European Journal of Technique

journal homepage: https://dergipark.org.tr/en/pub/ejt

Vol.12, No.2, 2022

Thermal Analysis of Insulation Materials Used for Exterior Walls of Buildings Considering the Wind Effect

Aynur UÇAR[1*]

[1*]Department of Mechanical Engineering, Firat University, 23279 Elazığ, Turkey. (e-mail: aucar@firat.edu.tr).

ARTICLE INFO

Received: Dec., 30. 2021
Revised: Aug., 18. 2022
Accepted: Nov, 30. 2022

Keywords:
Optimum insulation thickness
Wind speed
Insulation material
Thermal analysis

Corresponding author: *Aynur Uçar*

ISSN: | e-ISSN: *2536-5134*

DOI: https://doi.org/10.36222/ejt.1051230

ABSTRACT

The optimum thickness of insulation material dependent on wind speed and wall orientation were determined for selected insulation materials and external wall types in different compositions and orientations by using the Life Cycle Cost method. The methodology is applied as a case study by comparing the different combinations of thermally insulated walls with four different insulation materials for four different degree-day regions of Turkey considering the effect of wind speed and direction. In the economic analysis, the costs of the life cycle of each different combination of insulated walls were calculated. It was obtained from these results that heating requirement of the north orientation wall was the maximum and heating requirement of the south orientation wall was the minimum. The optimum thickness of insulation changes from 4.77 to 13.35 cm dependent on the insulation materials and orientations.

1. INTRODUCTION

Residential buildings have a considerable share in the consumption of renewable energy resources [1]. Today, energy consumption in buildings constitutes approximately 40% of total energy consumption, and the capacity of the residential sector will reach 67% by 2050 [2].

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. Preventions to prevent environmental pollution are not only limited to energy savings [3]. The optimum insulation thickness is determined by some researchers [4-10]. Özel et al. [11] are 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. Jie et al. [12] determined the optimum thickness of insulation for walls and roofs of buildings and they have developed an optimization model for this purpose. Their results showed that the optimum insulation thickness of walls and roofs could be calculated from this optimization model.

In this study, the optimum thermal insulation thickness is determined depending on the available costs of insulation materials and fuel for building external walls with different structure and orientation in the selected cities from four different climate regions of Turkey.

2. ANALYSIS

2.1. The investigated wall structures

The four walls in different structures are researched in this working. The place of insulation can be replaced by putting to different places in the wall. Fig.1 shows the examined wall structures.

Wall 1 consists of 2 cm interior and exterior plaster, 13 cm thick brick and insulation material. Wall 2 is a sandwich wall which has a compound structure consisting of 2 cm interior and exterior plaster, 10 cm each of two brick layers. Wall 3 consists of interior and exterior plaster, hollow concrete block, and insulation. In this wall configuration, the concrete thickness is 20 cm and interior and exterior plaster is 2 cm.

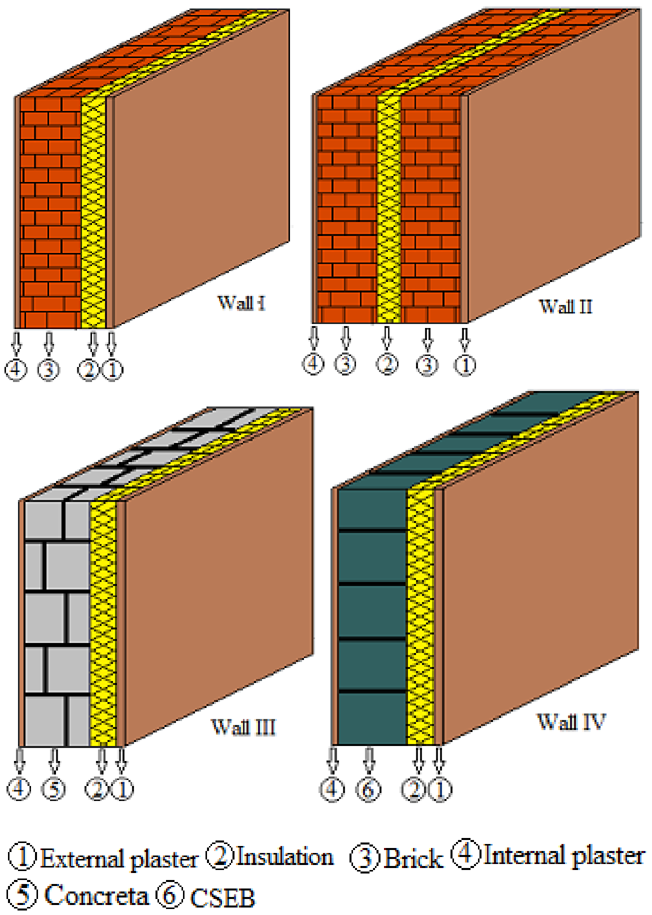

Figure 1. Cross-sectional views of the investigated external wall structures.

Wall 4 consist of 2 cm interior plaster, 30 cm CSEB (Compressed Stabilised Earth Block), insulation material and 2 cm exterior plaster. In this working, polyurethane (PU), extruded polystyrene (XPS), glass wool (GW) and expanded polystyrene (EPS) are preferred as insulation materials. The physical properties of each material used in the wall structures and economical parameters are shown in Table 1.

2.2. Climatic zones

Turkey has four different degrees-day regions according to TS 825 'Thermal Insulation Requirements for Buildings' standard. [13]. Each region has different heating and cooling degree-days values. The temperature of the different heating degree-day regions is about 7 times increases at the base temperature of 18 ° C [14]. The International Energy Agency (IEA) (2008) is defined six basic climatic regions for 18 °C base temperature and these regions is shown in Table 2.

TABLE 1.
PHYSICAL PROPERTIES OF WALL STRUCTURE AND ECONOMIC PARAMETERS

Wall type	Thickness (m)	Thermal conductivity (W/mK)	Resistance (m^2 K/W)	Insulation cost ($/$m^3$)
Wall 1			0.335	
Interior plaster	0.02	0.87		
Brick	0.13	0.45		
External plaster	0.02	0.87		
Wall 2			0.490	
Interior plaster	0.02	0.87		
Brick	0.10	0.45		
Brick	0.10	0.45		
External plaster	0.02	0.87		
Wall 3			0.379	
Interior plaster	0.02	0.87		
Hollow concrete block	0.20	0.60		
External plaster	0.02	0.87		
Wall 4			0.387	
Interior plaster	0.02	0.87		
CSEB	0.30	0.88		
External plaster	0.02	0.87		
Insulation Materials				
Polyurethane	*	0.024		260
Extruded polystyrene	*	0.031		180
Expanded polystyrene	*	0.039		120
Glass wool	*	0.040		75
Interest rate, i Inflation rate, d Lifetime, N	9% 8.81% 10			

* The optimum thickness of insulation material calculated using the life cycle cost analysis

TABLE 2.
CLASSIFIED CLIMATIC ZONES, AND HEATING AND COOLING DEGREE-DAY RANGES [13]

Climatic regions	**Heating degree-days**	**Cooling degree-days**
Cold climate	4000 ≤ HDD	CDD < 500
Medium cold climate	3000 ≤ HDD	500 ≤ CDD < 1000
Rather cold climate	2000 ≤ HDD	CDD < 1000
Moderate climate	HDD < 2000	CDD < 1000
Cooling-based climate	1000 ≤ HDD < 2000	1000 ≤ CDD
Hot climate	HDD < 1000	1000 < CDD

In this working, Hatay, Batman, Elazığ and Bayburt from the four different degree-day regions of Turkey are chosen and optimum values of insulation thickness for these cities found. The annual heating degree-days of Hatay in the southern region 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 yearly heating degree-days of Elazığ is 2653. Table 3 is given the climate characteristics of the selected cities.

TABLE 3.
CLIMATE CHARACTERISTIC OF SELECTED CITIES

City	Elavation (m)	Longitude (deg)	Latitude (deg)	Cooling degree-days (ºC-days)	Heating degree-days (ºC-days)
Hatay	85	36 º12'	36º 52'	614	1119
Batman	525	41º 07'	37º 52'	763	1823
Elazığ	1067	39º 14'	38º 41'	337	2653
Bayburt	1556	40º 15'	40º 16'	8	4149

2.3. Heat transfer from walls

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 internal 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

$$q = U(T_i - T_o) \tag{1}$$

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

$$U = \frac{1}{1/h_i + R_w + x_{ins}/k_{ins} + 1/h_o} \tag{2}$$

In this study, the convective heat transfer coefficient between internal surface of the wall with air is evaluated as follows

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

The convective heat transfer coefficient on the outer surface of wall depending on direction and speed of the wind can be calculated by using Eqs. (4) and (5) for the windward (ww) and leeward side (lw) as

$$h_{o,ww} = 1.53v + 1.43 \tag{4}$$

$$h_{o,lw} = 0.90v + 3.28 \tag{5}$$

It is accepted that Eq. (4) is for the north, west, and east wall surface, when Eq. (5) is for the south facing wall surface.

The Weibull distribution is the most widely used to represent the frequencies of the wind speed. The Weibull distribution function can be given as [15]

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{6}$$

In this study, k and c parameters are calculated from mean wind speed–standard deviation method.
The yearly energy need can be calculated by

$$E_A = \frac{86400\ HDD\ U}{\eta_s} \tag{7}$$

2.4. Economic analysis

In this working, the P_1-P_2 method is used the energy savings of each type of wall. The annual cost of heating for per unit area is found as [16]

$$C_A = \frac{86400\ HDD\ C_f}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) H_u\ \eta_s} \tag{8}$$

Costs, lower heating values and efficiencies of various fuel types used in this analysis are given in Table 4. 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

$$P_1 = [(1+d)/(d-i)]\left[1-((1+i)/(1+d))^N\right] \tag{9}$$

$$P_2 = 1 + P_1 M_S - R_v (1+d_f)^{-N} \tag{10}$$

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

$$C_{ins} = C_i x_{ins} \tag{11}$$

The heating energy savings during the life time per unit area

$$S = C_A P_1 - P_2 C_{ins} \tag{12}$$

or

$$S = \frac{86400\ HDD\ C_f}{\left(R_{wt} + \frac{x_{ins}}{k_{ins}}\right) H_u\ \eta_s} P_1 - P_2\ C_i\ x_{ins} \tag{13}$$

The maximum value of the energy gain is the optimum value. In MATLAB optimization Toolbox, Eq. (13) was received as an objective function and the optimum thickness of insulation was found.

The payback period N_p is determined as

$$N_p = \frac{\ln\left[1 - \frac{P_2 C_i\ H_u\ \eta_s \left(R_{wt} + R^2{}_{wt} k_{ins}\right)(d-i)}{86400\ HDD\ C_f\ (1+d)}\right]}{\ln[(1+i)/(1+d)]} \tag{14}$$

TABLE 4.
PRICES, LOWER HEATING VALUES AND EFFICIENCIES OF FUELS [17]

Fuel	Price	H_u	η_s
Coal	0.240 $/kg	29.295x10^{6}J/kg	0.65
Natural gas	0.332 $/m^3	34.526 x10^{6}J/m^3	0.90
Fuel-oil	0.343 $/kg	40.594 x10^{6}J/kg	0.80
LPG	1.265 $/kg	46.453 x10^{6}J/kg	0.88

3.RESULTS AND DISCUSSION

In the use of wind energy, it is very important to determine the wind speed according to the wind direction. The long-term wind data containing hourly wind speed and direction recorded during the last decade period were taken from Turkish State Meteorological Service and were used in this study. The relative frequencies of wind directions for four stations are shown in the wind rose diagram in Fig. 2. A wind rose is a graphic that shows distribution of the wind speed and direction at a specific area. The northwest and west-north-west wind directions at Elazığ and Bayburt are most windward directions. the most windward direction at Hatay and Batman are south–southwest and northeast, respectively. Fig. 3 shows the possibility density function of the yearly wind speed distribution. The peak point of frequencies values for selected the stations are shifted towards the high values of mean wind speed.

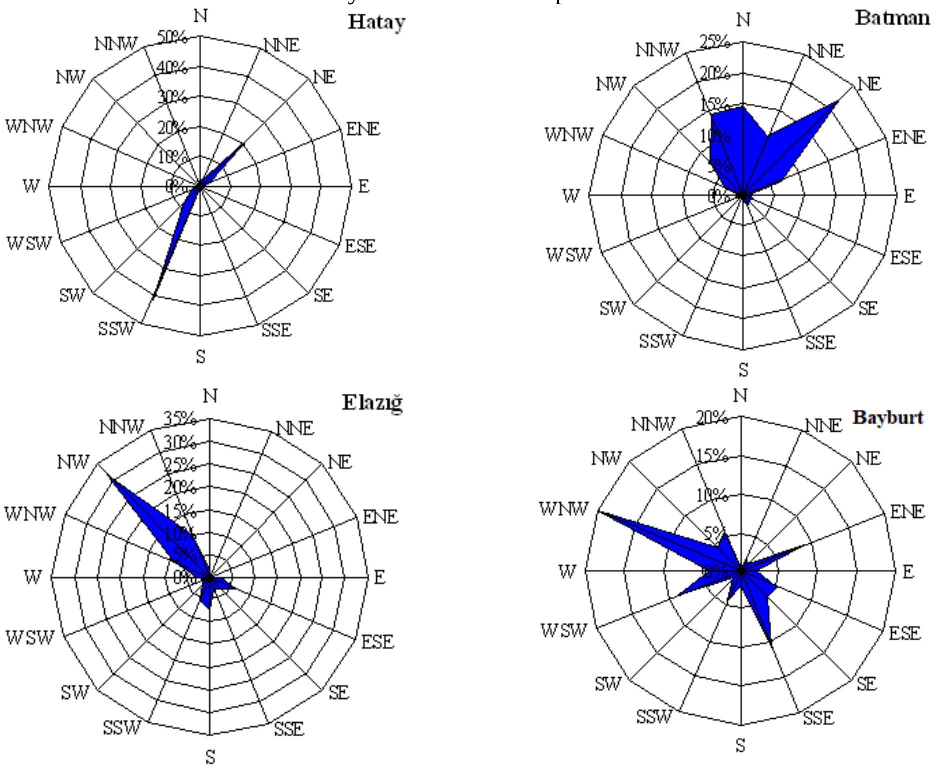

Figure 2. Frequencies (%) of wind directions for four cities.

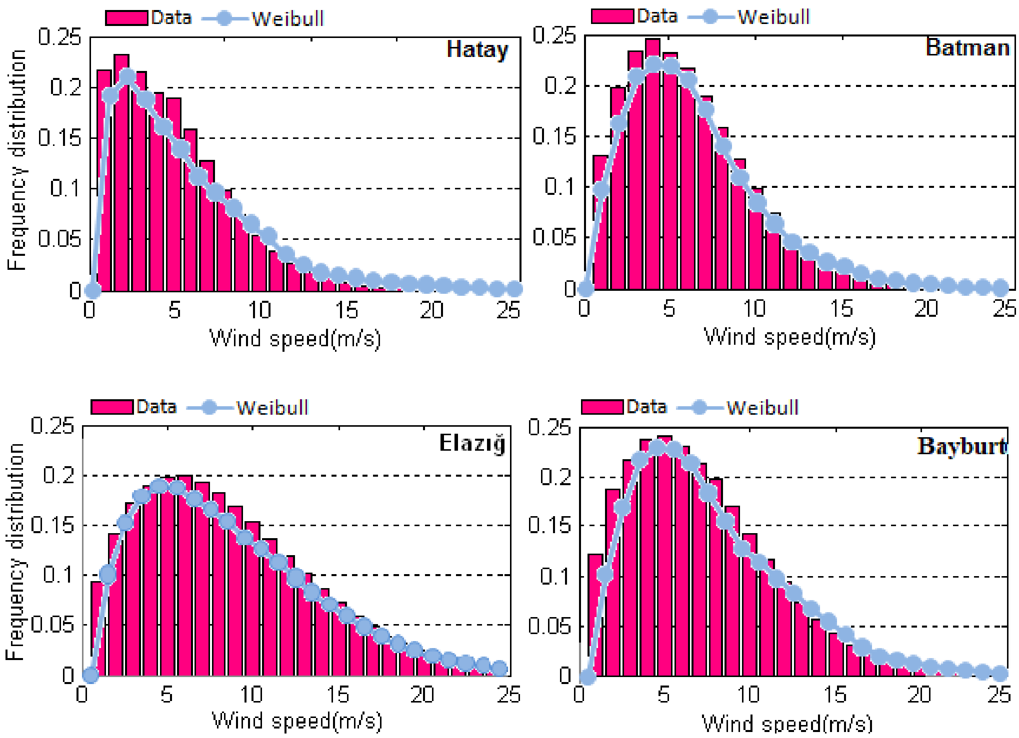

Figure 3. Annual frequency distributions of wind speed for four cities.

Fig.4 shows variation of the heating load with insulation thickness according to different directions and selected cities for sandwich wall with insulation. The heating load of the wall area reduces with the insulation thickness increasing. The heating load is found as highest for north facing wall. The heating load of south facing wall is lowest according to other orientations, because this surface has the high solar heat gain.

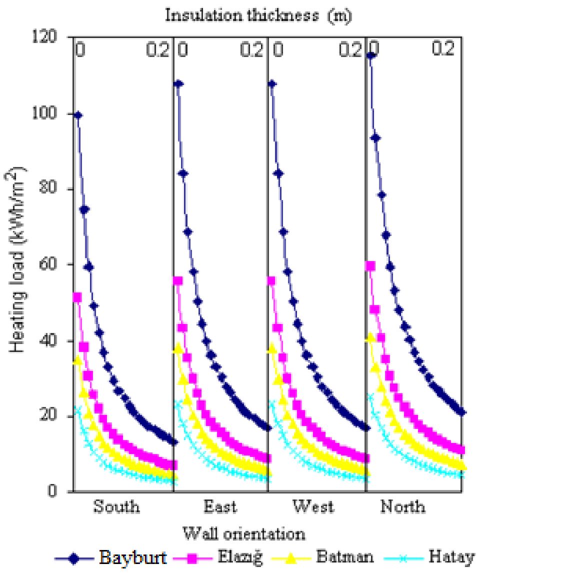

Figure 4. Variation of the heating load with insulation thickness according to different directions and selected cities for sandwich wall with insulation (Wall 2).

Fig. 5 shows the influence on energy savings of insulation thickness and wall orientations for four wall types. The energy savings increases with the insulation thickness increases and it achieves a maximum value in the optimum thickness of insulation. The insulated wall with polyurethane is reached greatest energy savings according to selected insulation materials for different orientations. The cost of polyurethane is higher than other selected insulation materials, while the thermal conductivity of polyurethane is lower.

The influence on energy savings of insulation thickness and wall orientations for four fuel types and insulated sandwich wall is shown in Fig.6 for Elazığ. The energy savings varies attached to the fuel cost. The energy savings of high cost fuels like LPG, coal and fuel-oil are higher than energy savings of other cheap fuels. It is found that LPG is the most suitable energy source in terms of energy savings, besides natural gas has the worst performance. Figs.7 presents the variations of energy savings and payback period with different wall structures and orientations for four fuel types and extruded polystyrene in Elazığ. The insulated sandwich wall (Wall 2) with thermal resistance of 0.49 m^{2}K/W has the lowest energy savings and highest payback period, while insulated external wall (Wall 1) with thermal resistance of 0.34 m^{2}K/W has the highest energy savings and lowest payback period.

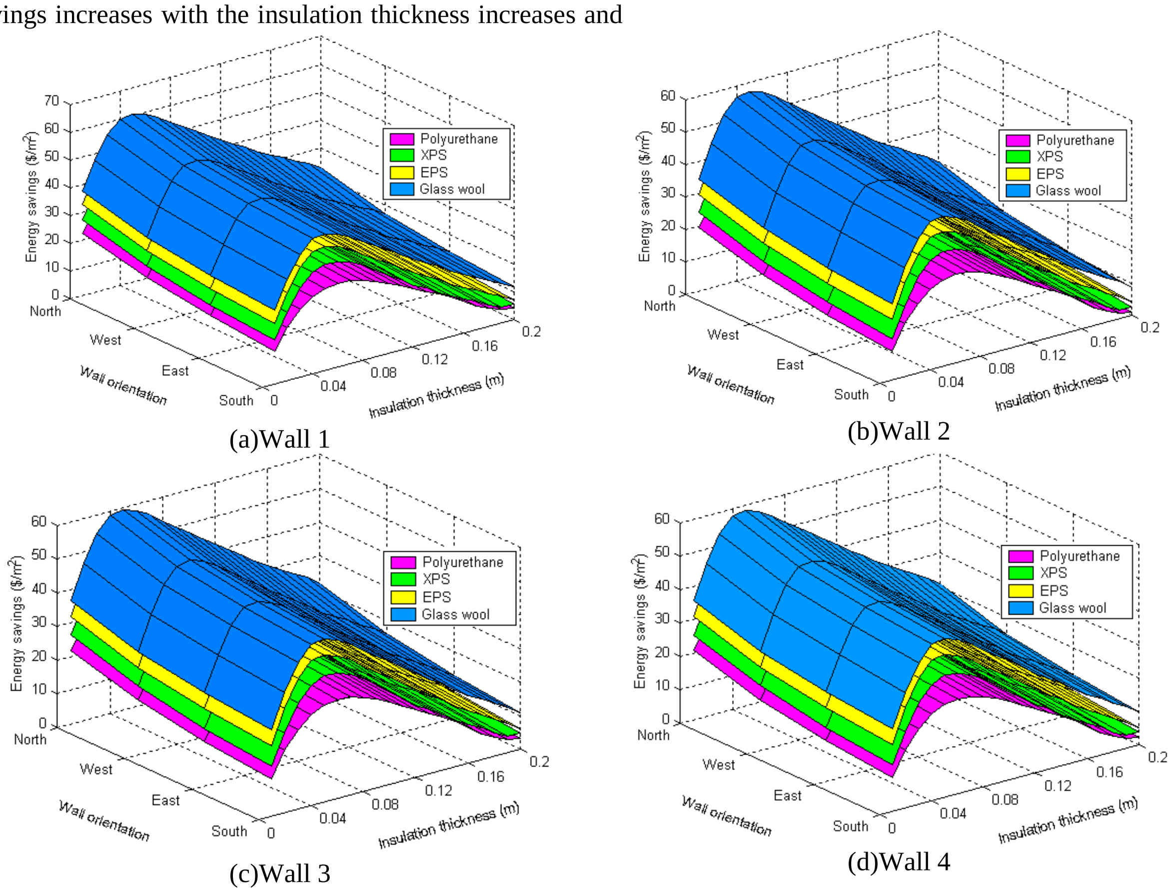

Figure 5. Influence on energy savings of insulation thickness and wall orientations for four wall types.

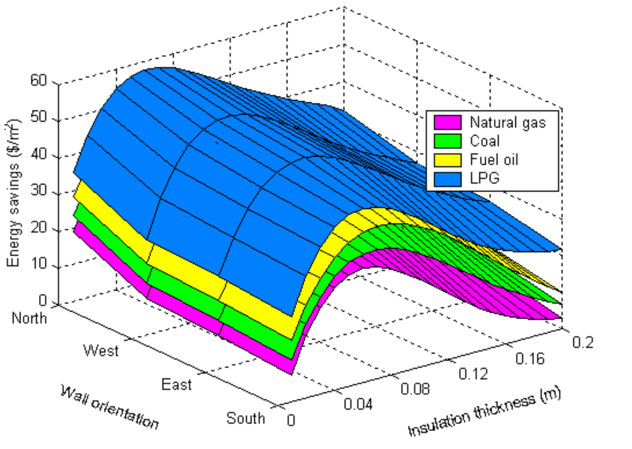

Figure 6. Influence on energy savings of insulation thickness and wall orientations for four fuel types and insulated sandwich wall (Wall 2).

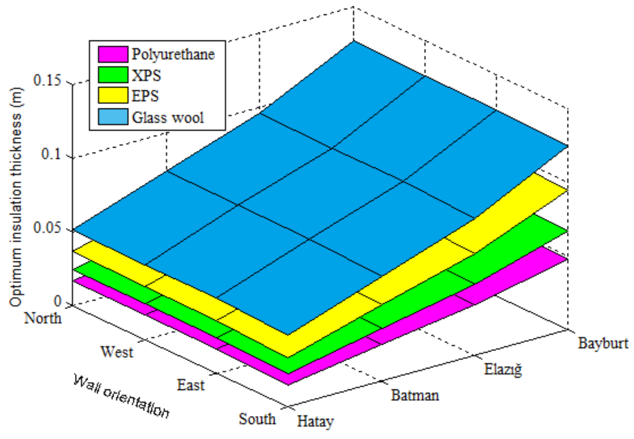

Figure 8. Variation of optimum insulation thickness with different wall orientations for selected four insulation materials and cities (for using fuel-oil as fuel type).

Fig.9 shows the effect on payback period of insulation thickness and different orientations for sandwich wall insulated with extruded polystyrene and selected cities. It is observed this figure that the payback periods vary depending on the heating degree days. For all orientations, the payback period reduces with heating degree days increasing. The cost of insulation increases because of the applying higher insulation thickness in cold climatic regions. But, the payback period is conversely shorter. For this reason, it is more advantageous to apply insulation in cold climatic regions. It is seen that the lowest payback period is reached for Bayburt having higher degree days and the north wall, while the highest payback period is obtained for Hatay having lower degree days and south wall.

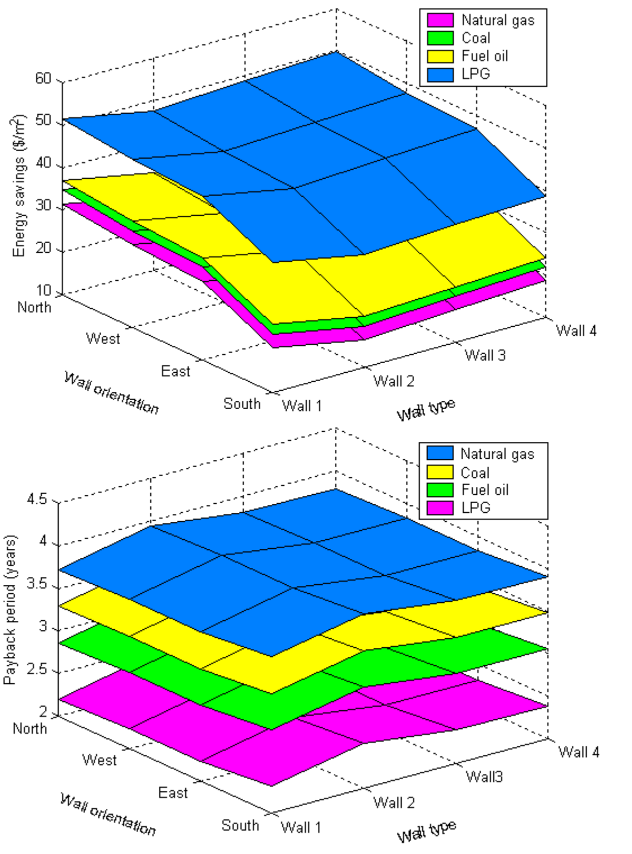

Figure 7. Variation of energy savings and payback period with different wall structures and orientations for different fuel types and extruded polystyrene insulation material in Elazığ

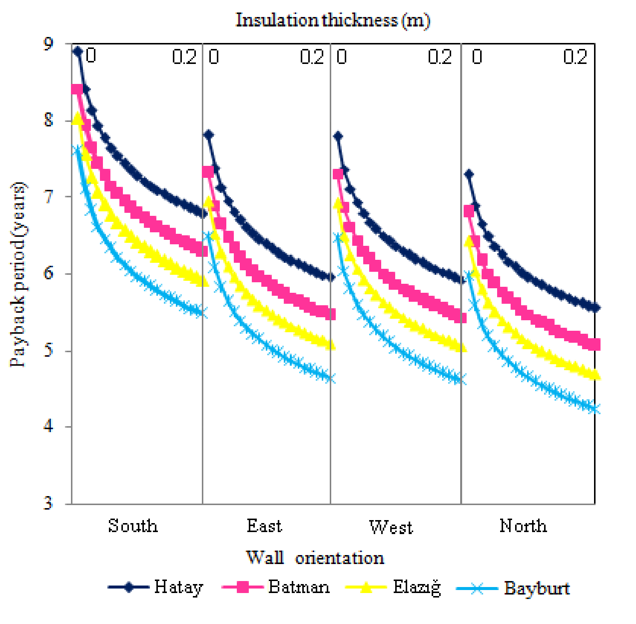

Figure 9. Effect on payback period of insulation thickness and different orientations for sandwich wall insulated with extruded polystyrene and selected cities.

Fig.8 shows variation of optimum insulation thickness with wall orientations for selected insulation materials and selected cities. The optimum insulation thickness varies depending on the climatic conditions of the region. The larger insulation thickness require for the cities in cold climate region which have higher heating degree days. The optimum insulation thickness in Bayburt is higher compared to regions of Hatay and Batman, located in the low-latitude region. The highest optimum insulation thickness is achieved in Bayburt for glass wool insulation material, when its lowest value is obtained in Hatay for polyurethane.

Table 5 shows the results of optimization and economic analysis calculated for selected four wall types, all wall orientations and selected insulation materials in Bayburt city. The optimum thickness of insulation changes from 4.77 to 13.35 cm dependent on the insulation materials and orientations.

TABLE 5.
RESULTS OF OPTIMIZATION AND ECONOMIC ANALYSIS CALCULATED FOR SELECTED FOUR WALL TYPES, INSULATION MATERIALS AND ALL ORIENTATIONS IN BAYBURT CITY.

Orientation	Type of wall	Insulation material	Optimum insulation thickness, cm	Energy savings,$/m^2	Payback period years
South	Wall 1	Polyurethane	5.15	26.81	3.24
		Extruded polystyrene	7.15	29.46	3.18
		Expanded polystyrene	10.06	33.30	3.10
		Glass wool	13.04	36.03	2.91
	Wall 2	Polyurethane	4.77	26.13	3.45
		Extruded polystyrene	6.67	28.59	3.39
		Expanded polystyrene	9.45	32.21	3.31
		Glass wool	12.42	34.91	3.12
	Wall 3	Polyurethane	5.04	26.61	3.30
		Extruded polystyrene	7.01	29.21	3.25
		Expanded polystyrene	9.89	32.99	3.16
		Glass wool	12.86	35.71	2.97
	Wall 4	Polyurethane	5.02	26.58	3.31
		Extruded polystyrene	6.99	29.17	3.26
		Expanded polystyrene	9.86	32.93	3.17
		Glass wool	12.83	35.65	2.98
East	Wall 1	Polyurethane	5.29	27.06	3.15
		Extruded polystyrene	7.33	29.78	3.09
		Expanded polystyrene	10.29	33.71	3.00
		Glass wool	13.27	36.45	2.81
	Wall 2	Polyurethane	4.91	26.39	3.38
		Extruded polystyrene	6.85	28.92	3.32
		Expanded polystyrene	9.68	32.62	3.23
		Glass wool	12.65	35.33	3.04
	Wall 3	Polyurethane	5.18	26.87	3.22
		Extruded polystyrene	7.19	29.54	3.16
		Expanded polystyrene	10.12	33.40	3.07
		Glass wool	13.09	36.13	2.88
	Wall 4	Polyurethane	5.16	26.83	3.23
		Extruded polystyrene	7.17	29.49	3.17
		Expanded polystyrene	10.09	33.35	3.09
		Glass wool	13.06	36.07	2.90
West	Wall 1	Polyurethane	5.29	27.06	3.15
		Extruded polystyrene	7.33	29.78	3.09
		Expanded polystyrene	10.29	33.71	3.00
		Glass wool	13.27	36.45	2.81
	Wall 2	Polyurethane	4.91	26.39	3.38
		Extruded polystyrene	6.85	28.92	3.32
		Expanded polystyrene	9.68	32.62	3.23
		Glass wool	12.65	35.33	3.04
	Wall 3	Polyurethane	5.18	26.87	3.22
		Extruded polystyrene	7.19	29.54	3.16
		Expanded polystyrene	10.12	33.40	3.07
		Glass wool	13.09	36.13	2.88
	Wall 4	Polyurethane	5.16	26.83	3.23
		Extruded polystyrene	7.17	29.49	3.17
		Expanded polystyrene	10.09	33.35	3.09
		Glass wool	13.06	36.07	2.90
North	Wall 1	Polyurethane	5.33	27.14	3.12
		Extruded polystyrene	7.39	29.89	3.06
		Expanded polystyrene	10.36	33.84	2.97
		Glass wool	13.35	36.58	2.78
	Wall 2	Polyurethane	4.96	26.47	3.35
		Extruded polystyrene	6.91	29.02	3.29
		Expanded polystyrene	9.76	32.75	3.21
		Glass wool	12.72	35.46	3.02
	Wall 3	Polyurethane	5.23	26.95	3.19
		Extruded polystyrene	7.25	29.64	3.13
		Expanded polystyrene	10.19	33.53	3.05
		Glass wool	13.17	36.26	2.86
	Wall 4	Polyurethane	5.21	26.91	3.20
		Extruded polystyrene	7.23	29.60	3.15
		Expanded polystyrene	10.16	33.48	3.06
		Glass wool	13.14	36.21	2.87

ISSN 2536-5010 | **e-ISSN** 2536-5134

TABLE 6.
RESULTS OF OPTIMIZATION AND ECONOMIC ANALYSIS FOR SELECTED CITIES, ALL FUEL TYPES AND ALL ORIENTATIONS.

Orientation	City	Fuel type	Optimum insulation thickness, cm	Energy savings, $/m^2	Payback period years
South	Hatay	Coal	2.23	12.64	4.05
		Natural gas	1.85	11.27	4.13
		Fuel-oil	1.83	11.19	4.14
		LPG	4.95	22.41	3.60
	Batman	Coal	3.56	17.40	3.80
		Natural gas	3.07	15.66	3.89
		Fuel-oil	3.04	15.55	3.90
		LPG	7.02	29.87	3.36
	Elazığ	Coal	4.82	21.94	3.62
		Natural gas	4.23	19.84	3.70
		Fuel-oil	4.20	19.71	3.71
		LPG	8.99	36.98	3.17
	Bayburt	Coal	6.66	28.59	3.39
		Natural gas	5.93	25.96	3.48
		Fuel-oil	5.89	25.79	3.49
		LPG	11.89	47.40	2.94
East	Hatay	Coal	2.41	12.97	3.98
		Natural gas	2.03	11.60	4.06
		Fuel-oil	2.01	11.51	4.07
		LPG	5.13	22.73	3.53
	Batman	Coal	3.74	17.73	3.74
		Natural gas	3.25	15.98	3.81
		Fuel-oil	3.22	15.88	3.82
		LPG	7.20	30.20	3.29
	Elazığ	Coal	5.00	22.27	3.55
		Natural gas	4.41	20.16	3.63
		Fuel-oil	4.38	20.03	3.64
		LPG	9.18	37.31	3.09
	Bayburt	Coal	6.84	28.92	3.32
		Natural gas	6.11	26.28	3.40
		Fuel-oil	6.07	26.12	3.41
		LPG	12.07	47.73	2.87
West	Hatay	Coal	2.41	12.97	3.98
		Natural gas	2.03	11.60	4.06
		Fuel-oil	2.01	11.51	4.07
		LPG	5.13	22.73	3.53
	Batman	Coal	3.74	17.73	3.74
		Natural gas	3.25	15.98	3.81
		Fuel-oil	3.22	15.88	3.82
		LPG	7.20	30.20	3.29
	Elazığ	Coal	5.00	22.27	3.55
		Natural gas	4.41	20.16	3.63
		Fuel-oil	4.38	20.03	3.64
		LPG	9.18	37.31	3.09
	Bayburt	Coal	6.84	28.92	3.32
		Natural gas	6.11	26.28	3.40
		Fuel-oil	6.07	26.12	3.41
		LPG	12.07	47.73	2.87
North	Hatay	Coal	2.47	13.07	3.95
		Natural gas	2.09	11.70	4.03
		Fuel-oil	2.07	11.62	4.04
		LPG	5.19	22.84	3.50
	Batman	Coal	3.79	17.83	3.71
		Natural gas	3.31	16.09	3.79
		Fuel-oil	3.28	15.98	3.80
		LPG	7.26	30.30	3.26
	Elazığ	Coal	5.06	22.37	3.52
		Natural gas	4.47	20.27	3.60
		Fuel-oil	4.44	20.14	3.61
		LPG	9.23	37.41	3.07
	Bayburt	Coal	6.90	29.02	3.29
		Natural gas	6.17	26.39	3.38
		Fuel-oil	6.13	26.23	3.39
		LPG	12.13	47.83	2.85

ISSN 2536-5010 | **e-ISSN** 2536-5134
https://dergipark.org.tr/en/pub/ejt

It is observed this table that the north-facing insulated wall (Wall 1) has highest optimum thickness for glass wool insulation material. The insulated sandwich wall (Wall 2) for selected insulation materials and wall orientations has lowest optimum thickness and the highest payback period. Besides, the minimum value of optimum insulation thickness and the largest value of payback period are found for the south-facing wall compared to the other orientations. Therefore, this wall is not economically advantageous. The energy savings of the south-facing sandwich wall (Wall 2) insulated with polyurethane insulation material is lowest compared to other wall types.

Table 6 shows the results of optimization and economic analysis for selected cities, all fuel types and all orientations. The energy savings change from 11.19 to 47.83 $/m^2 dependent on thermal properties of fuel. The highest energy savings and smallest payback period is found for LPG as fuel type and north-facing wall in Bayburt, when the smallest energy savings and highest payback period is found for fuel-oil as fuel type and south-facing wall in Hatay.

3. CONCLUSION

The optimum insulation thickness as a function of wall orientation and wind speed were calculated for selected insulation materials and four wall types in this working. Besides, the energy savings and payback periods were examined for four different cities of Turkey representing four different degrees-day regions.

It was obtained from these results that heating requirement of the north wall was the highest and heating requirement of the south wall was the lowest. The optimum insulation thickness was dependent on the climatic conditions. For glass wool insulation material and external wall (Wall 1) in Bayburt, the optimum thickness of insulation was the highest and payback period was the lowest, whereas the optimum thickness of insulation was the lowest and payback period was the highest for polyurethane insulation material and sandwich wall (Wall 2) in Hatay.

This study was applied here four different climate regions and four different wall types, but the same methodology can be replicated to other types of external wall and to different climatic conditions. The results obtained in this study will be helpful guide the choice of insulation material for building walls in different climates.

NOMENCLATURE

c	Weibull scale parameter
C_A	yearly energy cost ($/m^2 year)
C_i	unit cost of insulation material ($/m^3)
C_f	cost of fuel ($/kg)
d	inflation rate
HDD	heating degree days (ºC-days)
H_u	lower calorific value of fuel (J/kg)
i	interest rate
k	dimensionless shape parameter
k_{ins}	heat conduction coefficient of insulation material (W/m K)
M_s	rate of first year maintenance costs to first investment cost
N	lifetime (years)
N_p	payback period (years)
R_w	total thermal resistance of the wall (m^2 K/W)
S	savings ($/m^2)
T_i	inside air temperature (ºC)
T_o	average daily temperature (ºC)
U	total heat transfer coefficient (W/m^2 K)
v	wind speed (m/s)
q	yearly heat loss from wall (W/m^2)
x_{ins}	insulation material thickness (m)
η_s	efficiency of fuel

REFERENCES

[1] UNEP-SBCI Buildings and Climate Change: Status, Challenge and Opportunities, UNEP Publication, Paris, France, 2007.

[2] K. Yiğit and B. Acarkan, "Assessment of energy performance certificate systems: a case study for residential buildings in Turkey", Turkish Journal of Electrical Engineering & Computer Sciences, vol.24, pp. 4839 – 4848, 2016.

[3] A. Stephan, R.H. Crawford and K. Myttenaere, "Towards a comprehensive life cycle energy analysis framework for residential buildings," Energy Building, vol.55, pp. 592–600, 2012.

[4] M.K. Nematchoua, P. Ricciardi, S. Reiter and A. Yvon, "A comparative study on optimum insulation thickness of walls and energy savings in equatorial and tropical climate," International Journal of Sustainable Built Environment, vol.6, pp.170-182, 2017.

[5] M. Kayfeci, A. Keçebas and E. Gedik, "Determination of optimum insulation thickness of external walls with two different methods in cooling applications," Applied Thermal Engineering, vol.50 pp. 217-224, 2013.

[6] N. A. Kurekci, "Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers," Energy and Buildings, vol. 118, pp.197–213, 2016.

[7] K. Çomaklı and B. Yüksel, "Optimum insulation thickness of external walls for energy saving," Applied Thermal Engineering, vol. 23, no.4, pp. 473–479, 2003.

[8] K. Saafi and N. Daouas, "A life-cycle cost analysis for an optimum combination of cool coating and thermal insulation of residential building roofs in Tunisia," Energy, vol.152, pp. 925-938, 2018.

[9] A. Bolattürk, "Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey," Applied Thermal Engineering, vol.26, no.11, pp. 1301–1309, 2006.

[10] I. Axaopoulos, P. Axaopoulos, G. Panayiotou, S. Kalogirou and J. Gelegenis, "Optimal economic thickness of various insulation materials for different orientations of external walls considering the wind characteristics," Energy, vol. 90, pp. 939-952, 2015.

[11] G. Özel, E. Açıkkalp, B. Görgün, H.Yamık and N. Caner, "Optimum insulation thickness determination using the environmental and life cycle cost analyses based entransy approach," Sustainable Energy Technologies and Assessments, vol.11, pp. 87-91, 2015.

[12] P. Jie, F. Zhang, Z. Fang, H. Wang and Y. Zhao, "Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions," Energy, vol. 159, pp. 1132–1147, 2018.

[13] TS 825, Thermal Insulation Rules in Buildings, Turkish Standard Institution, Ankara, Turkey, 1998.

[14] O. Buyukalaca, H. Bulut and T. Yılmaz, "Analysis of variable-base heating and cooling degree days for Turkey," Applied Energy, vol.69, pp. 269–283, 2001.

[15] C. Ozay and M.S. Celiktas, "Statistical analysis of wind speed using two-parameter Weibull distribution in Alaçatı region," Energy Conversion and Management, vol.121, pp. 49–54, 2016.

[16] A. Ucar and F. Balo, "Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey," Applied Energy, vol. 86, pp.730–736, 2009.

[17] Energy and Environmental Systems Magazine (Enerji dünyası dergisi), Teknik yayıncılık tanıtım AŞ, 2008.

BIOGRAPHIES

Aynur UÇAR was born and lives in Elazığ (Turkey) in 1973. She holds a Master's Degree in 1999 and a doctoral degree in 2005 from Institute of Science of the Fırat University. She is an associate professor in Mechanical Engineering at the University of Fırat since 2012. Her research has ranged over heat transfer, renewable energy, energy storage, thermal insulation, finite element analysis, energy and heat pump.