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Research Article

Energy, exergy analysis and optimization of insulation thickness on buildings in a low-temperature district heating system

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ABSTRACT

In the study, energy and exergy analysis of the buildings on a campus in Turkey are conducted by using actual operating data and taking measurements in the district heating system as a case study. The energy and exergy demands, losses that stem from all buildings are calculated according to average daily outdoor temperature data. Due to the high heat losses in the buildings, determining the optimal insulation thickness for the exterior wall should be investigated. Therefore, optimal insulation thicknesses, energy savings, fuel consumptions and payback periods of the insulation material on the exterior wall of the building are examined by using Life Cycle Assessment and P_1–P_2 method for natural gas. Optimal insulation thicknesses are calculated for different insulation materials such as XPS, glass wool, rock wool and EPS for the climatic regions (HDD=800–4250°C days). According to average exergy losses from the building components per unit area, the average total exergy loss is calculated as 2.39×10^{-2} kW/m^2.year and 1.42×10^{-3} kW/m^2 (5.92%) of this loss stems from the exterior walls, 1.93×10^{-3} kW/m^2 (8.07%) from the floors, 7.37×10^{-4} kW/m^2 (3.08%) from the roofs, 1.58×10^{-2} kW/m^2 (65.99%) from the windows and doors, 4.04×10^{-3} kW/m^2 (16.92%) from the ventilation with infiltration. Energy requirement values of the building are found between 2.68–25.70 kWh/m^3 towards from the warmest to the coldest climatic region for the uninsulated wall. In the un-insulated state, fuel consumption varies between 1.93-18.48 m^3/m^2 from the warmest to the coldest region. The optimal insulation thickness values of the building's exterior wall are calculated as between 2.3–10.0 cm according to different climatic regions. In-state of exterior wall insulation of 3 cm, fuel consumption decreases by 46.63%–53.46% compared to different insulation materials and climatic regions compared to the un-insulated state.

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INTRODUCTION

In the world, energy demand is continuously increasing to cover this demand, different energy resources have been found or present energy resources new methods have been improved to use them more efficiently [1]. Nowadays, the efficient use of present energy resources is extremely important due to the decrease in fossil fuel resources and the increase in energy demand. In addition, energy efficiency has an increasing significance in Turkey and the world in terms of decreasing the negative effects on the environment of fossil fuels.

In the buildings, the biggest parts of the energy demand consist of space heating, cooling and domestic hot water production. To cover these demands mostly used fossil fuels, which released to the environment a high amount of CO_2 emissions. Therefore, energy is should be used more effectively in the building sector [2]. A district heating system (DHS) is transferred the heat produced in a Heat Plant to buildings for covering energy demands such as space heating and domestic hot water of the buildings on a campus or region. DHS is the only option in highly populated city centres because of advantages such as being more economical, more efficient and decreasing carbon emissions. The use of this system has been prevalent in highly populated cities and regions with cold climates in Turkey and the world [3-6].

In Turkey, total energy use in 2016 was 105 MTOE and 20% of this was consumed by the building sector [7]. To decrease this high energy use should be expanded more efficient and environmentally friendly heating systems. In energy use, to decrease waste energy and due to environmental problems, many countries have executed new standards to increase the efficiency of energy systems. Until 2050, the EU has planned to reduce energy use at the rate of 32-41% [8]. In the energy sector, decreasing carbon emissions caused by climatic changes has become an obligation to fulfil national and international standards. In the studies related to the district heating system, it has been mentioned to play an important role in the future of energy systems [9].

While energy is related to the first law of thermodynamics, exergy is related to the second law of thermodynamics. Energy cannot be created or destroyed; it only changes from one form to another. Exergy is described as the maximum work obtainable from a system. In real proses, exergy is always partially destroyed, and total exergy input always exceeds total exergy output. The exergy is interested in energy quality, not energy quantity. Exergy is the maximum theoretical work obtained from interaction with the system's environment until the system is reached a steady state between a system and its environment. In other words, exergy is a criterion of the potential of transformation to high-quality energy of energy flow [2]. Widely used in energy system analysis, exergy analysis is a useful method goal the more efficient use of energy resources for determining the real sizes, locations and types of irreversibilities or losses. To find where possible betterments can be made in the system is facilitated as the locations and sizes of exergy losses are identified thanks to the exergy method [10-11]. By applying to the building sector of the exergy method is obtained more complex information for the improvements and foresight in this field in the use of the energy flows [2].

While thermal insulation application in buildings is done to prevent the energy gained from the fuel burned in winter from turning into energy loss from the exterior walls in winter, to prevent the entry of hot air from the exterior walls into the interior in summer. With the application of thermal insulation in buildings, the fuel requirement can be decreased between 25% and 50% [12-13]. The advantages obtained by the application of thermal insulation in buildings can be listed as follows:

- Covering energy needs with less fuel consumption,
- Providing the comfort level in the buildings,
- To reduce environmental and air pollution and the greenhouse gas effect,
- To prevent the occurrence of adverse conditions affecting human health
- To reduce the fuel cost,
- To ensure that the surfaces of the buildings that are in contact with the outside air are affected by adverse weather conditions and that negative effects such as moisture, mould, and dampness do not occur,
- To reduce harmful gas emissions,
- Improving the life period of the building,
- Reducing the consumption of fossil fuel resources.

The thickness of the insulation material thickness must be determined by the thermal conductivity and cost of the insulation material with the average outdoor air temperature of the region. Increasing the insulation thickness not only fuel savings but also contributes to the decrease of $_{CO2}$ emissions. However, increasing the insulation thickness after a point will not affect the reduction of heat losses. Thus, a balance point should be determined between the insulation material cost with energy savings obtained, and this point is called the optimal insulation thickness [14-19].

The main purpose of investing is to contribute economically. For this reason, an economic analysis should be done before investing. In the economic analysis, parameters such as initial investment costs, interest and inflation rate, periodic income and expenses, economic life, and scrap value are taken into consideration. There are different economic analysis methods for determining and evaluating investments. Life Cycle Assessment is chosen between the economic analysis methods in identifying the optimal insulation thickness.

There are many studies related to the identification of the building performance with energy and exergy methods and optimization of insulation thickness in the building [20-26]. Zhou [27] investigated the thermal efficiency of the renewable energy used in library buildings in China through the exergy method. Elmegaard et al. [28] examined the conventional district heating system, which consists of 116 buildings, and has 159 m^2 of floor area and compared the energy and exergy efficiencies of the other heating systems. In the LTDH, solutions such as the utilization of electricity in the heating of domestic hot water annual heating costs were compared. In this study, annual hot water and space heating requirements of a building with a floor area of 159 m^2 were calculated respectively as 3200 kWh and 4010 kWh. The temperatures of supply and return water were measured between 30°C and 22°C for space heating and 50°C and 10°C for domestic hot water. Torio and Schmidt [2] conducted a study that examined a small district heating system in Kassel Province in Germany as a case study. . Some strategies were mentioned to increase the performance of the district heating systems based on waste heat and reported the results of the energy and exergy analysis of the district heating system in the study. Yazici [1] analyzed the energy and exergy methods of the Afyon geothermal heating system in Turkey. Sakulpipatsin et al. [29] performed the energy and exergy analysis on the office room simulated with 100 m^2 of floor area. Thermal energy and exergy losses were searched, and the exergy efficiency of all systems was calculated as 17.15%. Gonçalves et al. [30] conducted the exergy analysis by using real energy use data for a hotel building, located in Coimbra in Portugal. Annual energy demand and exergy efficiency were found as respectively 446 kWh and 17%. In this study, Gonçalves et al. [31] compared the performances of the energy and exergy relating to the space heating system in different outdoor circumstances. They designed a building model with 336 m^2 of floor area and 907.2 m^3 of heated volume. Yildiz and Gungor [32] performed the energy and exergy analysis of an office building with 240 m^2 of floor area in İzmir city in Turkey. In the study, indoor and outdoor temperatures were taken as respectively 20°C and 0°C. The energy and exergy analyses are done for all components of the space heating system in the building. Sayadi et al. [33] conducted the dynamic energy and exergy analyses of the buildings with 7,222 m^2 of total floor area on the campus of Aachen University in Germany by using data from 2015 year. In the study, U values of the exterior wall and window were calculated as respectively 1.22 and 0.19 W/m^2.°C. The annual energy requirements of the buildings were found as 105.1 kWh/m^2. Ozel [34] calculated the most suitable insulation thickness according to the climatic conditions of Elazig province in Turkey. In the study, energy savings and payback period are determined and the differences between uninsulated walls and insulated walls are explained with numerical data depending on the type of fuel used. The optimal insulation thickness for Elazig Province has been identified as 5.4 - 19.2 cm. It was determined that the energy-saving values ranged from 86.26 to 146.05 \$/m^2 and the payback period ranged from 3.56 to 8.85 years. Liu et al. [35] analyzed the optimal insulation thicknesses of three different cities in China, Changsha, Shaoguan and Chengdu based on the Life Cycle Assessment. In addition, payback periods of the insulation material have been determined in this study. Dombayci et al. [36] determined optimal thicknesses for provinces in four different climate regions in Turkey using the Life Cycle Assessment method. In the study, Polystyrene and polyurethane were chosen as insulation materials and natural gas was used as fuel. While minimum insulation thickness was found in warm areas for four climatic regions, maximum insulation thickness was obtained in cold areas. Bolattürk calculated optimal insulation thicknesses, energy savings, and payback periods for 16 cities in four different regions in Turkey. In his study, Life Cycle Assessment and Heating Degree Day method were used. Different types of fuel were used in the study such as natural gas, coal, fuel oil and electricity, and Polystyrene was chosen as the insulation material. According to the results obtained in this study, the optimal insulation thickness varied between 2 cm and 17 cm. The amounts of energy savings were calculated from 22% to 79%. The payback periods were determined as 1.3–4.5 years. Comakli and Yuksel [37] examined the optimization of thermal insulation for Turkey's coldest eastern provinces such as Kars, Erzurum, and Erzincan. In their study, the optimization analysis was based on the Life Cycle Assessment. According to research data, energy savings were obtained as 12.12 \$/m^2 for the province of Erzurum. Kaynakli [38] investigated thermal insulation thickness for the province of Bursa and a prototype building. In the study, the outdoor temperatures of Bursa province were taken into account from 1992 to 2005. In the calculations, optimal insulation thicknesses were compared according to different fuels according to Life Cycle Assessment and degree-hour values method. As a result of the analysis, for the province of Bursa, the optimal insulation thicknesses have been determined as between 5.3 - 12.4 cm. Kurekci [39] found the optimal thickness of 81 different cities in Turkey for four different fuels (natural gas, coal, LPG, and fuel oil) and five various insulation materials (expanded polystyrene, glass wool, rock wool, polyurethane, and extruded polystyrene). Kucuktopcu and Cemek [40]conducted a study based on thermal insulation for poultry buildings wall in different cities in 4 different climatic regions of Turkey. The investigations were made for the provinces of Samsun, Ankara, Erzurum, and Antalya. In the study, payback period, insulation thickness, and energy-saving calculations of the poultry buildings have been conducted; the calculations were examined according to five different fuel types (natural gas, coal, fuel oil, electricity, and LPG) and two different types of insulation material (extruded polystyrene and expanded polystyrene). Rosti et al. [41] conducted a study to identify the optimal insulation thickness for the exterior wall types of the building by first investment cost and payback period of insulation material for all climatic regions in Iran. In the study, the optimization was done by using the Life Cycle Assessment method with a numeric solution. Jie et al. [42] used an optimization model, which identified the effects on energy grade and amount of energy of the insulation to determine the optimal economic insulation thickness of the building's exterior walls in the DHS. An existing residential building in Beijing, China, was used as the basis of the case study.

In this study, energy and exergy analyses of the buildings on the campus of the 18th Regional Directorate of Highways, located in Kars Province of Turkey, are conducted by using actual operating data and taking measurements in the DHS as a case study. On the campus, there is a total of twenty-two buildings of different types and sizes, consisting of lodging buildings, office buildings and workshop buildings, laboratory buildings, gymnasiums, guest houses, head offices, and security buildings. The total floor area of the buildings is 17,836 m^2. Annual heating requirements of all buildings on the campus and the energy and exergy losses are calculated by using data on average daily outdoor temperatures. Due to the high heat losses in the buildings, the determination of the optimal insulation thickness for the exterior wall should be investigated. Therefore, optimal insulation thicknesses, energy savings, fuel consumptions, and payback periods of the insulation material of the building's exterior wall are examined by using the Life Cycle Assessment and P_1-P_2 method for natural gas. Optimal insulation thicknesses are calculated for different insulation materials such as XPS, glass wool, rock wool, and EPS for the climatic regions.

The novelty and literature contributions of this study mainly include the following points:

- Energy and exergy analysis of buildings has been conducted in a low-temperature district heating system as a case study.
- Optimal insulation thickness of the exterior wall on the buildings has been analysed based on heat gains consisting of the sun and internal heat gains and heat losses together. In the literature, many papers on the determination of optimal insulation thickness studied only heat losses, especially using the Heating Degree Method. Besides, optimal insulation thicknesses have been investigated for all climatic regions in Turkey.

ENERGY AND EXERGY ANALYSIS

In the district heating system, the heat generated in the boilers is transferred by heat distribution networks to the buildings on the campus. Space heating and domestic hot water demands of the buildings are covered with the heat transferred. The energy flows of the main parts of the system are indicated in Fig. 1.

Energy Analysis of Buildings on Campus

The equations can be used to calculate heat losses that occurred by conduction and convection from the exterior component such as the floor, roof, windows, doors and exterior wall in the building [43-44].

The specific heat loss from the building by heat transfer,

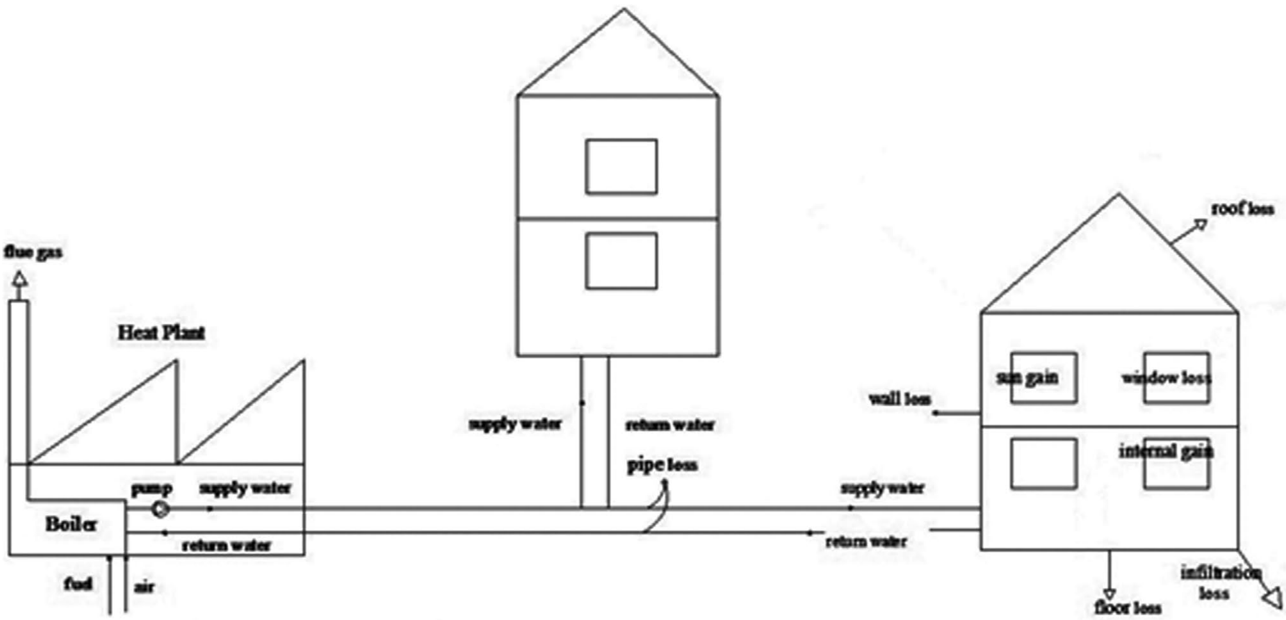

Figure 1. Scheme of the energy flows in the system.

$$H_T = \Sigma A \times U + L_{HB} \times U_{HB} \quad (1)$$

specific heat loss from the building by ventilation,

$$H_V = \rho \times C_P \times n_V \times V_V \quad (2)$$

and total specific heat loss (H) is expressed as:

$$H = H_T + H_V \quad (3)$$

In the building, internal heat gains consist of the cooking process, lighting system, electrical devices, and metabolic gain from the people. While in normally equipped buildings like houses and schools the internal gains are taken at a maximum of 5 W/m^2 per unit usage area, in buildings operated with abnormal electrical equipment like a factory or plant the internal gains are taken at a maximum of 10 W/m^2 per unit usage area according to "TS825 Thermal insulation requirement for building standard" [44].

$$\text{Ø}_{IG} = (5-10)\frac{W}{m^2} \times A_N \quad (4)$$

Sun gains,

$$\text{Ø}_{SG} = \Sigma r_I \times s_I \times I_I \times A_I \quad (5)$$

The monthly gain-loss ratio and gain-loss factor can be calculated as [43-44]:

$$GLR_M = \frac{(\text{Ø}_{IG} + \text{Ø}_{SG})_M}{H \times (T_i - T_O)_M} \quad (6)$$

$$\pi_M = 1 - e^{(-1/GLR_M)} \quad (7)$$

Energy requirements are given as these equations:

$$\dot{Q}_M = [H \times (T_i - T_O) - \pi_M \times (\text{Ø}_{IG} + \text{Ø}_{SG})] \times \mathrm{t} \quad (8)$$

$$\dot{Q}_Y = \Sigma \dot{Q}_M \quad (9)$$

Exergy Analysis of Buildings on Campus

The exergy balance equations of the buildings on the campus are shown as [45]:

$$\dot{E}_{SUPPLY} - \dot{E}_{RETURN} = \sum I_T \quad (10)$$

$$\dot{E}_{SUPPLY} - \dot{E}_{RETURN} = \dot{m}_W \times [(h_{WS} - h_{WR}) - T_O \times (S_{WS} - S_{WR})] = \dot{m}_W \times \left[C_P \times (T_{WS} - T_{WR}) - T_O \times C_P \times In\frac{T_{WS}}{T_{WR}} \right] \quad (11)$$

Net total heat losses are found by deducting the heat gains from the total heat losses of the system.

$$\dot{Q}_T = \dot{Q}_{PL} + \dot{Q}_{FL} + \dot{Q}_{VL} + \dot{Q}_{WL} + \dot{Q}_{GL} + \dot{Q}_{RL} - \dot{Q}_{SG} - \dot{Q}_{IG} \quad (12)$$

The total irreversibility of the system can be calculated as Eq.13.

$$\Sigma I_T = \dot{Q}_T \times \left(1 - \frac{T_O}{T_S}\right) \quad (13)$$

Optimization of Insulation Thickness of Building's Exterior Wall

Life Cycle Assessment and the P_1-P_2 method have been selected as economic analysis methods for identifying the optimal insulation thickness of a building's exterior wall. To conduct an economic analysis should be considered economic parameters such as fuel and insulation material costs, operation and maintenance costs, energy savings, lifetime and interest and inflation ratios.

Annual fuel consumption from heat losses of the exterior walls of the building

$$\dot{V}_{pl} = \frac{\dot{V}_f \times \dot{Q}_{wall}}{\dot{Q}_f \times \eta_s} \quad (14)$$

fuel energy consumed by the heating system,

$$\dot{Q}_f = \dot{V}_f x H_u \quad (15)$$

and the cost of the fuel consumption from heat losses of the walls can be calculated with these formulas.

$$C_{fl} = \dot{V}_{pl} x C_f \quad (16)$$

The cost of insulation material,

$$C_{ins} = A_{wall} x C_i \quad (17)$$

And energy savings can be found using the equations given below.

$$\dot{Q}_{es} = \dot{Q}_{un-ins} - \dot{Q}_{ins} = \left[\left(\frac{1}{R_i + \frac{d_1}{k_1} + \frac{d_2}{k_2} + \dots \frac{d_n}{k_n} + R_0} \right) - \left(\frac{1}{R_i + \frac{d_1}{k_1} + \frac{d_2}{k_2} + \frac{d_{ins}}{k_{ins}} + \dots \frac{d_n}{k_n} + R_0} \right) \right] \times (T_W - T_a) \quad (18)$$

To identify the optimal insulation thickness of the building's exterior walls, the Life Cycle Assessment has been preferred. While calculating the total cost, which consists sum of fuel cost and insulation material cost the lifetime and the current value factor (P_1) should be evaluated together. P_1 changes according to the interest ratio, inflation ratio and the lifetime of the insulation material. The net energy savings obtained by insulation material can be calculated by using the P_1-P_2 method. The present value factor can be found in the following equations [14-19].

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

$$P_1 = \frac{N}{(i+1)} \;\; if \;\; i = d \tag{20}$$

$$P_2 = 1 + P_1 \times C_m - \frac{r_v}{(1+d)^N} \tag{21}$$

In case the maintenance and operation costs are not available, the value indicating as P_2 can be taken as one. The total cost and net energy savings can be calculated annually by using the following formulas [41-47].

$$C_{tot} = P_1 \times C_{fl} + P_2 x C_{ins} \tag{22}$$

$$E_s = P_1 \times \dot{C}_f - P_2 \times C_{ins} \tag{23}$$

where C_f' shows the difference in energy costs between the uninsulated and insulated exterior walls of the building.

System Description

The space heating and domestic hot water needs of the buildings on the campus called as 18th Regional Directorate of Highways, located in Kars Province of Turkey, are supplied by the low-temperature district heating system (LTDH). In the LTDH, there are four condensing hot water boilers with an equal capacity of 1250 kW. The average yearly fuel use of the system was 809,793.50 m^3 for the last three years. The supply and return water temperatures of the boiler were measured in changing temperatures between 50°C and 60°C.

On the campus, there is a total of twenty-two buildings of different types and sizes, consisting of lodging buildings, office buildings and workshop buildings, laboratory buildings, gymnasium, guest house, head office and security buildings. The total ground floor area of the

Figure 2. The satellite image of the DHS.

Table 1. Calculated U values and areas of the buildings on the campus

Buildings		Exterior wall types				Roof	Floor	Door	Window
		EW1	EW2	EW3	EW4	R	F	D	W
U(m^2.K/W)		0.2335	0.2329	0.2298	0.2335	0.1497	0.4904	4	2.2
Head Office	1×A (m^2)	618	1894	773	425	3297	2943	168	1163
Guest House	1×A (m^2)	566	683	0	371	2121	1894	20.8	861
Lodging Buildings	8×A(m^2)	648	1648	528	208	377	337	20.8	460
Manager Residence	1×A (m^2)	503	608	180	117	314	281	12.5	280
Laboratory building	1×A (m^2)	319	1291	0	1006	2237	1997	6.6	662
Gymnasium	1×A (m^2)	318	849	0	490	1684	1503	12,25	422
Storehouses	2×A (m^2)	819	0	0	334	1112	993	47.25	69.2
Machine shop1	1×A (m^2)	0	642	0	287	383	342	6.6	168
Field supervisor	1×A (m^2)	0	572	0	481	353	315	12	121
Labour locker building	1×A (m^2)	0	501	0	171	223	199	13.2	38.4
Gas station	1×A (m^2)	72	45	0	0	49.3	44	4.62	7.46
Workshop	1×A (m^2)	2172	0	0	108	2811	2510	99	180
Machine shop2	1×A (m^2)	580	0	0	228	842	752	22.05	26.4
Security building 1	1×A (m^2)	298	0	0	0	31	28	4.6	19.76
Security building 2	2×A (m^2)	280	0	0	0	28	26.5	4.6	38
Repair and maintenance of building	1×A (m^2)	230	0	52	86	321	287	83.25	26.4

buildings is 17,836 m^2. In Fig. 2, satellite image of the DHS is given.

In the optimization analysis, the Life Cycle Assessment and P_1-P_2 method are used to identify the optimal insulation thickness of the building's exterior walls decreasing heat losses and saving energy. Optimal insulation thicknesses are calculated for different insulation materials such as XPS, glass wool, rock wool and EPS for natural gas and the climatic regions in Turkey.

RESULTS AND DISCUSSION

Energy and Exergy Analysis Buildings on Campus as a Case Study

To examine heat losses from the building envelopes on the campus should be severally calculated total thermal transmittance coefficients of the parts such as the exterior wall, floor and roof. The specific heat losses and annual energy requirements of all buildings on the campus are calculated.

Depending on the various materials in the components of the buildings, the different types of exterior wall U values are calculated as 0.2299 -0.2613. While depends on floor types U values are changed between 0.4879-0.4904, according to different roof types, U values are changed between 0.1497-0.1571. Calculated U values of all buildings and building component areas such as the exterior wall, roof and floor are shown in Table 1. U values of the building components such as doors and windows are taken the standard of TS EN ISO 13789[43].

Values of the hourly outdoor temperatures taken Turkish State Meteorological Service for December month are given in Fig 3. The annual heating energy demand of the Gymnasium building is calculated as 339,943.0 kWh. The specific heat losses and annual heating energy requirements of all buildings on the campus are calculated, and the results are shown in Table 2.

The total ground floor area of all buildings on the campus is 17,836 m^2 and total heat losses from all buildings are found as 76,163.5 W/K. Annual heating energy requirements of the buildings are calculated as 5,963,929.22 kWh. There are four natural gas-fired condensing boilers, with an equal capacity of 1250 kW in the Heat Plant of the DHS. The annual fuel use of the system was 809,793.50 m^3 for the last three years. Input fuel energy and exergy to the system are respectively calculated as 833.36 kW and 919.45 kW. In Fig. 4, monthly fuel exergy values calculated are shown in the 2018 year.

The total heat loss of all buildings on the campus is found as 691.55 kW, and 13.67% of this loss stems from the exterior walls, 5.76% from the floors, 3.17% from roofs, 26.33% from the doors and windows, and 51.06% from

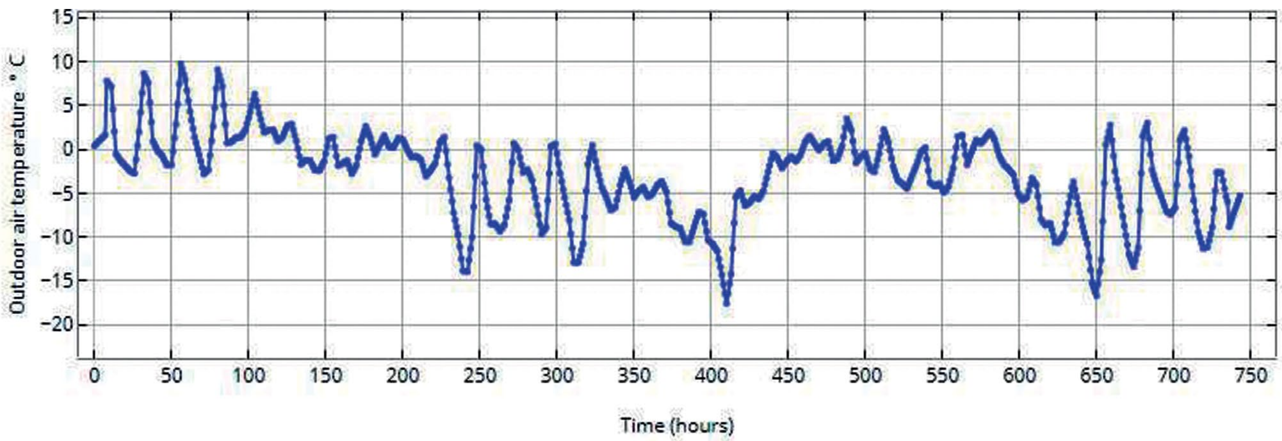

Figure 3. Hourly outdoor temperature values for December month.

Table 2. Annual heating energy demands of the buildings on the campus

	Floor area (m^2)	Heated volume (m^3)	Specific heat loss (W/K)	Heat supply kWh/year
Head Office	2,943	50,032	15,774.71	1,232,343.81
Guest House	1,894	20,834	7,387.42	561,995.01
Lodging Buildings	2,973	43,113	25,613.96	1,972,516.95
Office Buildings and Workshops	6,451	34,693	14,756.18	1,201,645.21
Laboratory building	1,997	23,964	7,909.22	615,840.95
Gymnasium	1,503	10,523	4,171.02	334,942.99
Security buildings	75	271	550.99	44,644.30
Total	17,836	183,430	76,163.50	5,963,929.22

the ventilation with infiltration. According to average heat losses from building components per unit area, the total heat loss is calculated as $3.6x10^{-2}$ kW/m^2 and $2.17x10^{-3}$ kW/m^2. year (6.04%) of this loss stems from the exterior walls, 6.31% from the floors, 3.14% from the roofs, 67.26% from the windows and doors, and 17.24% from the ventilation with infiltration.

The total exergy loss ratio of all buildings is calculated as 4.15%, and 0.56% of this stems from the exterior walls, 0.31% from the floors, 0.13% from the roofs, 1.07% from doors and windows, 2.08% from the ventilation with infiltration. The highest heating energy requirements of the buildings are found as 71.65 kW in January month. In Fig. 5, the chances of exergy loss from the building components are shown depending on outdoor temperatures. As can be seen in Fig. 5, the heat losses from the buildings increase depending on the outside temperatures the components such as the exterior wall and the window have a large contact area with the outdoor conditions. Therefore it has been increased the exergy losses from these components. But a large change has no observed in exergy losses from the roof and floor according to the other components of the building.

According to average exergy losses from the building components per unit area, the average total exergy loss is calculated as $2.39x10^{-2}$ kW/m^2.year and $1.42x10^{-3}$ kW/m^2 (5.92%) of this loss stems from the exterior walls, $1.93x10^{-3}$ kW/m^2 (8.07%) from the floors, $7.37x10^{-4}$ kW/m^2 (3.08%) from the roofs, $1.58x10^{-2}$ kW/m^2 (65.99%) from the windows and doors, $4.04x10^{-3}$ kW/m^2 (16.92%) from the ventilation with infiltration. In Fig. 6, the exergy losses for all buildings and the building per unit area according to average values in the campus are shown according to average daily outdoor temperatures during the 2018 year. Heat losses and exergy losses reach their maximum value on days when heating need is high due to low outdoor temperature values. However, in cases when the outdoor temperature value is high and there is no need for heating, the

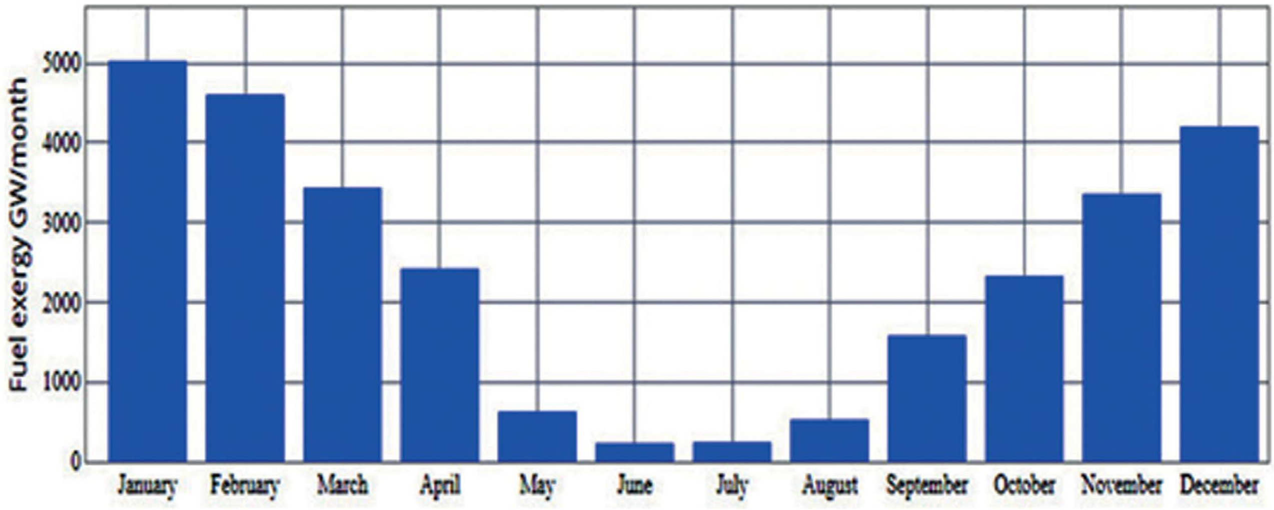

Figure 4. Input fuel exergy to the system.

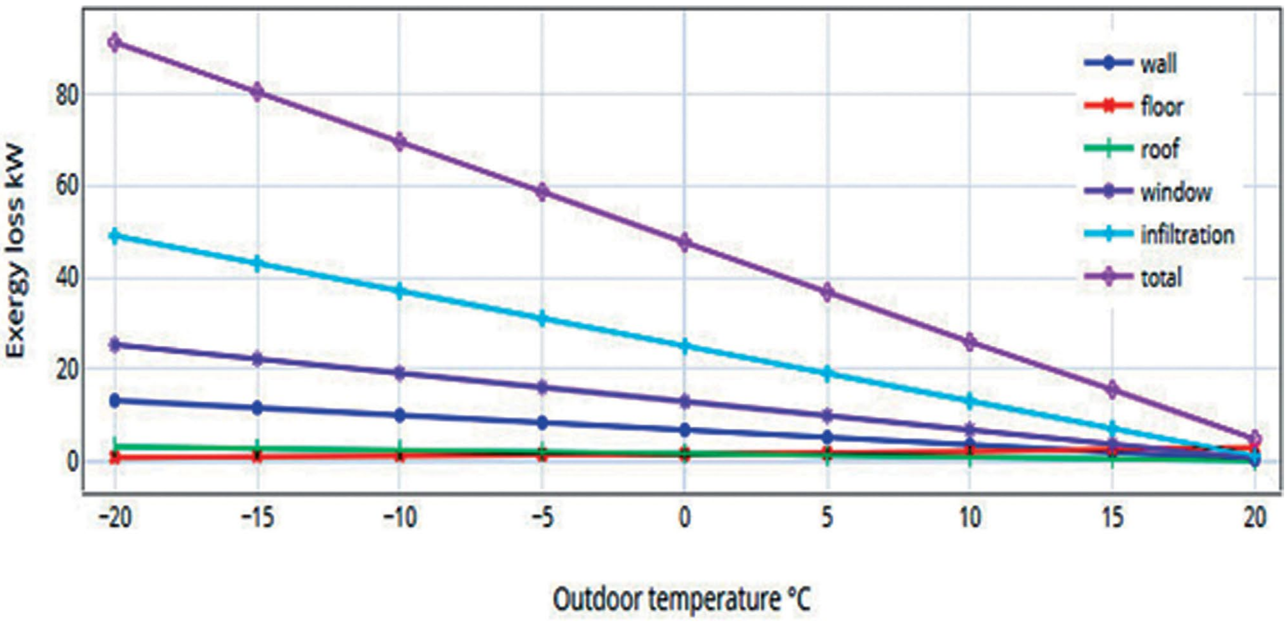

Figure 5. Exergy loss from buildings in the DHS depending on outdoor temperatures.

exergy losses take the minimum value. The highest exergy loss has occurred from the windows and doors with 65.99% per unit area.

The heat losses from the distribution networks in the DHS are figured out as 46.48 kW, and 31.07 kW of this loss stems from the supply and return water pipes and 15.41 kW from hot water and circulation pipes. Considering all components of the district heating system, the heat loss ratio from all pipes in the distribution networks is calculated as 5.44%. The exergy loss and ratio from the pipes in the distribution networks are respectively found as 41.55 kW and 4.52%, and 3.08% of this occurs from supply and return water pipes of the system. Input exergy to the system is losses of 4.52% from the distribution networks, 4.15% from all buildings, and 3.04% from the flue gas.

Optimization of Insulation Thickness of Building's Exterior Wall

Thermal insulation should be done to reduce heat losses and obtain energy savings in the buildings. Determining the optimal insulation thickness in thermal insulation applications is important in terms of less initial investment

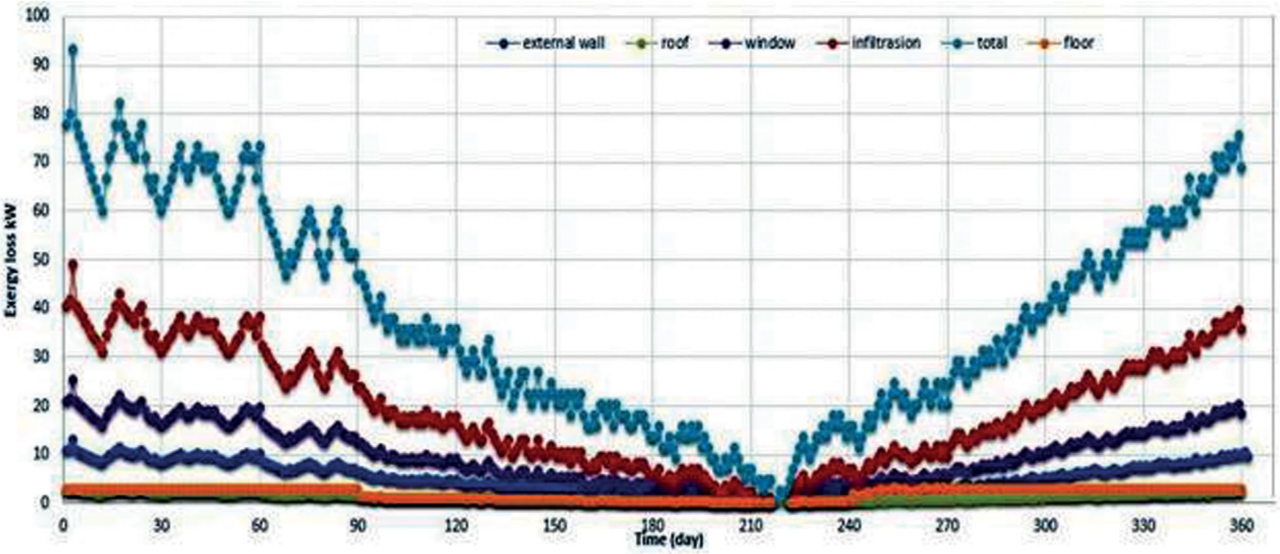

Figure 6. Exergy losses from the building components during 2018 year.

Table 3. Parameters used in the economic analysis [15;36;39]

Parameters	**Values**			
Heating degree day (HDD)	800–4250°C days			
Insulation material	XPS	EPS	Rock wool	Glass wool
Price, C_i	180 \$/m^3	120 \$/m^3	95 \$/m^3	75 \$/m^3
k_i	0.032 W/m^2.K	0.039 W/m^2.K	0.035 W/m^2.K	0.040 W/m^2.K
Fuel	Natural gas			
Price, C_f	0.5022 \$/m^3			
H_u	8250 kcal/m^3			
Efficiency of heating system	93%			
Interest rate, i	10%			
Inflation rate, d	11%			
Lifetime, N	10 years			

cost and high energy savings. Due to the high heat losses in the buildings, the determination of the optimal insulation thickness for the exterior wall should be investigated. In this study, the Life Cycle Assessment and P_1-P_2 method are used to determine the optimal insulation thickness on the exterior walls of buildings to decrease heat losses and save energy. The parameters and values used in the economic analysis are given in Table 3.

The heat loss from the exterior wall varies according to the different insulation materials and insulation thickness in the insulation applications in buildings. In Fig. 7, the change of heat loss from the building's exterior wall is shown according to insulation material types such as XPS, EPS, glass wool and rock wool and depending on insulation thickness. While the heat loss from the exterior wall decreases depending on the insulation thickness; it increases according to the size of the thermal conductivity coefficient of the insulation material. Among the materials analyzed, XPS thermal insulation material is the best material that reduces heat loss from the exterior wall because of low thermal conductivity.

The energy requirement of the building decreases as the insulation thickness on the exterior wall increases. In Fig. 8, the change of energy requirement is given for HDD = 2415°C days according to un-insulation, different insulation thicknesses and insulation materials. Because of low thermal conductivity, the minimum energy requirement is achieved with XPS insulation material, as it reduces

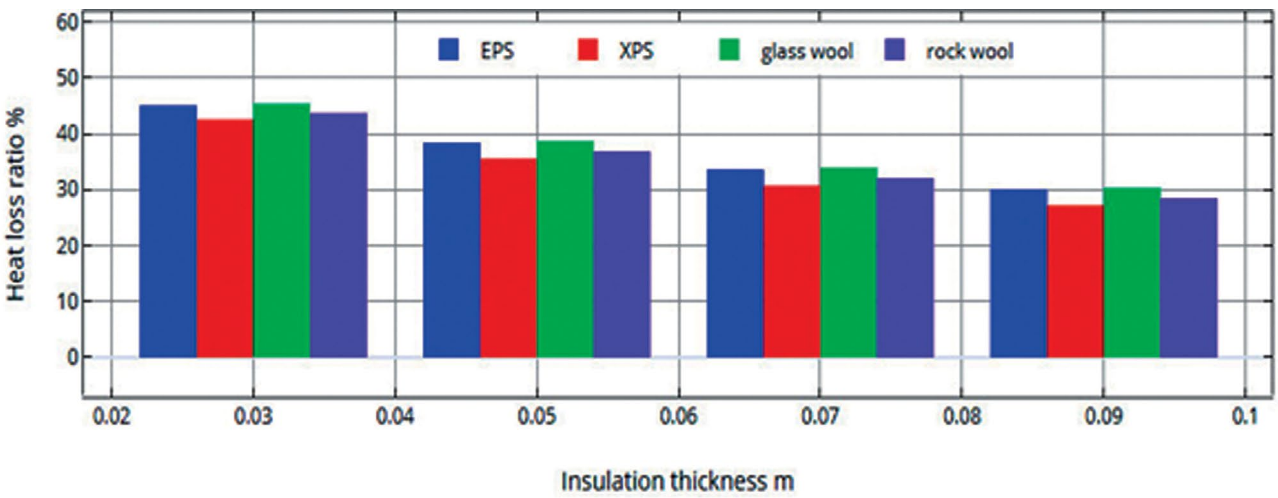

Figure 7. Change of heat loss ratio according to the insulation thickness on the exterior wall.

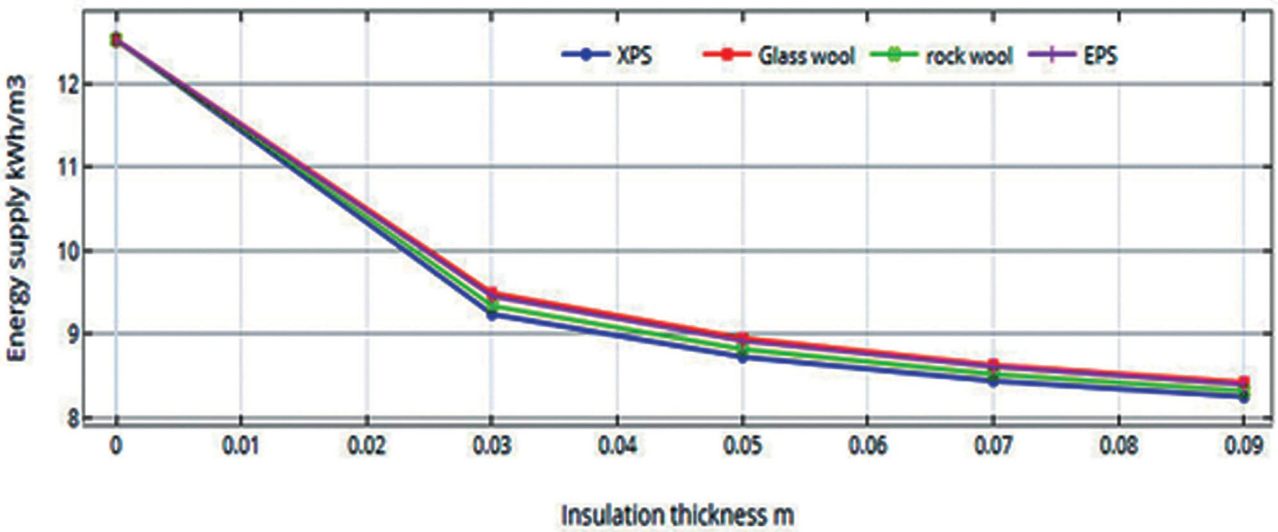

Figure 8. Effect on energy supply of building insulation thickness and material type for HDD= 2415°C days.

heat losses from the exterior wall by applying insulation on the exterior wall. In Fig. 9, the change in the energy requirements of the buildings is shown according to HDD and different insulation materials for insulation thickness. While the energy requirement values of the buildings varied between 2.68-25.70 kWh/m^3 from the warmest climatic region to the coldest climatic region for the un-insulated wall; the values fluctuated between 1.69-19.35 kWh/m^3 according to different insulation thicknesses and insulation materials.

Variations of insulation, fuel, and total annual costs depending on the insulation material thickness are given in Fig. 10 for HDD=1300°C days and XPS insulation material. Although the insulation material cost rises by increasing the insulation material thickness, the fuel cost decreases due to the reduction of heat losses thanks to the insulation material. The total cost curve decreases up to one point according to the insulation thickness and then starts to increase. The insulation thickness corresponding to this point indicates the optimal insulation thickness.

By the insulation application, heat losses from the building's exterior wall are reduced and fuel savings is provided. Using a bigger insulation thickness than the optimal insulation thickness doesn't increase energy savings and raises the insulation cost too.

The optimal insulation thickness of the building's exterior wall increases due to the decrease in the outdoor temperature values towards the coldest climate region. While

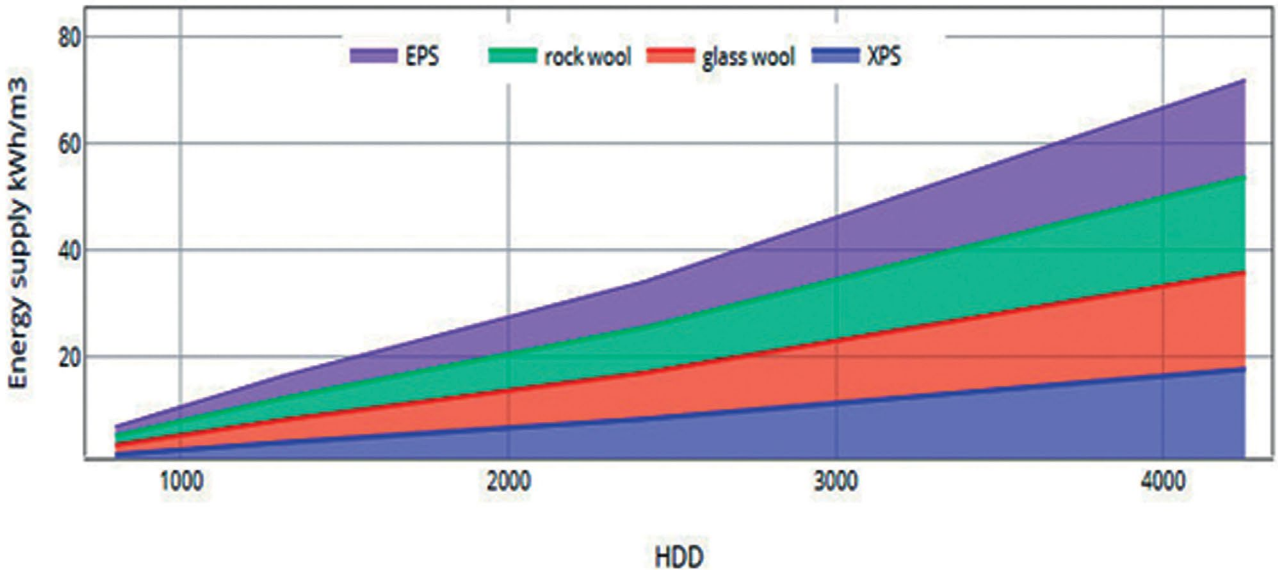

Figure 9. Effect on energy supply of the building of insulation material type depending on HDD.

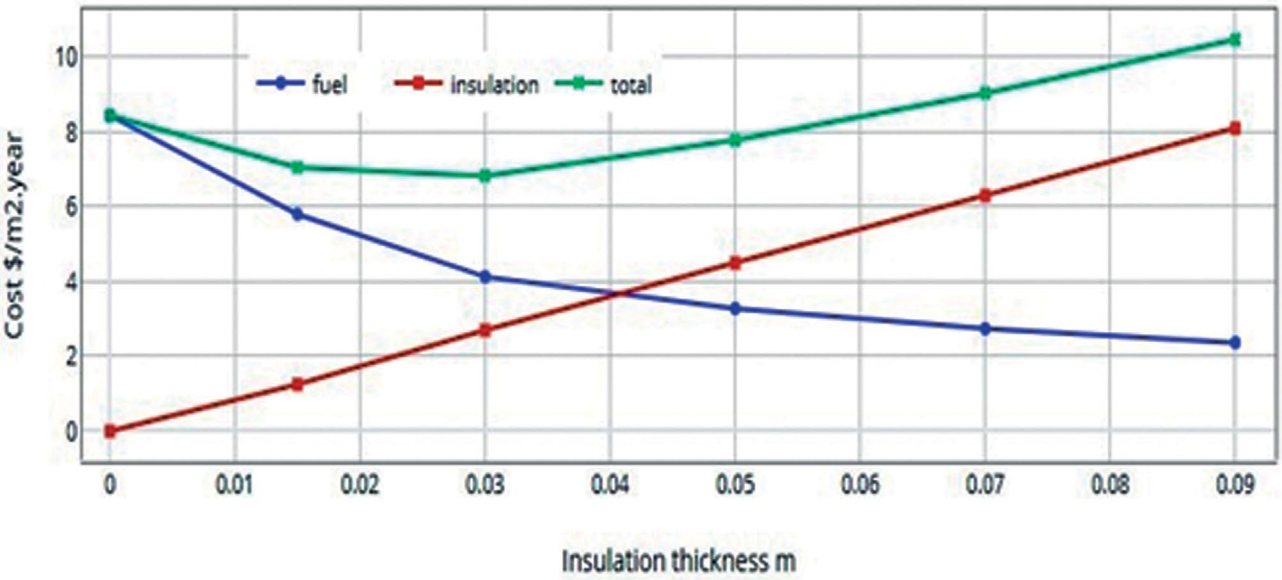

Figure 10. Changes of annual cost values according to the insulation thicknesses for XPS material and HDD=1300°C days.

the highest optimal insulation thickness values are obtained for glass wool material; the values are reached close to each other in the rock wool and EPS materials.

The lowest optimal insulation thickness values are reached for XPS insulation material because of lower thermal conductivity compared to other materials. The optimal insulation thickness values on the exterior wall are calculated as between 0.0230-0.0572 m for XPS, 0.0308-0.0777 m for EPS, 0.0341-0.0834 m for rock wool and 0.0412-0.1005 m for glass wool according to different climatic regions. Obtained results from the analysis were compared to the study by Kürekçi [39] and it was observed that the results were compatible with each other. In Fig. 11, optimal insulation thickness values on the exterior wall are given depending on the various climatic regions and insulation material.

Fuel consumption from heat losses of the building's exterior wall is changed between 1.93-18.48 m^3/m^2 in the un-insulated state from the warmest to the coldest region. In the insulated state, it has been observed that the fuel consumption varies between 0.50-9.05 m^3/m^2 for XPS,

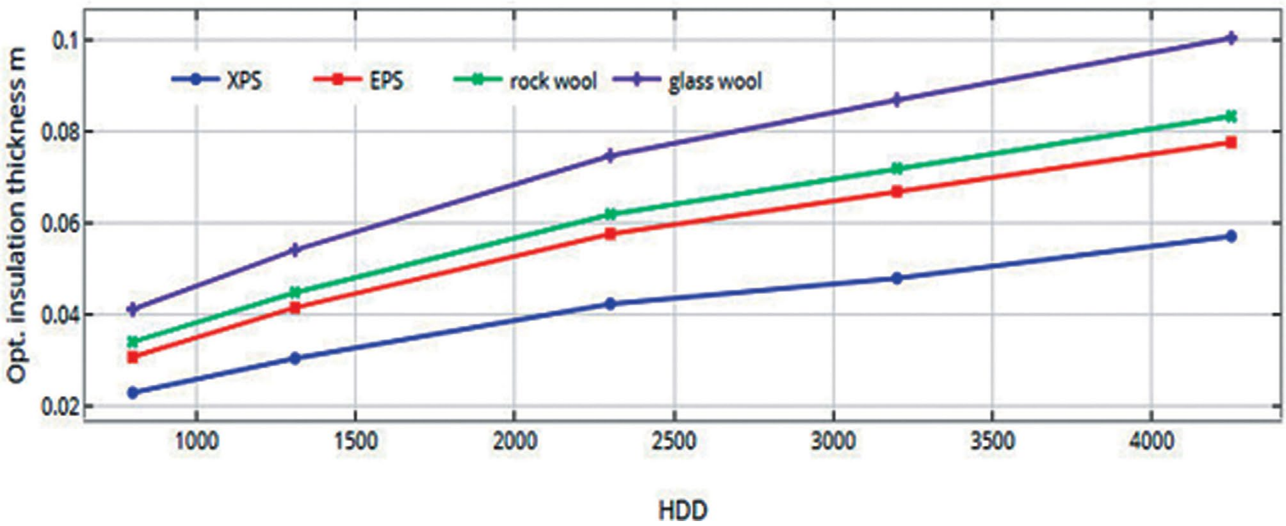

Figure 11. Optimal insulation thicknesses on exterior wall depending on the climatic regions and insulation material.

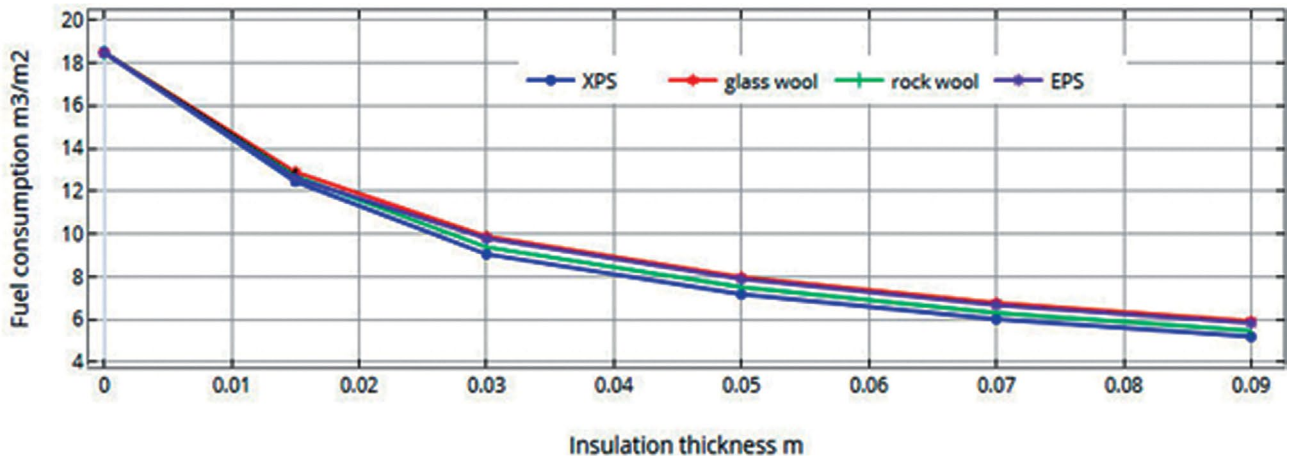

Figure 12. Fuel consumption from exterior wall for HDD = 4250°C days.

0.58-9.88 m^3/m^2 for glass wool, m^3/m^2 for rock wool, and 0.57-9.79 m^3/m^2 for EPS material. In Fig. 12, fuel consumption from the exterior wall is shown depending on various insulation thicknesses and insulation material types for HDD = 4250 °C days. As the insulation thickness increases, the fuel consumption values decrease. The lowest fuel consumption values are achieved in EPS material compared to other materials because of low thermal conductivity. In-state of exterior wall insulation of 3 cm, fuel consumption is decreased by 46.63% -53.46% compared to different insulation materials and climatic regions compared to the un-insulated state.

Total energy savings values are varied between 0.80-55.10 $/m² according to different insulation thicknesses, insulation materials, and climatic regions. According to the results, total energy savings is calculated as between 0.84-52.58 $/m² for XPS, 2.78-54.01 $/m² for glass wool, 2.09-55.10 $/m² for rock wool and 0.80-52.36 $/m² for EPS material. While the energy savings values provided by insulating during the economic life of insulation material reached the highest value in rock wool insulation material for certain insulation thickness and between HDD = 2400-4250°C days; the highest energy savings values are achieved in glass wool insulation material in the range of HDD = 800-2000°C days. In Fig. 13, energy savings values are given for rock wool insulation material according to different insulation thicknesses and climatic regions. The highest energy savings values are achieved by application

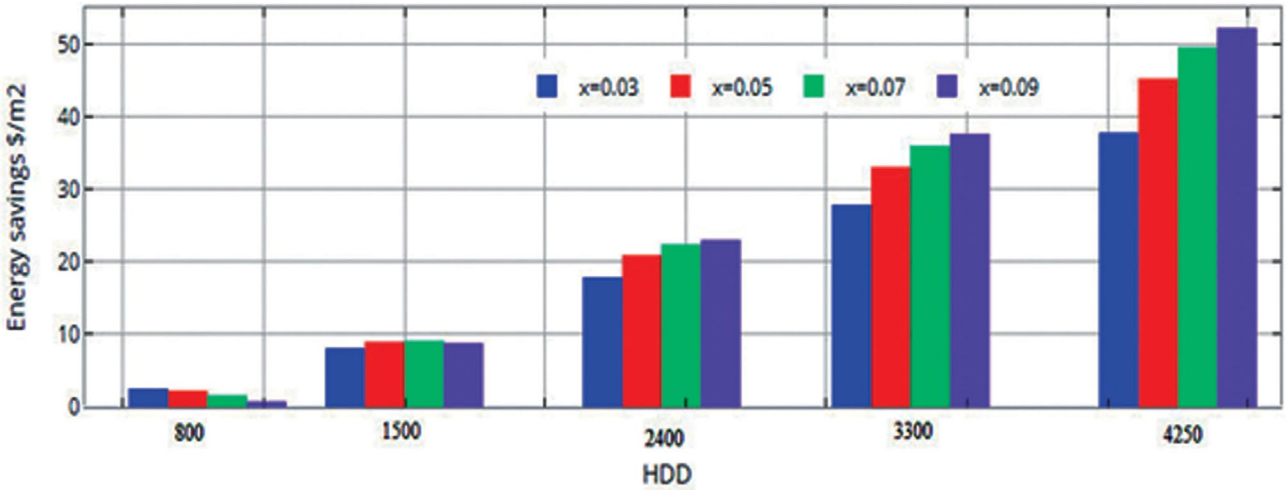

Figure 13. Energy savings values according to different insulation thicknesses and material type**.**

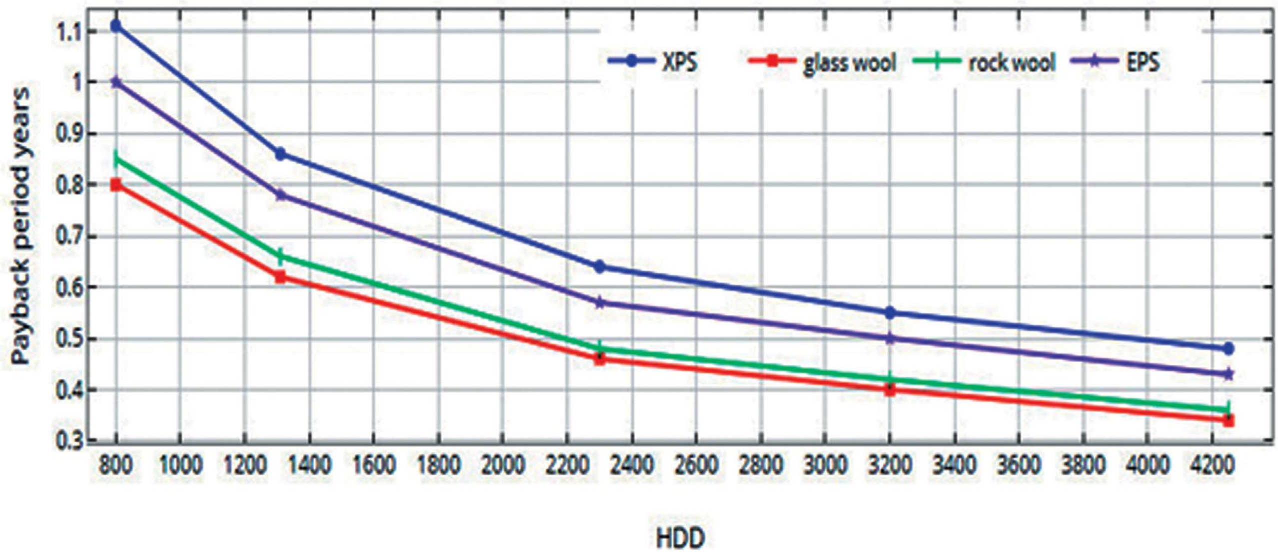

Figure 14. Changes in payback period values depending on the insulation material and HDD.

of the insulation in the coldest climatic regions. The importance of insulation is better understood from the figure, especially for cold climate regions.

The payback period that shows the value of energy savings achieved by applying insulation on exterior walls of buildings is equal to the initial investment cost and varies according to many variables such as fuel type, climatic region, insulation thickness and material type. Payback periods are obtained as between 0.2950-3.7161 years according to different insulation thicknesses, materials and climatic regions. As a result of the analysis, payback periods are found in the range of 0.6689-3.7161 years for XPS insulation material, 0.2950-1.3533 years for glass wool, 0.3553-1.7101 years for rock wool, and 0.4751-2.3378 years for EPS. In Fig. 14, payback period values are shown according to different insulation materials and climatic regions. Glass wool material has the lowest payback period in all climatic regions due to its low cost. In addition, payback periods decrease towards cold climates because of the high energy savings.

CONCLUSION

In this study, energy and exergy analyses of the buildings on the campus of the 18th Regional Directorate of Highways, located in the Kars Province of Turkey, are conducted by using actual operating data and taking measurements in the DHS as a case study. Annual heating requirements of all buildings on the campus and the energy and exergy losses are calculated by using data of average daily outdoor temperatures in 2018 year. Due to the high heat losses in the buildings, the determination of the optimal insulation thickness for the exterior wall should be investigated. Therefore, optimal insulation thicknesses, energy savings, fuel consumptions, and payback periods of the insulation material on the exterior wall of the building are examined by using the Life Cycle Assessment method for natural gas. Optimal insulation thicknesses are calculated for the different insulation materials such as XPS, glass wool, rock wool, and EPS for the climatic regions (HDD=800-4250°C days). The results of the energy, exergy and optimization analyses are summarized as:

- According to the results depending on the different materials in the building components in the buildings, the different types of exterior wall U values are changed to 0.2299 from 0.2613. While depends on floor types U values are changed between 0.4879-0.4904, according to different roof types U values are changed between 0.1497-0.1571. The total ground floor areas of all buildings on the campus are 17,836 m^2, and total heat losses from all buildings are found as 76,163.5 W/K. Annual heating energy demands of the buildings are calculated as 5,963,929.22 kWh. The annual fuel use of the system was 809,793.50 m^3 in 2018 year. The input fuel energy and exergy to the system are respectively calculated as 833.36 kW and 919.45 kW. The total heat loss of all buildings on the campus is found as 691.55 kW and 13.67% of this loss stems from the exterior walls, 5.76% from the floors, 3.17% from roofs, 26.33% from the doors and windows, and 51.06% from the ventilation with infiltration.
- The total exergy loss ratio of all buildings is calculated as 4.15% and 0.56% of this stems from the exterior walls, 0.31% from the floors, 0.13% from the roofs, 1.07% from doors and windows, and 2.08% from the ventilation with infiltration. According to average exergy losses from the building components per unit area, the average total exergy loss is calculated as $2.39x10^{-2}$ kW/m^2.year and $1.42x10^{-3}$ kW/m^2 (5.92%) of this loss stems from the exterior walls, $1.93x10^{-3}$ kW/m^2 (8.07%) from the floors, $7.37x10^{-4}$ kW/m^2 (3.08%) from the roofs, $1.58x10^{-2}$ kW/m^2 (65.99%) from the windows and doors, $4.04x10^{-3}$ kW/m^2 (16.92%) from the ventilation with infiltration. Input exergy to the system is losses of 4.52% from the distribution networks, 4.15% from all buildings, and 3.04% from the flue gas.
- Energy requirement values of the building are found between 2.68-25.70 kWh/m^3 towards from the warmest to the coldest climatic region for the uninsulated wall. In the uninsulated state, fuel consumption varied between 1.93-18.48 m^3/m^2 from the warmest to the coldest region. The lowest fuel consumption values are achieved in EPS material compared to other materials because of low thermal conductivity. In-state of exterior wall insulation of 3 cm, fuel consumption is decreased by 46.63% -53.46% compared to different insulation materials and climatic regions compared to the uninsulated state. While the highest optimal insulation thickness values are obtained for glass wool material; the values are reached close to each other in the rock wool and EPS materials. The lowest optimal insulation thickness values are reached for XPS material because of lower thermal conductivity compared to other materials. The optimal insulation thickness values on the exterior wall of the building are calculated as between 0.0230-0.1005 m according to different climatic regions. The total energy savings values to be provided during the economic life of the insulation are obtained as 0.80-55.10 $/$m^2$ depending on different insulation thicknesses, insulation materials and climatic regions. While the energy savings values provided by insulating during the economic life of the insulation material reached the highest value in rock wool insulation material for certain insulation thickness and between HDD = 2400-4250°C days; the highest energy savings values are achieved in glass wool insulation material in the range of HDD = 800-2000 °C days. Payback periods are obtained as between 0.2950-3.7161 years according to different insulation thicknesses, insulation materials and climatic regions. Glass wool material has the lowest payback period in all climatic regions because of low cost.

NOMENCLATURE

A_N	Building usage area, m^2
A_S	Surface heat transfer area, m^2
C_f	Fuel cost, $/$m^3$
C_{fl}	Annual fuel consumption cost occurred heat losses from wall, $/year
C_i	Cost of Insulation material per unit square, $/$m^2$
C_{ins}	Insulation cost, $
C_m	Maintenance and operation cost, $
C_{tot}	Total cost, $
C_p	Specific heat, kJ/kg.K
d	Inflation rate,%
d	Thickness of building component, m
$\dot{E}$	Exergy, kJ/s
E_s	Energy savings, $/m
GLR	Gain loss rate
h	Enthalpy, kJ/kg
H_u	Lower heating value of the fuel, kJ/m^3
i	Interest rate,%
I	Irreversibility

I_i	Sun radiation intensity in direction i, W/m^2
k	Thermal conductivity coefficient, W/m.K
L	Length, m
N	Lifetime, years
$\dot{m}$	Mass flow rate, kg/s
n_h	Air exchange rate, h^{-1}
R	Thermal transmittance resistance, m^2.K/W
r_i	Shading factor of transparent surfaces in direction I
r_v	Ratio of resale value to first cost
s	Entropy, kJ/kg.K
s_i	Solar energy transmission factor of the transparent elements in direction i
Q	Heat transfer rate, kJ/s
Q_f	Annual fuel energy consumed from the heating system, kJ/year
t	Time, s
T	Temperature, °C
To	Environment temperature, °C
U	Thermal transmittance coefficient, W/m^2.K
U_{HB}	Linear transmittance of heat bridge, W/m.K
V	Volume, m^3
V_f	Annual fuel consumption of heating system, m^3/year
V_{pl}	Annual fuel consumption occurred heat losses from wall, m^3/year

Greek symbols

ρ	Density, kg/m^3
Ø	Heat gains, kJ/s
η	Gain loss factor
η_s	Efficiency of heating system, %

Subscripts

i	Indoor
i	Insulation
un-ins	Uninsulation
C	Cost
D	Door
F	Floor
f	Fuel
G	Glass
G	Gain
HB	Heat bridge
HDD	Heating degree-day
LCCA	Life Cycle Assessment
L	Loss
M	Monthly
O	Outdoor
PL	Loss from pipe
R	Roof
S	Sun
t	Total
T	Transmission
TSE	Turkish Standard Institution
v	Ventilation
VL	Loss from ventilation or infiltration
WL	Loss from wall
WR	Return Water
WS	Supply Water
Y	Yearly

AUTHORSHIP CONTRIBUTIONS

Meryem Terhan: Investigation, Writing, Original draft, Software, Formal analysis, review & editing, Supervision, Methodology, Conceptualization, Project administration.

Sena Saliha Abak: Review & editing, Supervision.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

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

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