Isı Bilimi ve Tekniği Dergisi, 44, 1, 1-15, 2024
J. of Thermal Science and Technology
©2024 TIBTD Printed in Turkey
ISSN 1300-3615
e-ISSN 2667-7725
https://doi.org/10.47480/isibted.1493675

THE ANNUAL CO_2 EMISSIONS AND ENERGY COSTS OF DIFFERENT EXTERIOR WALL STRUCTURES IN RESIDENTIAL BUILDINGS IN TÜRKİYE

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(Geliş Tarihi: 13.01.2023, Kabul Tarihi: 21.11.2023)

Abstract: Carbon dioxide emissions are one of the most important causes of global climate change. It is accepted in the world today that the world urgently needs to reduce carbon dioxide emissions in order to avoid the worst impacts of climate change. In this study, the optimum thickness of each insulation material is determined depending on the available costs and the total annual CO_2 emissions of insulation materials for building external walls with different structure in the selected cities from different climate regions of Turkey. The different wall types insulated with four different insulation materials are presented. The results indicate that the optimum insulation thickness varies from 2.5 to 13 cm and is different for each wall type and insulation material. The total annual CO2 emission per unit area of the wall varies between 3.32 and 10.32 kg CO_2/m^2 depending on the insulation material and wall type.
Keywords: CO_2 emissions; life cycle cost; Optimum insulation thickness; Eco-efficiency

TÜRKİYE'DE KONUTLARDA FARKLI DIŞ DUVAR YAPILARININ YILLIK CO_2 EMİSYONLARI VE ENERJİ MALİYETLERİ

Özet: Karbondioksit emisyonları, küresel iklim değişikliğinin en önemli nedenlerinden biridir. İklim değişikliğinin en kötü etkilerinden kaçınmak için dünyanın acilen karbondioksit emisyonlarını azaltması gerektiği bugün dünyada kabul görmektedir. Bu çalışmada, her bir yalıtım malzemesinin optimum kalınlığı, Türkiye'nin farklı iklim bölgelerinden seçilen şehirlerde farklı yapıya sahip dış duvarlar için yalıtım malzemelerinin mevcut maliyetlerine ve yıllık toplam CO2 emisyonlarına bağlı olarak belirlenmiştir. Dört farklı yalıtım malzemesi ile yalıtılmış farklı duvar tipleri sunulmaktadır. Sonuçlar, optimum yalıtım kalınlığının 2.5 ile 13 cm arasında değiştiğini ve her duvar tipi ve yalıtım malzemesi için farklı olduğunu göstermektedir. Duvarın birim alanı başına yıllık toplam CO_2 emisyonu, yalıtım malzemesine ve duvar tipine bağlı olarak 3.32 ile 10.32 kg CO_2/m^2 arasında değişmektedir.
Anahtar Kelimeler: CO_2 emisyonları; Yaşam döngüsü maliyeti; Optimum yalıtım kalınlığı; Eko-verimlilik

NOMENCLATURE

C_A	yearly energy cost ($/m^2 year)
C_i	unit cost of insulation material ($/m^3)
d	discount rate (%)
HDD	heating degree days (ºC-days)
H_u	lower calorific value of fuel (J/kg)
i	inflation rate (%)
k_{ins}	heat cond. coeff. of ins. material (W/m K)
N	lifetime (years)
N_p	payback period (years)
R_w	total thermal resistance of the wall (m^2 K/W)
S	savings ($/m^2)
T_b	base temperature (ºC)
T_i	inside air temperature (ºC)
T_o	average daily temperature (ºC)
U	total heat transfer coefficient (W/m^2 K)
q	annual heat loss from wall (W/m^2)
Q_H	annual heating load per unit area (kWh/m^2)
Q_C	annual cooling load per unit area (kWh/m^2)

INTRODUCTION

Buildings play an important role in consumption of energy all over the world. The annual global CO_2 emissions generated by buildings are nearly 40%. The building operations are responsible from 28% of those total emissions annually, while building materials and construction (typically referred to as embodied carbon) are responsible for an additional 11% of those total emissions annually (Global ABC Global Status Report, 2018).

The recent works towards energy-saving design is not only in conditions of providing lower U-values, but also in the improving and use of natural and local insulation materials. In last years, the areas of thermal conservation in buildings are more concentrating on environmental properties. Measures to prevent environmental pollution are not only limited to energy savings (Stephan, Crawford and Myttenaere 2012). The optimum insulation thickness is determined by some researchers

(Nematchoua et al.2017; Kayfeci, Keçebas and Gedik 2013; Kurekci 2016; Çomaklı and Yüksel 2003; Dombaycı, Gölcü and Pancar 2006; Bolattürk 2006; Akan 2021).

The total CO_2 emissions of a building consist of operational and embodied emissions. Operational CO_2 emissions are emissions from the use of a building's heating and cooling system. Embodied carbon generally refers to the carbon dioxide (CO_2) emissions associated with the construction and material life throughout a building whole life span. Özel et al. (2015) determined the optimum insulation thickness using the environmental and life cycle cost analyses. They calculated the fuel consumption, the CO_2 emission and the environmental impacts of the system related to entransy loss. Gaarder et al. (2023) analyzed the influence of the energy emission factor and future climate change on the optimal insulation thickness. They used three independent models for case studies in Greenland and Norway. Jie et al. (2018) determined the optimum insulation thickness based on primary energy consumption, global cost and pollutant emissions and they analyzed four heat and cold sources for a case study. Akan and Akan (2022) determined CO_2 emissions based on the energy savings through the thermal insulation applied to the external walls of the buildings for eighty-one different zones using four diverse thermal insulation materials. They found that CO_2 emissions decreased by approximately 66-76% in the heating season and by 46-69% in the cooling season in buildings with thermal insulation. The environmental problems like global warming, acid rain, air pollution, urban sprawl, waste disposal, ozone layer depletion, water pollution, climate change affect all the human, animal and nation on world. The Life Cycle Assessment (LCA) methodology is used as a tool to assess potential environmental impacts of products along their life cycle. LCA is applied in many researches to evaluate the impact of different insulation materials (Braulio-Gonzalo 2017; Lazzarin, Busato and Castellotti 2008; Cabeza et al. 2014; Ferrández-García, Ibánez-Forés and Bovea 2016; Axaopoulos et al. 2019; Atmaca 2016; Huang et al. 2020).

As energy consumption in developing countries such as Turkey increase, environmental pollution and greenhouse gas emissions are increasing every year. Residential buildings are very important in reducing energy needs and greenhouse gas emissions. In this study, the optimum thickness of each insulation material is determined depending on the available costs and the total annual CO_2 emissions of insulation materials for residential building external walls with different structure in the selected different cities of Turkey. Firstly, the optimum value of Insulation thickness is determined by maximizing the net energy savings for heating, cooling and both heating and cooling found by the Life Cycle Costing (LCC) method. Secondly, the optimum insulation thickness is found by minimizing the total annual CO_2 emissions. In this study, the four wall types commonly used in Turkey were selected. The same methodology can be repeated for other wall types and different climatic conditions.

METHODOLOGY

The methodology is applied to residential building external walls with different structure as a case study by comparing four insulation materials. Methodological framework is presented in Fig.1.

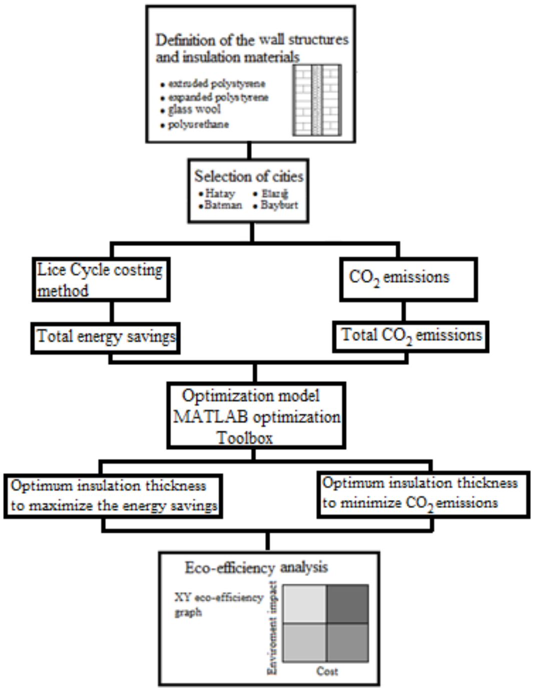


Fig.1. Methodological framework.

Description of the building and wall structures

The gross area of studied building is about 140 m^2 per story, three stories, and two dwellings per story. Each dwelling unit has three bedrooms and a living room and a bathroom. Fig.2 presents the detailed floor plan of building.

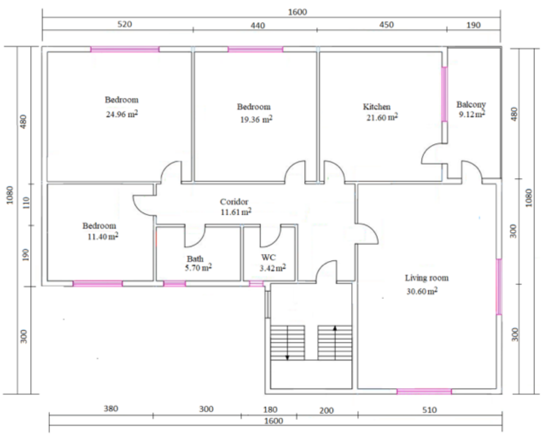
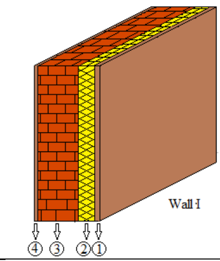
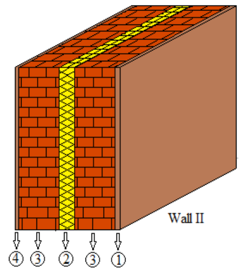
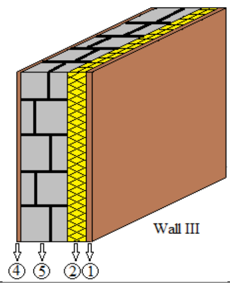
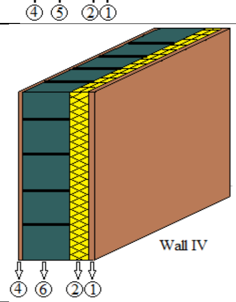


Fig.2. The floor plan of the studied building

The heat losses to environment from the external walls of buildings is occurred. Wall 1 consist of 2 cm inner plaster, 13 cm brick, insulation material and 2 cm external plaster. Wall 2 is a sandwich wall which has a compound structure consisting of 2 cm inner plaster, 10 cm each of two brick layers and 2 cm external plaster. The materials used in Wall 3 are inner plaster, hollow concrete block, insulation and external plaster. In this wall configuration, the assumed total thickness for concrete is 20 cm, while the thickness for interior plaster is 2 cm and for exterior plaster is 2 cm. Wall 4 consist of 2 cm inner plaster, 30 cm CSEB (Compressed Stabilised Earth Block), insulation material and 2 cm external plaster. In this working, polyurethane (PU), extruded polystyrene (XPS), glass wool (GW) and expanded polystyrene (EPS) are selected as insulation materials. The physical properties of each material used in the wall structures are given in Table 1.

Table 1. Thermal characteristics of wall structures

Wall type	Thickness (m)	Thermal conductivity (W/mK)	Resistance (m^2 K/W)	Insulation cost (\$/m^3)	Cross-sectional views of the investigated external wall structures.
Wall 1 4-Interior plaster *(TS EN 998-1)* 3-Brick *(TS EN 771-1)* 2-Insulation 1-External plaster *(TS EN 998-1)*	 0.02 0.13 * 0.02	 0.87 0.45 0.87	0.335		
Wall 2 4-Interior plaster 3-Brick 3-Brick 2-Insulation 1-External plaster	 0.02 0.10 0.10 * 0.02	 0.87 0.45 0.45 0.87	0.490		
Wall 3 4-Interior plaster 5-Hollow concrete block *(TS EN 771-3)* 2-Insulation 1-External plaster	 0.02 0.20 * 0.02	 0.87 0.60 0.87	0.379		
Wall 4 4-Interior plaster 6-CSEB 2-Insulation 1-External plaster	 0.02 0.30 * 0.02	 0.87 0.88 0.87	0.387		
Insulation Materials Polyurethane *(TS EN 13165)* Extruded polystyrene *(TS EN 13164)* Expanded polystyrene *(TS EN 13163)* Glass wool *(TS EN 13167)*	 * * * *	 0.024 0.031 0.039 0.040		 260 180 120 75	

* The optimum thickness of insulation material which is found by the life cycle cost analysis

Table 2. The parameters used in calculations (Evin and Ucar, 2019)

Parameter	Value			
Cities	*Hatay*	*Batman*	*Elazığ*	*Bayburt*
HDD	1119	1823	2653	4149
CDD	614	763	337	8
Natural gas (Heating)				
C_F	0.332 \$/m^3			
H_u	34.526 x10^{6}J/m^3			
η_s	0.90			
f_H	0.181 kgCO_2/kWh			
Electricity (Cooling)				
C_e	0.3496 \$/kWh			
f_C	0.588 kgCO_2/kWh			
f_{ins} (CO_2 emission factor of materials (kgCO_2/kg))				
Polyurethane	3.75			
Extruded polystyrene	4.42			
Expanded polystyrene	2.35			
Glass wool	1.16			
Brick	0.246			
Plaster	0.23			
Concrete	0.170			
CSEB	51.5			
Interest rate, i (TCMB, 2022)	7.5%			
Inflation rate, d(TCMB, 2022)	64%			
Lifetime, N	10			
T_i	20°C			

Climatic zones

The degree-day method is one of the commonly used methods to estimate the amount of energy required for heating or cooling. The total number of annual heating and cooling degree-days (HDDs and CDDs) is calculated by

$$HDD = \sum_{days}(T_b - T_o)^+ \tag{1}$$

$$CDD = \sum_{days}(T_o - T_b)^+ \tag{2}$$

The plus sign above the parentheses indicates that only positive values are to be counted (Kaynakli 2012). In this study, the annual heating and cooling degree-days of studied cities are taken for base temperatures of 18 °C for heating and 22 °C for cooling. According to the updated code TS 825 Thermal Insulation Requirements for Buildings, Turkey is divided into five climatic zones in relation to their average temperature degree-days of heating (TS 825, 2013). Energy performance of the different types of buildings, the calculation method of annual heating energy demand, thermal transmittance "U" values for each region, which is defined by using the "degree day method" in TS-825, and the maximum heating demand values according to regions were described (Evin and Uçar, 2019). The heating and cooling degree-days of each region are different from each other due to their climatic characteristics. Heating degree-day values in the cities on the coast have lower values compared to cities in the eastern and inner regions. In this study, Hatay from the coastal region and Batman from the southern region were selected. Elazig and Bayburt cities with different climatic characteristics of Turkey were selected from the eastern and inner regions and optimum values of insulation thickness were found. The annual heating degree-days of Hatay in the southernmost of Turkey is 1119, while degree-days of Bayburt in the north-east of Turkey is 4149. Batman is a Turkish province southeast of Anatolia and the annual heating degree-day of its is 1823. The annual heating degree-days of Elazığ is 2653. Table 2 shows the parameters used in calculations.

Life Cycle Costing (LCC) method

The heat transfer in building walls is realized by three mechanisms of heat transfer. Firstly, the solar radiation coming to the outside surface of the building wall is absorbed by wall surface and then, the heat transfer into the wall by conduction is occurred. The heat transfer between ambient air with the outside surface of wall and also between the inside surface of the wall with indoor air are occurred by convective.

Heat transfer rate from a unit area of building wall can be found as

$$q = U(T_i - T_o) \tag{3}$$

The annual heat rate from unit area can be determined using the degree days, as given by the following equation

$$q_H = 86400\ HDD\ U \tag{4}$$

$$q_C = 86400\ CDD\ U \tag{5}$$

The total heat transfer coefficient for an insulated wall can be written by

$$U = \frac{1}{1/h_i + R_w + x_{ins}/k_{ins} + 1/h_o} \tag{6}$$

where x_{ins} is insulation material thickness (m) and k_{ins} is heat conduction coefficient of insulation material (W/m K). h_i is inner convective heat transfer coefficient (W/m^{2}K) and h_o is outer convective heat transfer coefficient (W/m^{2}K). In this study, the convective heat transfer coefficient between inner and outer surface depending on speed and direction of the wind can be evaluated as follows (Axaopoulos et al., 2015)

$$h_i = 1.31\left(T_{s,i} - T_i\right)^{1/3} \tag{7}$$

$$h_{o,ww} = 1.53v + 1.43 \tag{8}$$

$$h_{o,lw} = 0.90v + 3.28 \tag{9}$$

where v is wind speed, T_i is inside air temperature and $T_{s,i}$ is the inner surface temperature of wall. The wind speed and common direction data are received from examined weather stations in this working. It is accepted that Eq. (8) is for the east, north and west facing wall surface, when Eq. (9) is for the south facing wall surface.

The surface temperatures of wall components are calculated as follows (Ucar, 2010)

$$T_{s,i} = T_i - \frac{1}{h_i} q \tag{10}$$

$$T_1 = T_{s,i} - \frac{l_1}{k_1} q \tag{11}$$

$$T_2 = T_1 - \frac{l_2}{k_2} q \tag{12}$$

$$T_n = T_{n-1} - \frac{l_n}{k_n} q \tag{13}$$

$$T_{s,o} = T_o - \frac{1}{h_o} q \tag{14}$$

The annual energy needs for heating and cooling can be calculated by (Evin and Ucar 2019);

$$E_H = \frac{86400\ U\ HDD}{H_u\ \eta_s} \tag{15}$$

$$E_C = \frac{86400\ U\ CDD}{COP} \tag{16}$$

where η_s is efficiency of fuel and COP is coefficient of performance of the heat pump. In this working, the energy savings of each type of wall is calculated by using the life cycle cost (LCC) method. The annual heating and cooling energy cost of per unit area, C_A, is found by (Ucar and Balo, 2011)

$$C_{A,H} = \frac{86400\ U\ HDD\ C_F}{H_u\ \eta_s} \tag{17}$$

$$C_{A,C} = \frac{86400\ U\ CDD\ C_e}{COP} \tag{18}$$

where C_F is cost of fuel (\$/kg) and C_e is cost of fuel (\$/kWh). P_1 is the rate of energy savings obtained from fuel during the life cycle to the energy savings provided during the first year. P_2 is the rate of expenses during life cycle to first investment. This method facilitates economic analysis by collecting all the parameters in the economic analysis into P_1 and P_2. The P_1 and P_2 are determined by (Ertürk, 2016; Kumar et al., 2020)

$$P_1 = \frac{1}{(d-i)}\left[1 - \left(\frac{(1+i)}{(1+d)}\right)^N\right] \text{ if } i \neq d \tag{19}$$

and

$$P_1 = \frac{N}{(1+i)} \qquad \text{if } i = d$$

$$P_2 = 1 + P_1\, M_S - R_v (1+d)^{-N} \tag{20}$$

where i is inflation rate, d is discount rate, N is lifetime, M_s is the ratio of the annual maintenance and operation cost to the original first cost and R_v is the ratio of the resale value to the first cost. Since there is no maintenance and operating cost in the insulation application, the P_2 value is taken as 1.

The total insulation cost (C_{ins}) can be defined by

$$C_{ins} = C_i x_{ins} \tag{21}$$

Total heating and cooling costs are the total of the cost of insulation and the annual energy cost and they are determined as

$$C_H = C_{A,H} P_1 + P_2 C_i x_{ins} \tag{22}$$

$$C_C = C_{A,C} P_1 + P_2 C_i x_{ins} \tag{23}$$

The net energy savings for heating and cooling are determined as

$$S_H = \frac{86400\ HDD\ C_F}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) H_u \eta_s} P_1 - P_2 C_i\, x_{ins} \tag{24}$$

$$S_C = \frac{86400\ CDD\ C_e}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) COP} P_1 - P_2 C_i\, x_{ins} \tag{25}$$

$$S_T = \left(\frac{86400\ HDD\ C_F}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) H_u \eta_s} + \frac{86400\ CDD\ C_e}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) COP}\right) P_1 - P_2 C_i\, x_{ins} \tag{26}$$

The maximum value of the net energy savings for heating, cooling and both heating and cooling is the optimum value. In MATLAB optimization Toolbox, Eqs. (24)–(26) were taken as an objective function and the optimum thickness of insulation was found.

CO_2 emissions and Eco-efficiency analysis

In 2020, the largest share of CO_2 emissions in total greenhouse gas emissions was energy-related emissions with 70.2%, followed by agriculture with 14%, industrial processes and product use with 12.7%, and waste sector with 3.1% (Turkish Statistical Institute, 2020).

The annual total CO_2 emissions are divided into operational and embodied emissions. Operational CO_2 emissions are emissions from the use of the building's heating systems in winter and cooling systems in summer. The annual heating and cooling CO_2 emissions can be calculated by (Axaopoulos et al. 2019);

$$EM_{CO_2,H} = \frac{Q_H\, f_H}{\eta_s} \tag{27}$$

$$EM_{CO_2,C} = \frac{Q_C\, f_C}{COP} \tag{28}$$

where f_H is CO_2 emission factor for thermal energy production from fuel ($kgCO_2/kWh$) and f_C is CO_2 emission factor resulting from the electricity ($kgCO_2/kWh$). Annual embodied CO_2 emissions are emissions due to manufacture, transportation and installation procedures of the insulation material. The annual embodied CO_2 emissions of insulation material can be defined by

$$EM_{ins} = \frac{\rho \, x_{ins} \, f_{\text{ins}}}{N} \quad (29)$$

where f_{ins} is CO_2 embodied emission factor of insulation material ($kgCO_2/kg$) and is given in Table 2. The total annual CO_2 emissions are calculated as,

$$EM_{tot} = EM_{CO_2,H} + EM_{CO_2,C} + EM_{ins} \quad (30)$$

The optimum insulation thickness is calculated by minimize the total annual CO_2 emissions. Total annual CO_2 emissions from Eq. (30) is taken as objective function and the optimum thickness of insulation is obtained using MATLAB optimization Toolbox.

The products and processes are studied both economically and ecologically in eco-efficiency analysis. Eco-efficiency is often defined as a ratio between reduced environmental impact and increased production. (Ferrández-García et al. 2016).

RESULTS AND DISCUSSION

According to the life cycle cost analysis, the heating, cooling and total energy demands and costs for the studied building has been calculated with Eqs. (15)–(16) and Eqs. (22)–(23). Total heating demands of four wall types and insulation materials for four cities are shown in Fig. 4. Total energy demand of building in Bayburt is extremely high, while total energy demand of building for Hatay in hot region is the lowest. Total heating demand of the sandwich wall (Wall 2) insulated with glass wool (GW) is lowest compared to other wall types. The largest value of total heating load is found for the external wall (Wall1) insulated with Polyurethane (PU) at the optimum thickness.

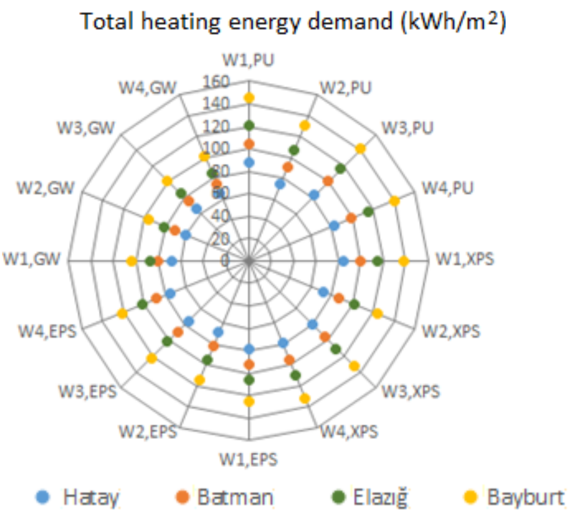


Fig. 4. Total heating energy demand of four wall types and insulation materials for four cities in Turkey.

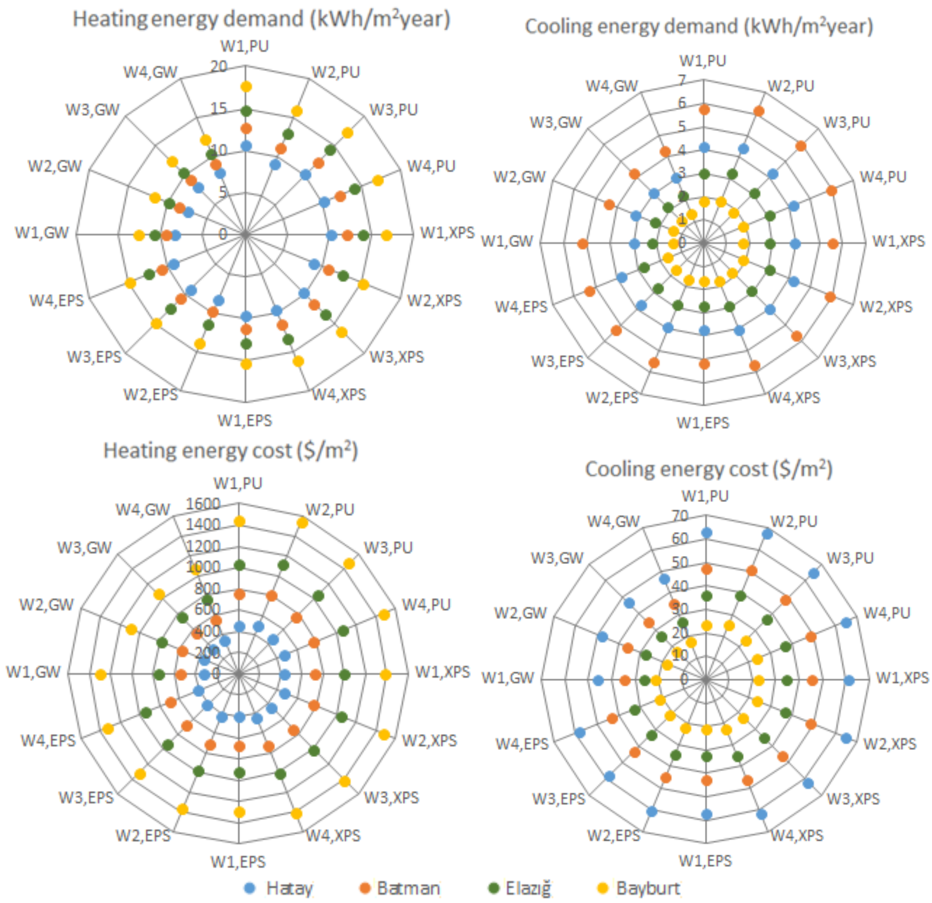


Fig. 5. Heating and cooling energy demand and cost of four wall types and insulation materials for selected cities.

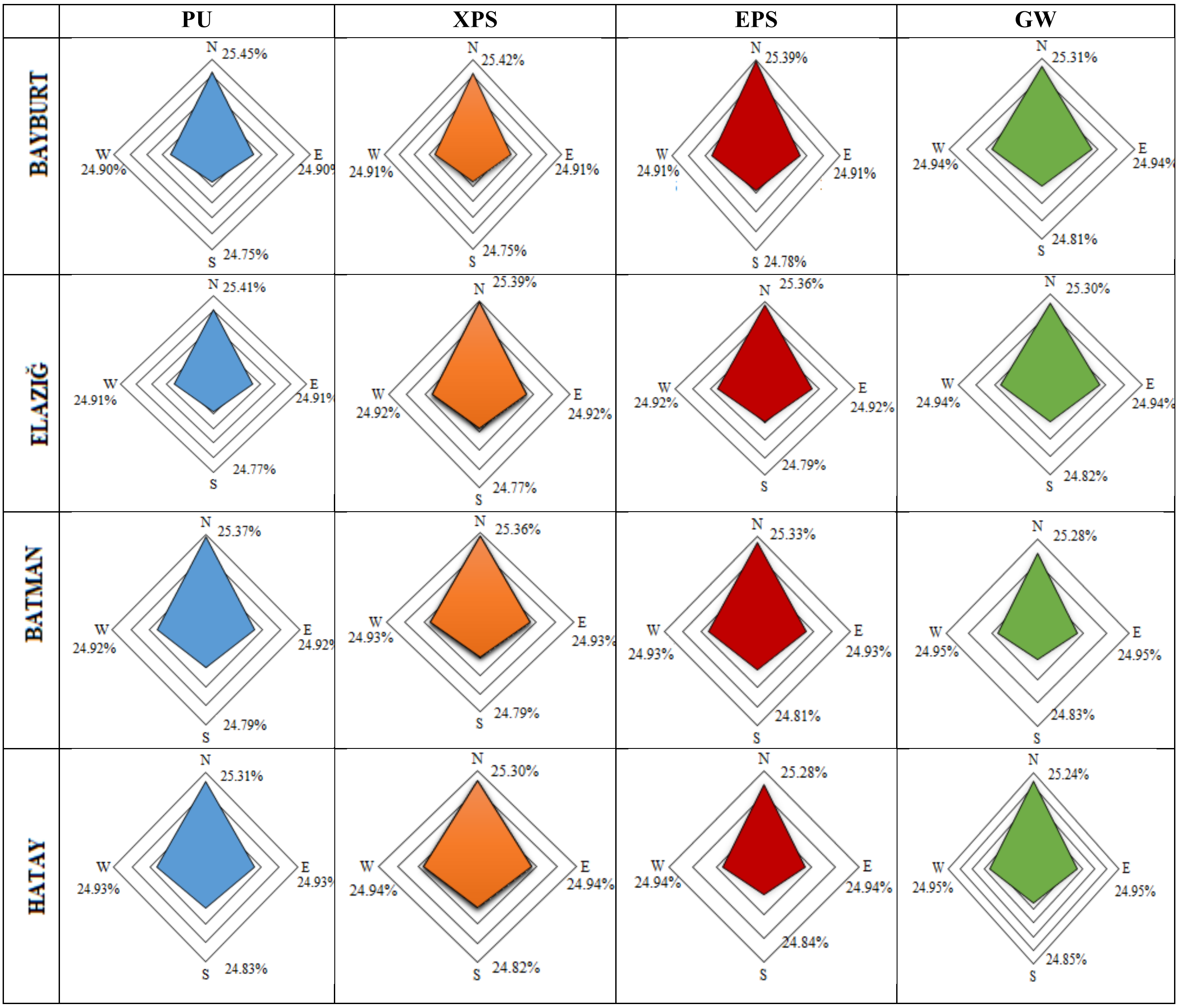


Fig.6. Each orientation percentage of the total heat transfer per unit area of external wall for different climatic conditions and insulation materials (for Wall 1)

Fig.5 shows the heating and cooling energy demand and cost found from the life cycle cost analysis for the studied building according to four cities by using natural gas as an energy source. The heating demand for the province of Bayburt (4149 ºC-days), located in the fourth degree day region of Turkey, is the highest among the three cities in the other regions. The total heating energy demand of building in Hatay is lowest, while cooling energy demand of building is the highest. The total energy costs of external walls insulated with glass wool (GW) has least among external walls insulated with other insulation materials. GW insulation material has the highest thermal conductivity coefficient among the selected insulation materials, but it also has the lowest cost.

Fig.6 shows the each orientation percentage of the total heat transfer per unit area of external wall for different climatic conditions and insulation materials (for Wall 1). The heating loss for north facing exterior surface of wall has highest percentage. The south facing exterior surface of wall has the lowest values according to other orientations for all climate conditions and wall structures, because this surface has the high solar heat gain.

Insulation thicknes versus CO_2 emissions for wall 1 type and Elazığ found are showed in Fig.7. The heat loss of external wall decreases with the insulation thickness increases. Therefore, the emissions resulting from the combustion of fuels will also decrease due to the reduction in annual fuel consumption. The total CO_2 emissions, achieved by adding these two values decreases with increase of insulation thickness until it reaches a minimum point and it increases again after a minimum value. This minimum point of total CO_2 emissions curve shows optimum insulation thickness.

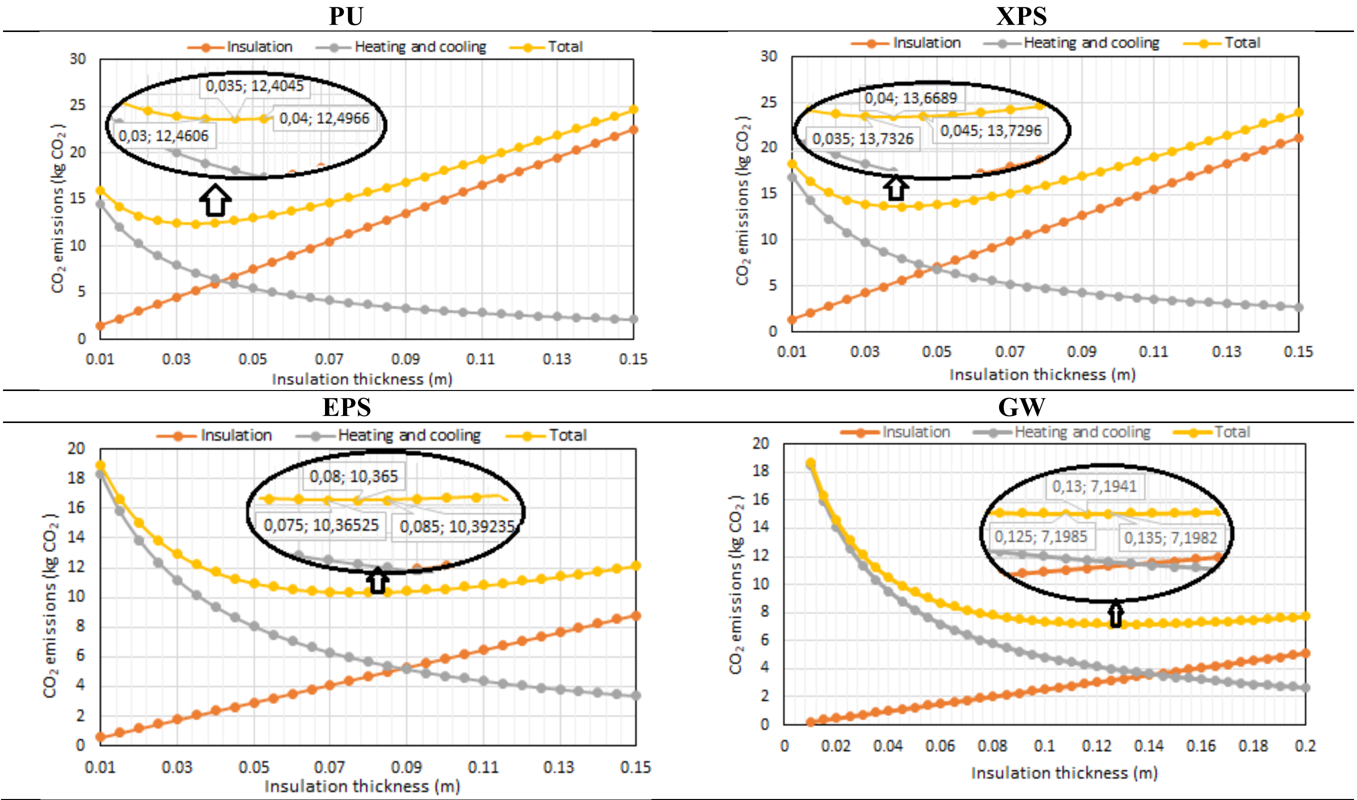


Fig.7. Insulation thicknes versus CO_2 emissions for four insulation materials and Elazığ (for wall 1 type)

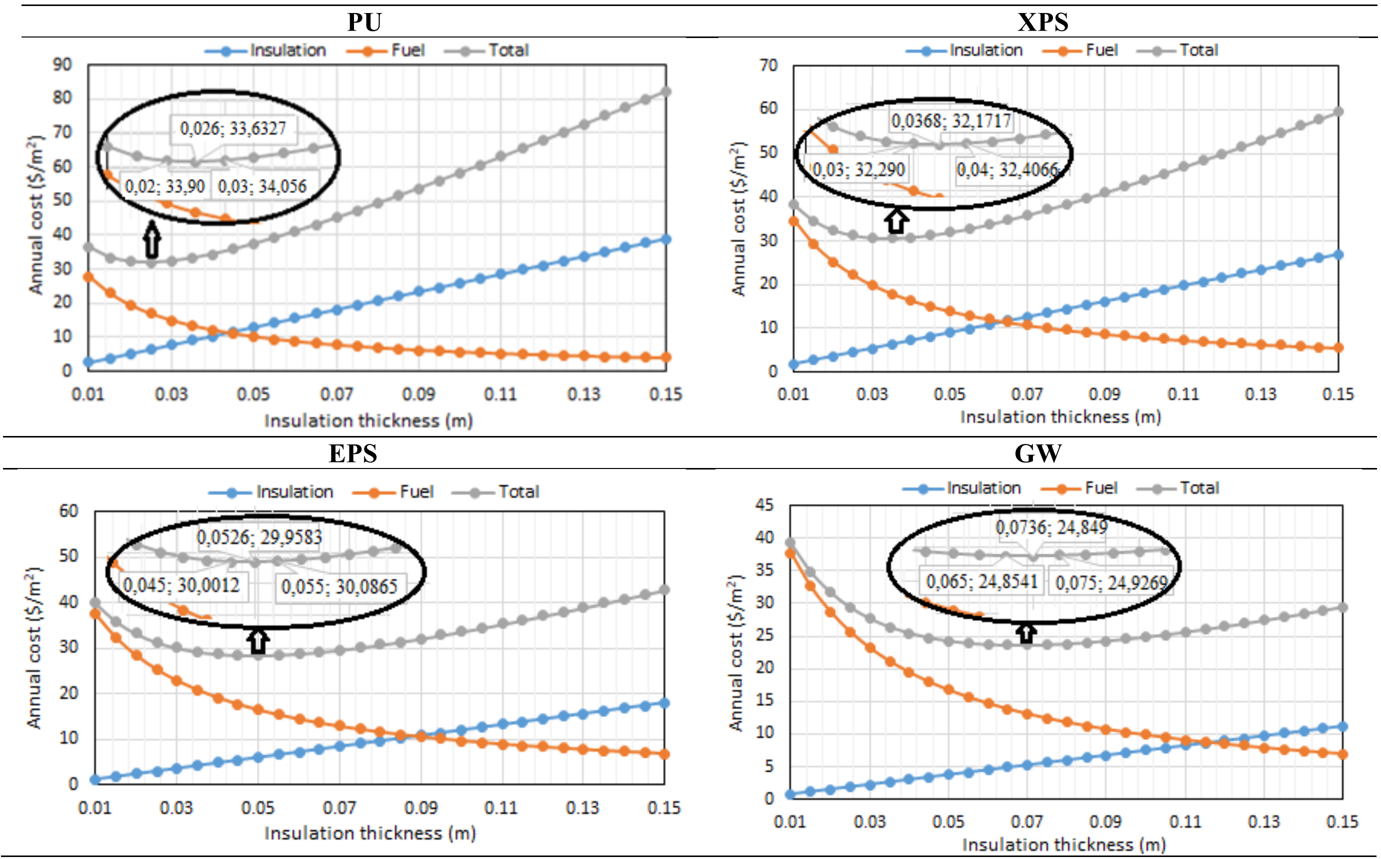


Fig. 8. Insulation thicknes versus annual cost heating and cooling for four insulation materials and Elazığ found using Life Cycle Cost (LCC) method (for wall 1 type)

The lowest value of CO_2 emission per unit area of wall insulated with GW insulation material were found as 7.19 kg CO_2 at optimum thickness (13 cm). the highest (13.67 kg CO_2) CO_2 emissions were obtained for the wall insulated with XPS insulation material at the optimum thickness (4 cm). Fig.8 shows the insulation thicknes versus annual cost heating and cooling for four insulation materials and Elazığ found using Life Cycle Cost (LCC) method. The insulation cost increases linearly with insulation thickness, while operating costs corresponding to heating and cooling decreases. The optimum insulation thickness for external wall is minimum value of total cost which equals the summation of the insulation cost and operating cost.

The optimum insulation thickness for external wall insulated with PU has lowest value among other insulation materials. The optimum thickness for external wall insulated with XPS insulation material is 0.0368 m, whereas in case of insulation with EPS there is 0.0526 m. The optimal insulation thickness for external wall insulated with PU has lowest value among other insulation materials.

Fig. 9 shows the environmental impacts per unit area (Global warming, kg CO_2 eq.) of each construction material for the selected four wall types. In global warming potential (GWP) impact category, XPS insulation material has the highest GWP impact among the four insulation materials and the lowest impact belongs to GW which is 68% lower than XPS. The GWP of concrete (83.47 kg CO_2/m^2) used in wall 3 is quite high compared to materials used in the other external wall types. It is obtained that the CO_2 emissions of CSEB used in wall 4 is lowest than brick and concrete used in the other external wall types.

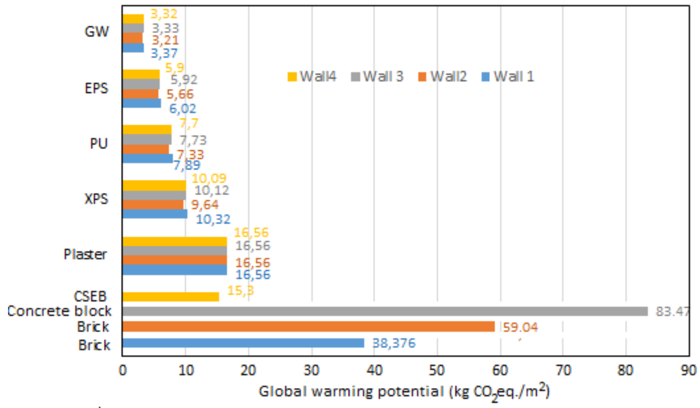


Fig. 9. The environmental impacts per unit area (GW, kg CO_2 eq.) of each construction material for the selected four wall types

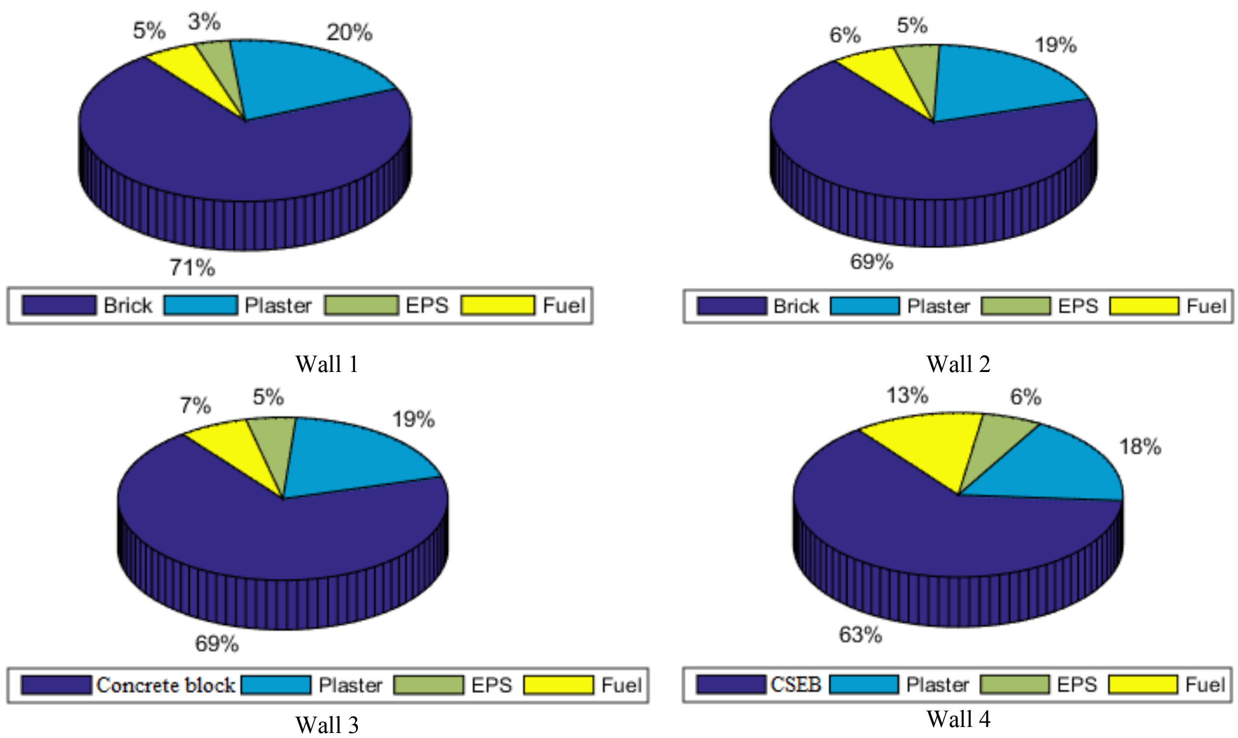


Fig. 10. Percentages of environmental impacts per unit area (Global warming, kg CO_2 eq.) each construction material for the selected four wall types

The percentages of environmental impacts per unit area (Global warming, kg CO_2 eq.) each construction material for the selected four wall types are shown Fig. 10. 69% of total GWP for wall 3 type belongs to hollow concrete block while 71% of total GWP for wall 1 type belongs to brick. While the highest CO_2 emission of natural gas which is used as an energy source is found for wall 4, the lowest CO_2 emission is obtained for wall 1. CO_2 emissions of EPS in the optimum thickness found using Life Cycle Cost (LCC) method present 3-6% of total CO_2 emissions for all wall types. Fig.11 shows the insulation thicknes versus annual cost and CO_2 emissions for selected cities. The difference between the optimum thicknesses of XPS insulation material found using these two method is 37-50% for the four selected cities. The optimum thickness of the insulation, where the total cost is minimum is 4.52 cm in Elazığ, while it is 2.6 cm in Hatay. The optimum thicknesses of insulation for minimum CO_2 emissions for Bayburt and Batman are 9.3 cm and 6.6 cm, respectively.

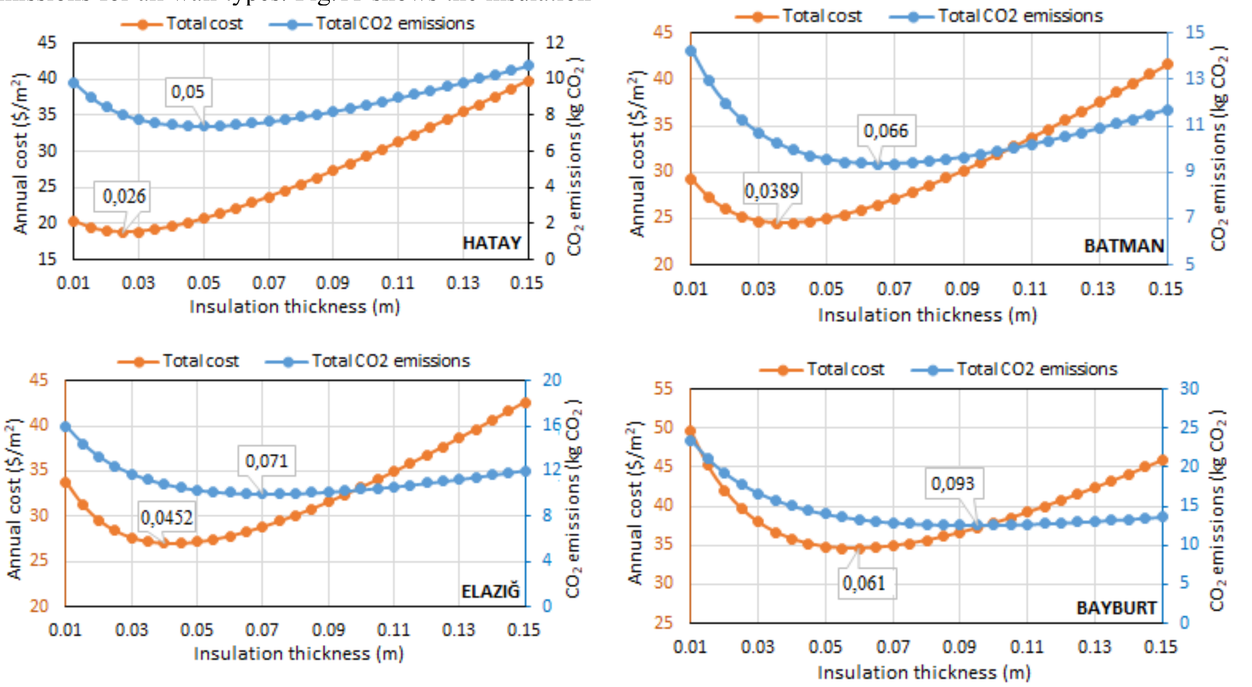


Fig.11. Insulation thicknes versus annual cost and CO_2 emissions for selected cities (for wall 1 type and XPS insulation material)

The environmental impacts per unit area (Global warming, kg CO_2 eq.) of the selected four cities and insulation materials is shown in Fig.12. It can see that CO_2 emissions of XPS insulation material are highest compared to the other insulation materials for four wall types and selected cities. The sandwich wall (wall 2) among all wall type studied displays greatest advantage with respect to the reduced CO_2 emissions per unit area of the wall.

The environmental impact assessments for selected four wall types and insulation materials are given in Fig.13. The four regions - Eco-Friendly, Stay Clear, Profiteering, and Eco-Efficient – are shown in each figure. Reduction in environmental impact and an increase in cost characterize this region. Despite the eco-friendly region, the Profiteering region is a region where there is a decrease in cost with the increase in global warming potential. While both the global warming potential and cost are the highest in Stay Clear region, they have the lowest values in the Eco-efficient region. Eco-efficient region displays contrasting features with the Stay Clear region. The external walls insulated with PU at the optimum thickness fall into the Eco-Efficient quadrant for the category global warming potential and the abiotic depletion of fossil resources. All constructions of the insulated external wall with glass wool positioned in region, which has low environmental impact and high cost.

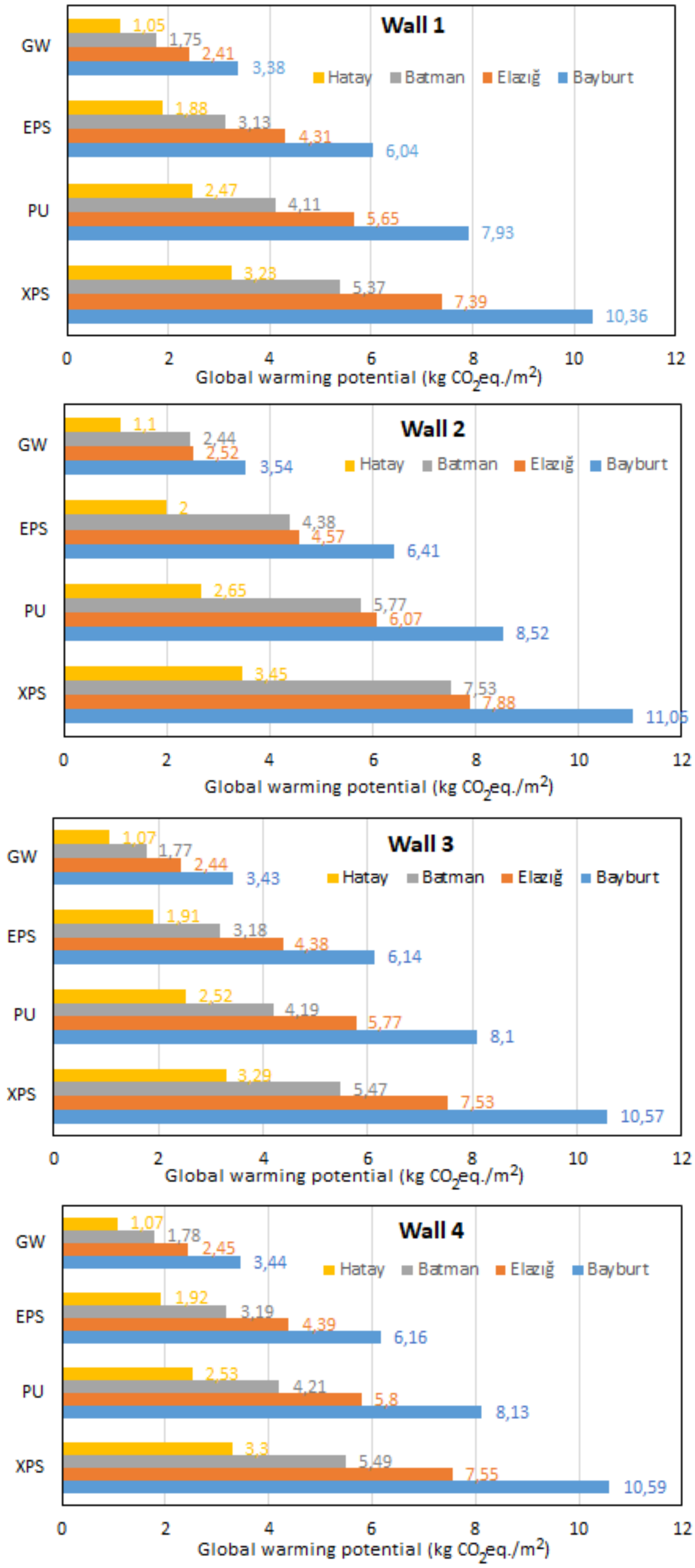


Fig.12. The environmental impacts per unit area (Global warming, kg CO_2 eq.) of the selected four cities and insulation materials

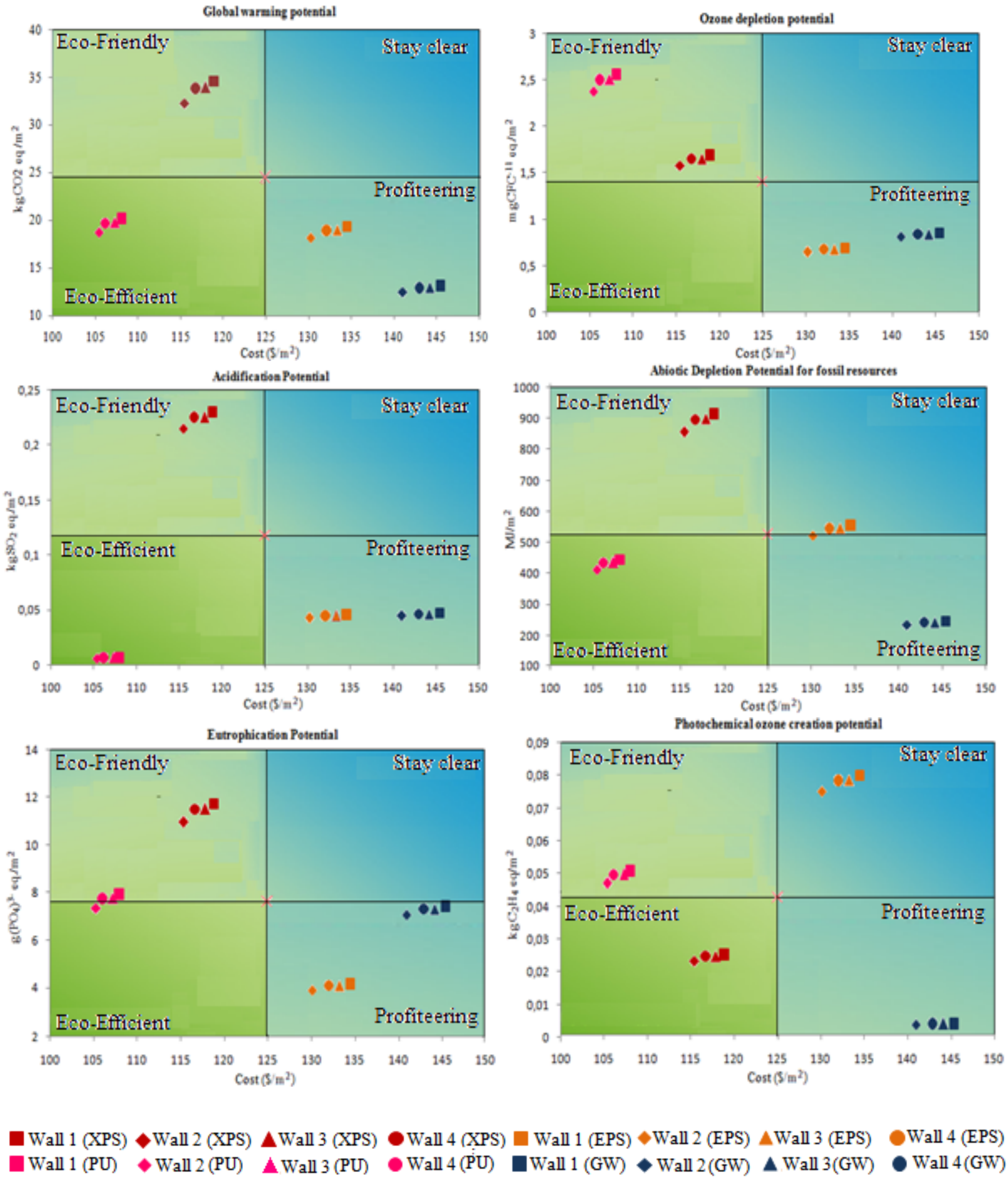


Fig.13. Eco-efficiency analysis results of selected four wall types and insulation materials

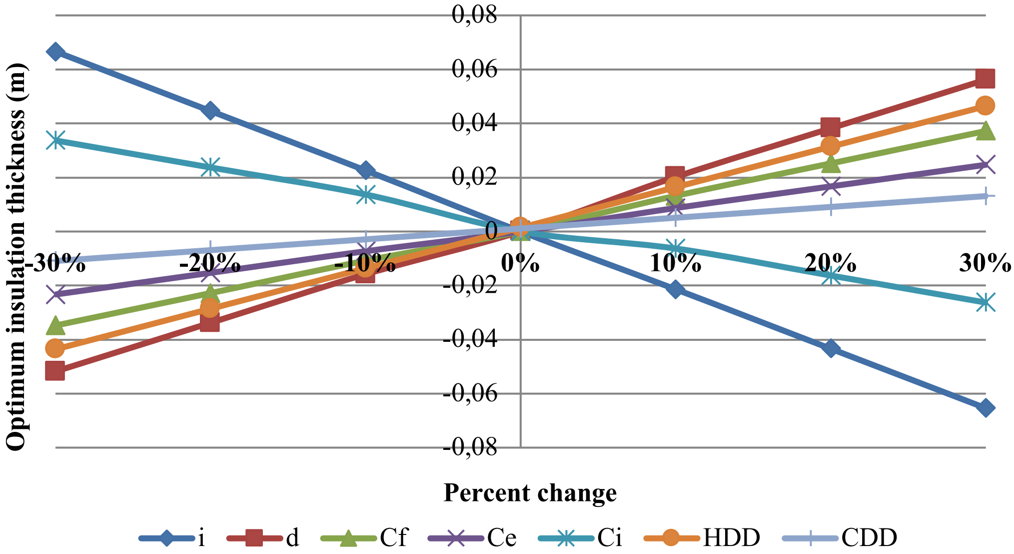


Fig. 14. A sensitivity analysis result of optimum insulation thickness for XPS insulation material and wall 1 type.

Fig. 14 shows a sensitivity analysis result of optimum insulation thickness for XPS insulation material and wall 1 type. It appears that the sensitivity degrees of increase in the interest rate, discount rate and heating degree-days the impacts on the optimum insulation thickness of wall are greater than other parameters.

CONCLUSION

The optimum insulation thicknesses are calculated depending on the heating-cooling energy need and energy cost using Life Cycle Cost (LCC) method for external walls with different structure in the selected cities. In addition, the annual embodied CO_2 emissions of each building material are calculated for four wall types. It was presented from these results that The heating loss for north facing exterior surface of wall has highest percentage. The south facing exterior surface of wall has the lowest values according to other orientations for all wall structures and all climate conditions. The heating demand for the province of Bayburt, located in the fourth degree day region of Turkey, is the highest among the three cities in the other regions. The total energy costs of external walls insulated with glass wool (GW) has least among external walls insulated with other insulation materials.

The lowest value of CO_2 emission per unit area of wall insulated with GW insulation material were found as 7.19 kg CO_2 at optimum thickness (13 cm). The highest (13.67 kg CO_2) CO_2 emissions per unit area of wall were obtained for the wall insulated with XPS insulation material at the optimum thickness (4 cm). XPS insulation material has the highest global warming potential (GWP) impact among the four insulation materials and the lowest impact belongs to GW insulation material which is 68% lower than XPS. The GWP of concrete (83.47 kg CO_2/m^2) used in wall 3 is quite high compared to materials used in the other external wall types. The sandwich wall (wall 2) among all wall type studied displays greatest advantage with respect to the decreased CO_2 emissions per unit area of the wall. In addition, the external walls insulated with PU at the optimum thickness are located in Eco-Efficient quadrant for the category global warming potential and the abiotic depletion of fossil resources.

This study was applied here in to four wall different and residential building, but the same methodology can be replicated to other kinds of buildings and to different climatic conditions. In addition, the results acquired in this study will be helpful guide the choice of insulation and wall type for building in different climates.

Carbon dioxide emissions are one of the most important causes of global climate change. It is accepted in the world today that the world urgently needs to reduce carbon dioxide emissions in order to avoid the worst impacts of climate change. The annual CO_2 emissions can be importantly reduced with the correct selection of wall type, insulation material and insulation thickness. Therefore, this study contributes to the fight against climate change caused by future carbon dioxide emissions.

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