cost and the optimum insulation thickness in terms of CO_2 emissions increases. Conversely, for a summer house scenario, as it is moved from hot climate to cold climate regions (From Zone I to Zone IV), it is seen that the difference between the optimum insulation thickness in terms of cost and the optimum insulation thickness in terms of CO_2 emissions decreases.

It is determined that insulation application should be made for the purpose of the building's use. To give an example for Zone I, it is observed that when considering financial purpose and using fuel oil as heating source, EPS as insulation material the ideal insulation thicknesses are determined to be 5.9 cm for an all-season house, 3.4 cm for a winter house, and 3.6 cm for a summer house. Variations in insulation thickness of up to 2.5 cm are observed for different usage scenarios. Under the same conditions, the relevant values for Zone IV are determined as follows: 10.5 cm for an all-season house, 10.2 cm for a winter house, and 0.4 cm for a summer house. It is seen that there is an insulation difference of up to 11.1 cm for different usage purposes.

Table 4 illustrates the energy requirements of uninsulated buildings situated in diverse climatic regions. Heating, cooling, and annual energy requirements of the buildings for various heating sources are presented. When each zone is examined separately in Tables 4 and it becomes evident that heating, and annual energy needs are different due to the diverse efficiency of the heating sources. Since it is assumed that the building is constantly cooled with air conditioning, there is no change in cooling energy needs. As the highest efficiency is in electricity at 99%, as seen in Table 2, when each climatic zone is examined separately, lowest heating, and annual energy needs are obtained when electricity is used as the heating source. Conversely, when using fuel oil as the heating

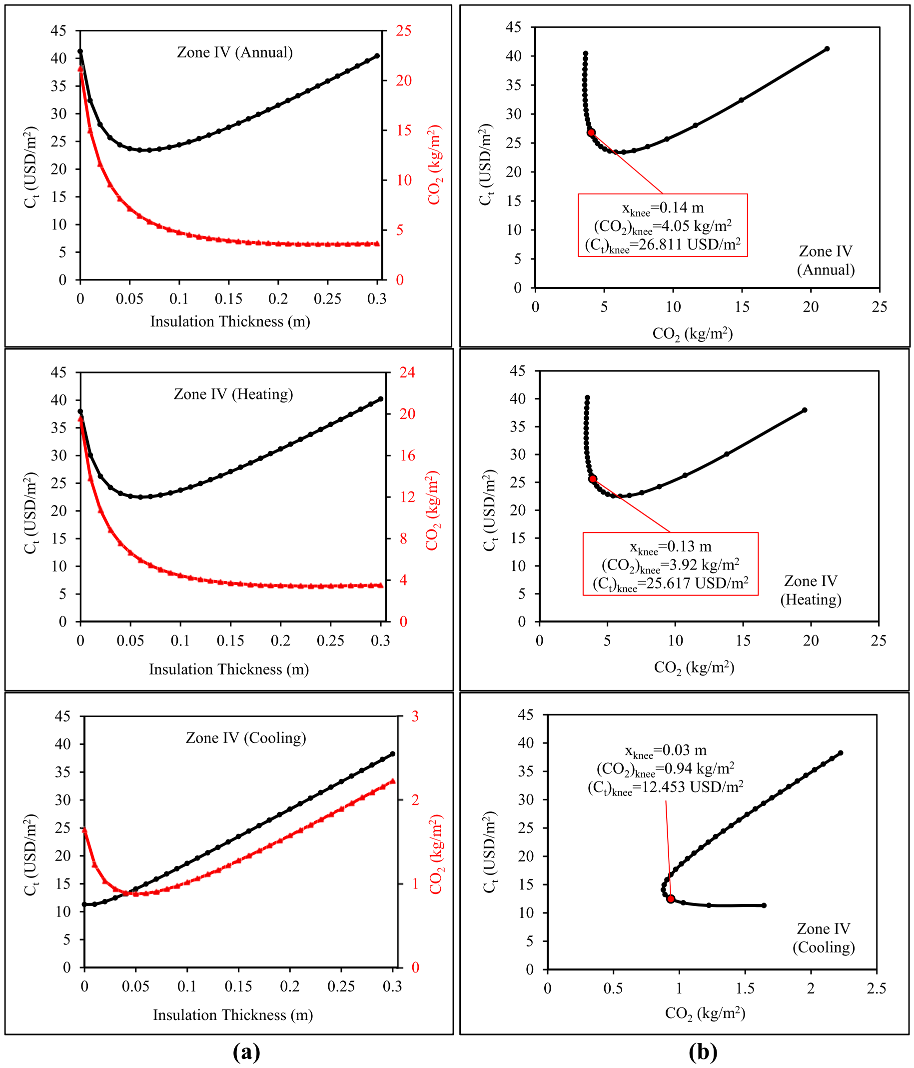

Fig. 8. Variation of CO_2 and total cost with insulation thickness **(a)** and optimum insulation thickness considering both CO_2 and total cost **(b)** for zone IV.

Table 5
Optimum insulation thicknesses that minimize total cost and CO_2 emission for different heating sources.

	Natural Gas			Electricity			Fuel Oil		
	Heating (m)	Cooling (m)	Annual (m)	Heating (m)	Cooling (m)	Annual (m)	Heating (m)	Cooling (m)	Annual (m)
Zone I for Cost	0.015	0.036	0.047	0.042	0.036	0.065	0.034	0.036	0.059
Zone I for CO_2	0.094	0.135	0.174	0.175	0.135	0.231	0.126	0.135	0.194
Zone II for Cost	0.032	0.018	0.046	0.072	0.018	0.080	0.059	0.018	0.069
Zone II for CO_2	0.146	0.088	0.180	0.263	0.088	0.284	0.192	0.088	0.219
Zone III for Cost	0.051	0.014	0.060	0.104	0.014	0.110	0.088	0.014	0.094
Zone III for CO_2	0.205	0.077	0.226	0.362	0.077	0.375	0.266	0.077	0.283
Zone IV for Cost	0.061	0.004	0.065	0.120	0.004	0.123	0.102	0.004	0.105
Zone IV for CO_2	0.233	0.051	0.244	0.410	0.051	0.416	0.302	0.051	0.310

source, which has the lowest efficiency at 80% in this study, the energy requirements are found to be the highest in all three scenarios. When examined on a regional basis, it is seen that the building located in Zone IV has the highest heating and annual energy requirements, while the maximum cooling energy is required for the building located in Zone I.

Table 5 presents the optimum insulation thicknesses for different heating sources when only the total cost or only CO_2 emissions are taken as the target function. As previously mentioned, it is evident that the lowest energy consumption for heating the building occurs when electricity is used as the heating source. However, since heating sources have different lower heating values and prices, the insulation thicknesses that minimize the total cost do not vary only depending on the energy needs of the building.

In buildings across all climatic regions, the order of insulation thicknesses that minimize the total costs for heating and annual energy needs with diverse heating sources is as follows: $x_{cost,\ electricity} > x_{cost,\ fuel\ oil} > x_{cost,\ natural\ gas}$. As mentioned before, since it is assumed that the building is constantly cooled with air conditioning, there is no change in cooling energy needs.

As previously stated, CO_2 emission varies depending on the energy needs of the building as well as the emission factors of the heating sources. Table 5 clearly shows that, for various heating sources, the

Table 6
Optimum insulation thicknesses that minimize total cost and CO_2 emission for different insulation materials.

	Expanded Polystyrene (EPS)			Extruded Polystyrene (XPS)		
	Heating (m)	Cooling (m)	Annual (m)	Heating (m)	Cooling (m)	Annual (m)
Zone I for Cost	0.015	0.036	0.047	0.008	0.025	0.034
Zone I for CO_2	0.094	0.135	0.174	0.069	0.101	0.132
Zone II for Cost	0.032	0.018	0.046	0.022	0.010	0.033
Zone II for CO_2	0.146	0.088	0.180	0.110	0.065	0.137
Zone III for Cost	0.051	0.014	0.060	0.038	0.007	0.045
Zone III for CO_2	0.205	0.077	0.226	0.157	0.056	0.174
Zone IV for Cost	0.061	0.004	0.065	0.045	0.000	0.049
Zone IV for CO_2	0.233	0.051	0.244	0.179	0.035	0.188
	Mineral Wool (MW)			**Polyurethane Foam (PUR)**		
	Heating (m)	Cooling (m)	Annual (m)	Heating (m)	Cooling (m)	Annual (m)
Zone I for Cost	0.039	0.009	0.039	0.027	0.004	0.027
Zone I for CO_2	0.104	0.104	0.192	0.100	0.050	0.100
Zone II for Cost	0.025	0.013	0.038	0.016	0.006	0.026
Zone II for CO_2	0.162	0.098	0.199	0.083	0.047	0.104
Zone III for Cost	0.043	0.009	0.051	0.029	0.003	0.036
Zone III for CO_2	0.226	0.085	0.250	0.119	0.040	0.133
Zone IV for Cost	0.052	0.000	0.056	0.036	0.000	0.039
Zone IV for CO_2	0.258	0.056	0.269	0.137	0.023	0.144

insulation thicknesses that minimize CO_2 emissions in buildings across all climatic regions are ranked as follows: $x_{env,\ electricity} > x_{env,\ fuel\ oil} > x_{env,\ natural\ gas}$.

For instance, when considering the total costs and CO_2 emissions at the optimal insulation thickness for the building's annual energy requirements in Zone I, it is calculated that when natural gas is selected as the heating source and 4.7 cm insulation is installed, the total cost is obtained as 18.82 USD/m^2, when electricity is selected and 6.5 cm insulation is installed, the total cost is obtained as 23.45 USD/m^2, and when fuel oil is selected and 5.9 cm insulation is installed, the total cost is obtained as 22.21 USD/m^2. When examining CO_2 emissions, it is found that with 17.4 cm insulation and natural gas, the CO_2 emission is 2.61 kg/m^2; with 23.1 cm insulation and electricity, it's 3.41 kg/m^2; and with 19.4 cm insulation and fuel oil, it's 2.90 kg/m^2.

When these values are examined, it is seen that, both financially and environmentally, using natural gas as a heating source in buildings can be an ideal solution for insulation applications as it provides the lowest total cost and CO_2 emissions in the same scenarios. In terms of financial and environmental suitability, heating sources that enable minimum total cost and CO_2 emission can be sorted as follows: Natural Gas > Fuel Oil > Electricity.

Table 6 presents the optimum insulation thicknesses that minimize the total cost and CO_2 emissions for different insulation materials, separately When examined in terms of cost, the conductivity and price of the insulation material are essential factors on the optimum insulation thickness (see Table 3). In buildings across all climatic regions, the order of insulation thicknesses that minimize the total costs for heating and annual energy needs with various insulation material is as follows: $x_{cost,\ EPS} > x_{cost,MW} > x_{cost,XPS} > x_{cost,PUR}$.

The density and emission factor of the insulation material affect CO_2 emissions (see Table 3). It is understood from Table 6 that, in buildings across all climatic regions, the order of insulation thicknesses that minimize the CO_2 emissions for heating and annual energy needs with diverse insulation material is as follows: $x_{cost,MW} > x_{cost,EPS} > x_{cost,XPS} > x_{cost,PUR}$.

This time, as an example, the total costs and CO_2 emissions that would occur at optimum insulation thicknesses for the annual energy needs of the building in Zone II are examined. When EPS with 4.6 cm thickness is used as the insulation material, the total cost is calculated to be 19.61 USD/m^2, when XPS with 3.3 cm thickness is applied, the total cost is determined as 21.72 USD/m^2, when 3.8 cm of MW is used, the total cost is determined as 21.33 USD/m^2, and when 2.6 cm of PUR is used, the total cost is obtained as 22.95 USD/m^2. When CO_2 amounts are calculated in a similar manner, it is observed that for EPS with 18 cm thickness, the CO_2 emission is 2.69 kg/m^2; for XPS with 13.7 cm thickness, it's 3.43 kg/m^2; for MW with 19.9 cm thickness, it's 2.71 kg/m^2; and for PUR with 10.4 cm thickness, it's 4.14 kg/m^2.

These results show that the minimum total cost and lowest CO_2 emissions cannot be achieved when using PUR, which has the least thickness among the optimal insulation thicknesses in Table 6. It is observable that, both financially and environmentally, using EPS as an insulation material can be an ideal solution for insulation applications as it provides the lowest total cost and CO_2 emissions in the same scenarios. In terms of financial and environmental suitability, insulation materials that enable minimum total cost and CO_2 emission, can be sorted as follows: EPS > MW > XPS > PUR.

In Table 7 presents an evaluation focusing solely on the reduction in energy costs, accordingly energy cost savings (ECS), payback periods and, saving rates are computed. According to the results obtained, if minimum payback period is selected as the objective function, electricity stands out as the most suitable heating source (see Table 7). In terms of financial and environmental suitability, heating sources that enable minimum payback periods, can be sorted as follows: Electricity > Fuel Oil > Natural Gas.

In the scenario where the minimum payback period is the objective function, if the insulation is applied with the aim of minimum cost, it is seen that EPS is the most suitable insulation material since its payback period is the shortest (see Table 8). In terms of financial suitability, insulation materials that enable minimum payback periods, can be sorted as follows: EPS > MW > XPS > PUR. Besides that, according to the results obtained, although EPS still stands out as the most suitable insulation material in terms of environmental suitability, general ranking has changed as follows: EPS > XPS > PUR > MW.

When examined on a regional basis, it is seen that the building located in Zone IV has the shortest payback period. It is determined that the investment pays for itself in a shorter time if the insulation is applied with the aim of minimum cost. Besides, in case the insulation is applied with the aim of minimum CO_2 emission, it is observed that more energy is saved since thicker insulation is applied, but the payback period is longer.

In Fig. 9 Carbon Saving (*CS*) over the system's lifetime and Carbon Savings Rate (*CSR*) are presented for different heating sources. In this analysis, when a certain heating source is selected, the difference between the amount of CO_2 the building emits to the environment when it

Table 7
Annual energy cost saving, payback period and saving rate for different heating sources.

	Natural Gas			Electricity			Fuel Oil		
	ECS (USD/m^2)	Payback (Year)	Saving Rate	ECS (USD/m^2)	Payback (Year)	Saving Rate	ECS (USD/m^2)	Payback (Year)	Saving Rate
Zone I for Cost	14.20	9.0	67%	24.54	5.9	73%	20.73	6.7	71%
Zone I for CO_2	18.75	13.6	88%	30.33	10.3	91%	25.87	10.6	89%
Zone II for Cost	13.62	9.3	66%	35.39	4.5	77%	27.31	5.5	75%
Zone II for CO_2	18.21	14.3	88%	42.29	8.6	92%	33.05	9.1	90%
Zone III for Cost	21.37	6.6	72%	61.88	3.1	82%	46.87	3.7	80%
Zone III for CO_2	26.94	11.4	91%	70.76	6.4	94%	54.13	6.7	92%
Zone IV for Cost	24.38	6.0	73%	76.07	2.7	84%	56.93	3.2	82%
Zone IV for CO_2	30.31	10.7	91%	85.84	5.8	95%	64.83	6.0	93%

Table 8
Annual energy cost saving, payback period and saving rate for different insulation materials.

	Expanded Polystyrene (EPS)			Extruded Polystyrene (XPS)		
	ECS (USD/m^2)	Payback (Year)	Saving Rate	ECS (USD/m^2)	Payback (Year)	Saving Rate
Zone I for Cost	14.20	9.0	67%	12.48	10.5	59%
Zone I for CO_2	18.75	13.6	88%	18.00	15.5	85%
Zone II for Cost	13.62	9.3	66%	11.93	10.9	58%
Zone II for CO_2	18.21	14.3	88%	17.50	16.3	85%
Zone III for Cost	21.37	6.6	72%	19.34	7.6	65%
Zone III for CO_2	26.94	11.4	91%	26.10	13.0	88%
Zone IV for Cost	24.38	6.0	73%	22.24	6.9	67%
Zone IV for CO_2	30.31	10.7	91%	29.43	12.3	89%
	Mineral Wool (MW)			**Polyurethane Foam (PUR)**		
	ECS (USD/m^2)	Payback (Year)	Saving Rate	ECS (USD/m^2)	Payback (Year)	Saving Rate
Zone I for Cost	12.77	10.3	60%	11.26	11.8	53%
Zone I for CO_2	18.74	17.6	88%	17.23	16.3	81%
Zone II for Cost	12.21	10.6	59%	10.73	12.3	52%
Zone II for CO_2	18.20	18.6	88%	16.78	17.2	81%
Zone III for Cost	19.67	7.5	66%	17.89	8.5	60%
Zone III for CO_2	26.92	15.0	91%	25.26	13.7	85%
Zone IV for Cost	22.59	6.7	68%	20.70	7.6	62%
Zone IV for CO_2	30.29	14.2	91%	28.55	12.9	86%

is uninsulated and the amount of CO_2 it emits to the environment when the building is insulated at the optimum thickness is presented. The graph makes it apparent that while electricity offers significant carbon savings, natural gas has lower carbon savings for every climatic zone.

Similarly, (*CS*) and (*CSR*) are determined for diverse insulating materials as shown in Fig. 10. According to the graph, EPS demonstrates the highest carbon savings rate, while PUR exhibits the lowest carbon savings rate across all climatic zones. In addition, it is evident from the Figs. 9 and 10, Zone IV is determined to be the region with the highest CO_2 emission reduction and the highest *CSR*.

4. Conclusion

It is observed from this study that, from both a financial and environmental perspective, the utilization of natural gas as a heating source and EPS as an insulation material in buildings emerges as an optimal choice for insulation applications, offering the dual benefits of the lowest total cost and CO2 emissions across various scenarios.

When the insulation investment is examined according to its payback period, electricity stands out as the most suitable heating source in terms of financial and environmental suitability. Additionally, EPS emerges as the most suitable insulation material due to its shortest payback period when considering financial and environmental suitability.

On a regional basis, it becomes evident that the building situated in the coldest climatic zone experiences the shortest payback period. The saving rate which ranges from 53% to 93% depends on heating source, insulation material and location, gradually increases as it is moved from the hot climate region to the cold climate region.

According to the results obtained in the study, it is clearly demonstrated that purpose of the building's use (summer house, winter house or all-season house) is a highly influential factor to decide the insulation thickness to be applied, especially for the cold climate zones.

As a result, within the scope of the factors discussed in this study, it can be said that using EPS as an insulation material and natural gas as a heating source are the most ideal solutions in terms of financial and environmental perspectives. The situation that minimizes the payback period is achieved when EPS is selected as the insulation material and electricity is selected as the heating source, in case applying insulation taking into account both environmental and financial purposes. In addition, it can be said that the knee point approach is a method that can be used to give the most ideal result in insulation applications where there are two different objective functions to be optimized simultaneously. Lastly, the equations that give the environmentally optimum insulation thicknesses for minimizing the amount of CO_2 released into the atmosphere have been derived and presented to the researchers.

CRediT authorship contribution statement

A.S. Canbolat: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

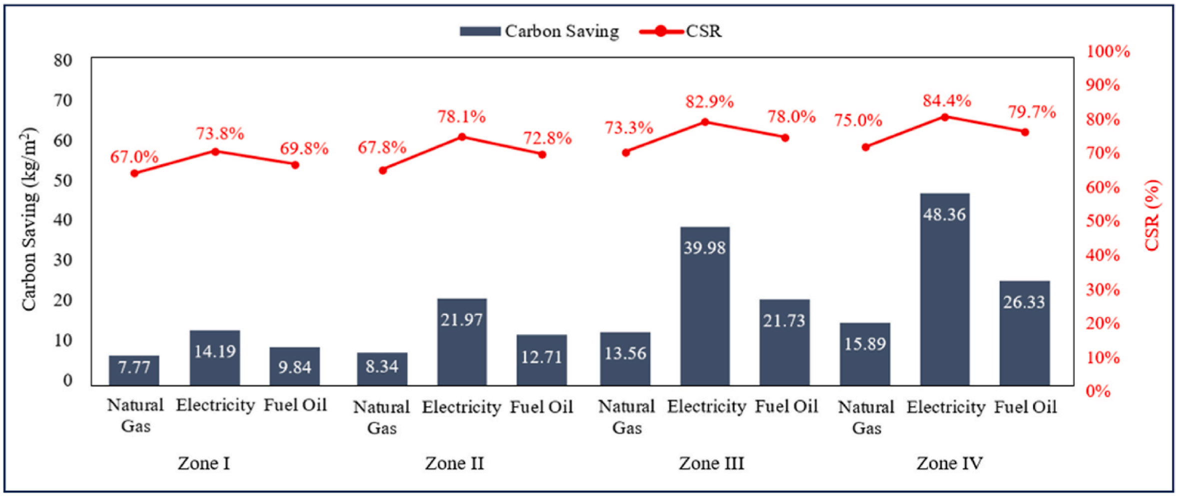

Fig. 9. Variation of carbon saving and CSR for various heating sources.

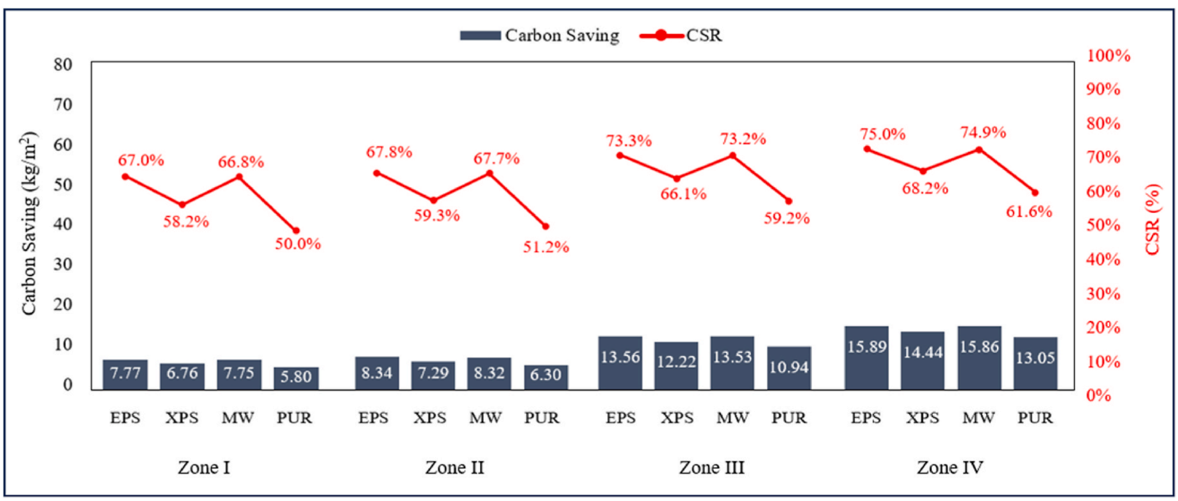

Fig. 10. Variation of carbon saving and CSR for various insulation materials.

Data availability

No data was used for the research described in the article.

References

Açıkkalp, E., Kandemir, S.Y., 2019. A method for determining optimum insulation thickness: combined economic and environmental method. Therm. Sci. Eng. Prog. 11, 249–253. https://doi.org/10.1016/j.tsep.2019.04.004.

Akan, A.E., 2021. Determination and modeling of optimum insulation thickness for thermal insulation of buildings in all city centers of Turkey. In: International Journal of Thermophysics. Springer US. https://doi.org/10.1007/s10765-021-02799-9.

Akan, A.P., Akan, A.E., 2022. Modeling of CO2 emissions via optimum insulation thickness of residential buildings. Clean Technol. Environ. Policy 24, 949–967. https://doi.org/10.1007/s10098-021-02233-6.

Al-Khawaja, M.J., 2004. Determination and selecting the optimum thickness of insulation for buildings in hot countries by accounting for solar radiation. Appl. Therm. Eng. 24, 2601–2610. https://doi.org/10.1016/j.applthermaleng.2004.03.019.

Albak, E.İ., 2021. Crashworthiness design for multi-cell circumferentially corrugated thin-walled tubes with sub-sections under multiple loading conditions. Thin-Walled Struct. 164 https://doi.org/10.1016/j.tws.2021.107886.

Alsayed, M.F., Tayeh, R.A., 2019. Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings. J. Build. Eng. 22, 101–112. https://doi.org/10.1016/j.jobe.2018.11.018.

Altun, A.F., 2022. Determination of optimum building envelope parameters of a room concerning window-to-wall ratio, orientation, insulation thickness and window type. Buildings 12. https://doi.org/10.3390/buildings12030383.

Anastaselos, D., Giama, E., Papadopoulos, A.M., 2009. An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. Energy Build. 41, 1165–1171. https://doi.org/10.1016/j.enbuild.2009.06.003.

Arslanoglu, N., Yigit, A., 2017. Investigation of efficient parameters on optimum insulation thickness based on theoretical-Taguchi combined method. Environ. Prog. Sustain. Energy 36, 1824–1831. https://doi.org/10.1002/ep.12628.

Axaopoulos, I., Axaopoulos, P., Gelegenis, J., Fylladitakis, E.D., 2019a. Optimum external wall insulation thickness considering the annual CO2 emissions. J. Build. Phys. 42, 527–544. https://doi.org/10.1177/1744259118774711.

Axaopoulos, I., Axaopoulos, P., Gelegenis, J., Fylladitakis, E.D., 2019b. Optimum external wall insulation thickness considering the annual CO2 emissions. J. Build. Phys. 42, 527–544. https://doi.org/10.1177/1744259118774711.

Axaopoulos, I., Axaopoulos, P., Panayiotou, G., Kalogirou, S., Gelegenis, J., 2015. Optimal economic thickness of various insulation materials for different orientations of external walls considering the wind characteristics. Energy 90, 939–952. https://doi.org/10.1016/j.energy.2015.07.125.

Aydin, N., Biyikoğlu, A., 2021. Determination of optimum insulation thickness by life cycle cost analysis for residential buildings in Turkey. Sci. Technol. Built Environ. 27, 2–13. https://doi.org/10.1080/23744731.2020.1776066.

Bektas Ekici, B., Aytac Gulten, A., Aksoy, U.T., 2012. A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey. Appl. Energy 92, 211–217. https://doi.org/10.1016/j.apenergy.2011.10.008.

Bolattürk, A., 2008. Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. Build. Environ. 43, 1055–1064. https://doi.org/10.1016/j.buildenv.2007.02.014.

Bolattürk, A., 2006. Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. Appl. Therm. Eng. 26, 1301–1309. https://doi.org/10.1016/j.applthermaleng.2005.10.019.

Büyükalaca, O., Bulut, H., Yılmaz, T., 2001. Analysis of variable-base heating and cooling degree-days for Turkey. Appl. Energy 69, 269–283. https://doi.org/10.1016/S0306-2619(01)00017-4.

Canbolat, A., Bademlioglu, A., Saka, K., Kaynakli, O., 2019. Investigation of parameters affecting the optimum thermal insulation thickness for buildings in hot and cold climates. Therm. Sci. 68. https://doi.org/10.2298/TSCI181105068C.

Carreras, J., Boer, D., Guillén-Gosálbez, G., Cabeza, L.F., Medrano, M., Jiménez, L., 2015. Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact. Energy Build. 88, 335–346. https://doi.org/10.1016/j.enbuild.2014.12.007.

Cengel, Y., 2002. Heat Transfer: A Practical Approach, second ed. McGraw-Hill, New York.

Central Bank of Türkiye. Available online. https://www.tcmb.gov.tr. (Accessed 12 November 2023).

Daouas, N., 2011. A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads. Appl. Energy 88, 156–164. https://doi.org/10.1016/j.apenergy.2010.07.030.

Daouas, N., Hassen, Z., Aissia, H. Ben, 2010. Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. Appl. Therm. Eng. 30, 319–326. https://doi.org/10.1016/j.applthermaleng.2009.09.009.

Djuric, N., Novakovic, V., Holst, J., Mitrovic, Z., 2007. Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools. Energy Build. 39, 471–477. https://doi.org/10.1016/j.enbuild.2006.08.009.

Doi, R., 2022. Are new residential areas cooler than older ones? Emerg. Sci. J. 6, 1346–1357. https://doi.org/10.28991/ESJ-2022-06-06-08.

Dombayci, O.A., Ulu, E.Y., Guven, S., Atalay, O., Ozturk, H.K., 2020. Determination of optimum insulation thickness for building external walls with different insulation materials using environmental impact. Assessment. Therm. Sci. 24, 303–311. https://doi.org/10.2298/TSCI180903010D.

Duan, S., Tao, Y., Han, X., Yang, X., Hou, S., Hu, Z., 2014. Investigation on structure optimization of crashworthiness of fiber reinforced polymers materials. Composites, Part B 60, 471–478. https://doi.org/10.1016/j.compositesb.2013.12.062.

Duffie, J.A., Beckman, W.A., 1991. Solar Engineering of Thermal Processes. Wiley, New York, USA.

Guven, S., 2019. Calculation of optimum insulation thickness of external walls in residential buildings by using exergetic life cycle cost assessment method: case study for Turkey. Environ. Prog. Sustain. Energy 38, 1–10. https://doi.org/10.1002/ep.13232.

Harsito, C., Triyono, T., Rovianto, E., 2022. Analysis of heat potential in solar panels for thermoelectric generators using ANSYS software. Civ. Eng. J. 8, 1328–1338. https://doi.org/10.28991/CEJ-2022-08-07-02.

Huang, H., Zhou, Y., Huang, R., Wu, H., Sun, Y., Huang, G., Xu, T., 2020. Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. Sustain. Cities Soc. 52, 101840 https://doi.org/10.1016/j.scs.2019.101840.

International Energy Agency. Available online. https://www.iea.org/topics/global-energy-crisis. (Accessed 15 August 2023).

Iqbal, I., Al-Homoud, M.S., 2007. Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate. Build. Environ. 42, 2166–2177. https://doi.org/10.1016/j.buildenv.2006.04.011.

Jraida, K., Farchi, A., Mounir, B., Mounir, I., 2017. A study on the optimum insulation thicknesses of building walls with respect to different zones in Morocco. Int. J. Ambient Energy 38, 550–555. https://doi.org/10.1080/01430750.2016.1155490.

Kallioğlu, M.A., Ercan, U., Avcı, A.S., Fidan, C., Karakaya, H., 2020. Empirical modeling between degree days and optimum insulation thickness for external wall. Energy Sources, Part A Recover. Util. Environ. Eff. 42, 1314–1334. https://doi.org/10.1080/15567036.2019.1651797.

Kaynakli, O., 2011. Parametric investigation of optimum thermal insulation thickness for external walls. Energies 4, 913–927. https://doi.org/10.3390/en4060913.

Kaynakli, O., 2008. A study on residential heating energy requirement and optimum insulation thickness. Renew. Energy 33, 1164–1172. https://doi.org/10.1016/j.renene.2007.07.001.

Kaynakli, Ö., 2013. Optimum thermal insulation thicknesses and payback periods for building walls in Turkey. J. Therm. Sci. Technol. 33, 45–55.

Kaynakli, Ö., Kaynakli, F., 2016. Determination of optimum thermal insulation thicknesses for external walls considering the heating, cooling and annual energy requirements. Uludağ Univ. J. Fac. Eng. 21, 229. https://doi.org/10.17482/uujfe.27323.

Kilic, A., Ozturk, A., 1983. Solar Energy. Kipas Distribution Inc., Istanbul in Turkish.

Kon, O., Caner, İ., 2022. The effect of external wall insulation on mold and moisture on the buildings. Buildings 12. https://doi.org/10.3390/buildings12050521.

Kurekci, N.A., 2016. Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers. Energy Build. 118, 197–213. https://doi.org/10.1016/j.enbuild.2016.03.004.

Li, F., Sun, G., Huang, X., Rong, J., Li, Q., 2015. Multiobjective robust optimization for crashworthiness design of foam filled thin-walled structures with random and interval uncertainties. Eng. Struct. 88, 111–124. https://doi.org/10.1016/j.engstruct.2015.01.023.

Masoso, O.T., Grobler, L.J., 2008. A new and innovative look at anti-insulation behaviour in building energy consumption. Energy Build. 40, 1889–1894. https://doi.org/10.1016/j.enbuild.2008.04.013.

Minne, E., Wingrove, K., Crittenden, J.C., 2015. Influence of climate on the environmental and economic life cycle assessments of window options in the United States. Energy Build. 102, 293–306. https://doi.org/10.1016/j.enbuild.2015.05.039.

Nistratov, A.V., Klimenko, N.N., Pustynnikov, I.V., Vu, L.K., 2022. Thermal regeneration and reuse of carbon and glass fibers from waste composites. Emerg. Sci. J. 6, 967–984. https://doi.org/10.28991/ESJ-2022-06-05-04.

Ozbek, K., Gelis, K., Ozyurt, O., 2022. Optimization of external wall insulation thickness in buildings using response surface methodology. Int. J. Energy Environ. Eng. 13, 1367–1381. https://doi.org/10.1007/s40095-022-00490-9.

Ozel, M., 2013. Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate. Energy Convers. Manag. 66, 106–114. https://doi.org/10.1016/j.enconman.2012.10.002.

Ozel, M., 2012a. The influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness. Renew. Energy 39, 347–355. https://doi.org/10.1016/j.renene.2011.08.039.

Ozel, M., 2012b. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. Energy Build. 49, 552–559. https://doi.org/10.1016/j.enbuild.2012.03.002.

Ozel, M., 2011. Thermal performance and optimum insulation thickness of building walls with different structure materials. Appl. Therm. Eng. 31, 3854–3863. https://doi.org/10.1016/j.applthermaleng.2011.07.033.

Ozel, M., Pihtili, K., 2007. Optimum location and distribution of insulation layers on building walls with various orientations. Build. Environ. 42, 3051–3059. https://doi.org/10.1016/j.buildenv.2006.07.025.

Peng, Y., Wang, S., Yao, S., Xu, P., 2017. Crashworthiness analysis and optimization of a cutting-style energy absorbing structure for subway vehicles. Thin-Walled Struct. 120, 225–235. https://doi.org/10.1016/j.tws.2017.09.006.

Radhi, H., 2009. Can envelope codes reduce electricity and CO2 emissions in different types of buildings in the hot climate of Bahrain? Energy 34, 205–215. https://doi.org/10.1016/j.energy.2008.12.006.

Robert, A., Kummert, M., 2012. Designing net-zero energy buildings for the future climate, not for the past. Build. Environ. 55, 150–158. https://doi.org/10.1016/j.buildenv.2011.12.014.

Su, X., Luo, Z., Li, Y., Huang, C., 2016. Life cycle inventory comparison of different building insulation materials and uncertainty analysis. J. Clean. Prod. 112, 275–281. https://doi.org/10.1016/j.jclepro.2015.08.113.

Thermal Insulation Requirements for Buildings, 2013. TS 825. Turkish Standards Institution.

Tiris, M., Tiris, Ç., Türe, I.E., 1995. Diffuse solar radiation correlations: applications to Turkey and Australia. Energy 20, 745–749. https://doi.org/10.1016/0360-5442(95)00022-9.

Tran, T., Hou, S., Han, X., Tan, W., Nguyen, N., 2014. Theoretical prediction and crashworthiness optimization of multi-cell triangular tubes. Thin-Walled Struct. 82, 183–195. https://doi.org/10.1016/j.tws.2014.03.019.

Turkish Statistical Institute. Available online: www.tuik.gov.tr. (Accessed 12 November 2023).

Ucar, A., Balo, F., 2010. Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls. Renew. Energy 35, 88–94. https://doi.org/10.1016/j.renene.2009.07.009.

Ucar, A., Balo, F., 2009. Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey. Appl. Energy 86, 730–736. https://doi.org/10.1016/j.apenergy.2008.09.015.

Yiğit, A., Atmaca, İ., 2010. Solar Energy. Alfa Aktüel, Bursa, Turkey in Turkish.

Yu, J., Yang, C., Tian, L., Liao, D., 2009. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. Appl. Energy 86, 2520–2529. https://doi.org/10.1016/j.apenergy.2009.03.010.

Yuan, J., Farnham, C., Emura, K., 2017. Optimum insulation thickness for building exterior walls in 32 regions of China to save energy and reduce CO2 Emissions. Sustain. Times 9. https://doi.org/10.3390/su9101711.