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Energy analysis of different types of buildings in Gonen geothermal district heating system

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ABSTRACT

Turkey is one of the top five countries for geothermal direct applications. However, in the space heating applications, a considerable amount of geothermal energy is wasted through the low thermal quality building envelopes. In the present study, the residential buildings in Gonen geothermal district heating system (GDHS) have been investigated to analyze their energy performance. The optimum insulation thicknesses of the building components, energy savings and payback periods were calculated for the four different insulation materials applied commonly on the building components. The optimization was based on the life-cycle cost analysis and the calculations were also extended to include coal and natural gas considering their wide usage for heating in the rest of the buildings in Gonen. The results proved that depending on the type of the energy and the insulation material optimum insulation thickness of the external walls, ceilings and floors varied between 2.2–12.2, 5.5–13.3 and 3.6–7.6 cm, respectively. In case of using optimum insulation thicknesses for all Gonen GDHS buildings the highest annual savings and the shortest payback periods for external walls, ceilings and floors were calculated as 1,926,454, 1,455,785 and 520,248 US$; 1.83, 1.23, and 1.44 years, respectively.

1. Introduction

Renewable energy is commonly accepted as a key subject for future life in the world primarily due to its advantages over the fossil fuels. The most important environmental benefit of the geothermal energy utilization is displacing the fossil fuel usage and reducing the adverse environmental impacts of the fossil fuel consumption [1]. Turkey is one of the top five countries for the direct geothermal applications because of its large installed capacity of geothermal district heating systems [2]. Almost 6 million m^2 of indoor space heated using geothermal energy in 20 district heating systems, in December 2008 [3]. As of December 2009, the total installed capacity of these systems (792 MWt) accounts for 17.2% of the estimated worldwide capacity of the district heating systems (4582 MWt) [4]. However, particularly in space heating applications of geothermal energy, a considerable amount of energy is wasted through the low thermal quality building envelopes, since it is regarded as cheaper and plentiful. While a large number of buildings could be heated by the district heating systems, it is much less virtually. Furthermore, crucial problems occur in many district heating systems, such as low comfort levels in buildings and the need of extra energy sources since no or little insulation is used in existing and new buildings. The local government officials in the town of Sandıklı had to install a coal-fired boiler to provide additional hot fluids to the existing geothermal district heating system. Similarly, in Bigadic, the temperature of the geothermal waters is raised by heating them using natural gas [3].

The heat losses in buildings generally occur through external walls, windows, ceiling, floors and air infiltration. Therefore, thermal insulation plays an important role in the reducing the heating energy consumption in buildings [5].

The thickness of the insulation material is chosen by considering the average ambient temperature of the region, thermal conductivity of the insulation material and its price. Increasing the thickness of the insulation material will not only increase energy saving but also decrease the air pollution. However, an insulation thickness which allows zero heat loss is neither practical nor economical. A balance point should be determined between the insulation material cost and the savings obtained. The balance point indicates the optimum insulation thickness [6].

There are many studies in the literature related to energy savings in the buildings and determination of optimum insulation thickness. Mohsen and Akash [7] calculated the heating loads for

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Nomenclature

C	cost (US\$/kg, US\$/m^3)
C_D	correlation factor
d	allowable error amount of the main mass average
DD	degree-days (°C-days)
E_A	required annual heating energy (J/m^2-year)
F	quantity of fuel (kg)
g	inflation rate
H_u	heating value (J/kg, J/m^3, kWh/kg)
i	interest rate
k	surface multiplication factor
m_fA	annual fuel consumption (kg/m^2-year, m^3/m^2-year)
n	sample size (number)
N	lifetime (years)
N	the main mass amount (number)
n_h	the amount of samples in the h layer (number)
N_h	the amount of layers in the h layer (number)
PWF	present-worth factor
q	heat loss (W/m^2)
Q	total heat loss (kW)
R	thermal resistance (m^{2}K/W)
S_h	the standard deviation of the h layer (number)
T	temperature (°C)
U	coefficient of heat conductivity (W/m^2 K)
x	insulation thickness (m)
z	the theoretical value of the standard normal distribution table

Greek letter

λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
η_s	efficiency of heating system

Subscripts

A	annual
cal	calculated
f	fuel
i	inside
I	insulation material
ins	insulation
o	outside
opt	optimum
sc	structural component material
sct	total structural componenet excluding insulation material
t	total

Abbreviations

EPS	expanded polystyrene
GDHS	geothermal district heating system
LCCA	life-cycle cost analysis
TS	Turkish Standard
XPS	extruded polystyrene

a typical single house using different insulation materials. It was shown that energy savings up to 76.8% could be achieved when expanded polystyrene was used for the wall and the roof insulation in Jordan. Hasan [8] used life-cycle cost analysis to determine the optimum insulation thickness for different wall structures. The results proved that savings up to 21 US\$/m^2 of the wall area were possible for rock wool and polystyrene insulation. The payback periods were determined as 1–1.7 years for rock wool and 1.3–2.3 years for polystyrene insulation depending on the type of the wall structure. Comaklı and Yuksel [9] determined the optimum insulation thickness of external walls of buildings for the three coldest cities of Turkey, Erzurum, Kars and Erzincan, and calculated 12 US\$/m^2-year savings could be achieved when the optimum insulation thickness was applied in Erzurum. Sisman et al. [6] determined the optimum insulation thickness of the external walls and the roofs for the four different degree-days regions of Turkey. They calculated the amount of the savings between 1.28 and 5.67 US\$/m^2-year for external walls, and 0.92–4.92 US\$/m^2-year for the roof. Bolatturk [5] determined optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours. The most important result stated in the study is that the use of insulation in building walls with respect to cooling degree-hours is more significant for energy savings compared to heating degree-hours in the first climatic zone, which has the warmest summer conditions, of Turkey. Kaynakli [10] calculated the optimum insulation thickness on a prototype building in Bursa. The variation of annual energy requirement of the building was investigated for various architectural design properties. The results show that the optimum insulation thicknesses vary between 5.3 and 12.4 cm depending on the fuel types and the most suitable fuel with respect to costs appears to be natural gas for all climatic regions in Turkey. Ucar and Balo [11] calculated the optimum insulation thickness of the external wall for four cities from four climate zones of Turkey, energy savings over a lifetime of 10 years and payback periods for the five different energy types and four different insulation materials applied externally on walls. The net energy savings were calculated using the P1–P2 method, which is a practical, well-known method and can be used for optimizing the size of insulation of external walls [5]. The results showed that energy cost savings vary between 4.2 US\$/m^2 and 9.5 US\$/m^2 depending on the city and insulation materials. Comaklı and Yuksel [12] investigated the environmental impact of thermal insulation for Erzurum province. They determined that CO$_2$ emissions were decreased by 50% when the optimum insulation thickness was used in external walls of buildings.

The Gonen GDHS, installed in Gonen, Balıkesir, is the first district heating system of Turkey. It began operation for 600 residences in 1987. As of the first quarter of 2009, the number of subscribers to the Gonen GDHS reached 2636 residences. In Gonen, the geothermal energy is used not only for residential heating but also for hotel heating and in process water preparation for tanneries. A large number of buildings in Gonen GDHS are old structures with inadequate insulation so their thermal quality doesn't satisfy the present insulation standards. This causes the rate of energy consumption related to heating of the buildings to be extremely high. In this paper, the residential buildings in Gonen GDHS have been investigated in order to analyze their energy performance. For simplicity in the analyses, sample buildings which characterize Gonen GDHS buildings were selected considering the structural diversity and the number of the buildings. The investigations conducted in the sample buildings have showed that the four different types of external wall and floor and the three different types of ceiling constructions have been mainly used in Gonen GDHS buildings. Using data collected from the sample buildings a reasonable estimation for the whole system buildings is made. The optimum insulation thicknesses of the building components (external walls, ceilings and floors), energy savings and payback periods are calculated for the four different insulation materials applied commonly on building components. Extruded polystyrene and expanded polystyrene as wall, glass wool and rock wool as ceiling and expanded polystyrene as floor insulation materials are selected. The optimization is based on the LCCA and the calculations are also extended to include coal and natural gas considering their wide usage for heating in the rest of the buildings in Gonen.

2. Structural features of the buildings

The existing structural features of the Gonen GDHS building components (external wall, ceiling and floor) were identified using the results of the investigations conducted on the sample buildings. The main mass in the sampling consists of 300 buildings, which is the total number of the residential buildings heated by the Gonen GDHS as of the first quarter of 2009. A number of 14 buildings, which disrupted the average, were excluded from the sampling in view of the sampling method used. So the sampling was carried out with remaining 286 buildings. The building complexes which consist of several (2–4) blocks separately were assumed to be a single building block since the blocks had the same structural features. The number of the sample buildings can be obtained by the Neyman method which is one of the stratified random sampling methods [13]:

$$n = \frac{\left(\sum N_h S_h\right)^2}{N^2 D^2 + \sum N_h S_h^2} \tag{1}$$

where n is the sample size, N is the number of buildings included in the main mass, N_h is the number of the buildings in the layer h, S_h is the standard deviation of layer h. In the above equation, $D^2 = d^2/z^2$ and, d is the amount of allowable error from the average of the main mass and z is the value in the standard normal distribution table.

According to the above equation, the buildings, which constitute the main mass, are divided into two layers with normal distribution. The layers include the buildings with 1–5 and 6 or more residences separately. The sample size (n) was calculated to be 56 with the error margin of 10%. The number of the samples entering each layer (n_h) in proportion to the standard deviation of the layers was determined by the following formula and are given in Table 1.

$$n_h = \frac{N_h S_h}{\sum N_h S_h} \cdot n \tag{2}$$

The selection of 56 buildings was made by using Kendall and Smith's random number table. Some of the data required for the analyses were obtained via measurements and survey studies carried out on the sample buildings in 2009 winter season. The constructions of the building components were determined by reviewing the architectural drawings obtained from the Council of Gonen GDHS.

The survey studies have showed that 91% of the sample buildings selected from Gonen GDHS does not comply with the "Thermal Insulation Regulation in Buildings" which is still being implemented in Turkey. Although insulation material is used in the new buildings (built after 2000), almost no insulation is available in the building components built before the year 2000. However, thermal rehabilitation has been detected to be performed later in some buildings in which heating problems were experienced during the winter seasons.

Table 1
Number of sample buildings and percentages.

Width of groups	Total number of buildings	%	Number of sample buildings	%
1–5 residences	203	71	12	21
6 and more residences	83	29	44	79
Total	286	100	56	100

A total of 300 buildings (2636 residences with 275,462 m^2 closed area) in the Gonen GDHS form the main mass in the study. Accordingly, the average area of a residence is to be 104.5 m^2. The number of floors and the percentage rates of the number of residences in each floor were determined via the survey studies conducted in the sample buildings. The total areas of the external walls, ceilings and floors of the whole Gonen GDHS buildings were calculated using the percentage rates. Tables 2–4 show the existing (with no or little insulation) and after optimum insulated situations of the Gonen GDHS building components, for mainly used types of wall, ceiling and floor constructions, respectively. In addition, the U values of the different types of constructions for each component and the total surface areas of old and new types of buildings are also given.

3. Determination of the optimum insulation thickness for structural components

In thermal insulation applications of the buildings, thickness of the insulation material can be determined by optimizing the target rate of energy saving and the investment costs. While the optimum insulation thickness is determined, some criteria such as number of heating days, daily heating period, ambient air temperature, unit price and the heating value of the fuel used, efficiency of heating system, insulating ability of thermal insulation material, unit price of thermal insulation material, lifetime of insulation material, inflation and interest rates and heat transfer characteristics of the building components must be taken into consideration. In this study, LCCA is used to determine the optimum insulation thickness.

According to TS 825, The Turkish Thermal Insulation Standard in Buildings, Turkey is divided into four degree-days regions. Gonen is in the second degree-days region and its value of heating degree-days is 1914 (at a base temperature of 18 °C) [14]. The unit prices and the lower heating values of geothermal energy, coal and natural gas, and the efficiency values of heating systems used in the calculations are given in Table 5.

Geothermal subscribers in Gonen GDHS paid as heating dues of 70 TL (Turkish Lira) (47.6 US$) per month for a residence with an area of 100 m^2 in 2009. In this case, the annual payment is to be 840 TL (571.4 US$). The unit price for geothermal energy is determined calculating the annual fuel consumption by [15],

$$F = \frac{24(\mathrm{DD})C_\mathrm{D}Q}{\eta_\mathrm{s}(T_\mathrm{i} - T_\mathrm{o})H_\mathrm{u}} \tag{3}$$

where DD is the value of degree-days (°C-days), C_D ($C_\mathrm{D} = 0.8$) is degree-days correlation factor for 18 oC base temperature, Q is the total heat loss (kW), η_s is system efficiency, T_i and T_o are internal and external temperatures (°C), respectively, and H_u is the lower heating value of the fuel (kWh/kg). In the calculation, the total heat loss for a residence with an area of 100 m^2 as 8.83 kW and $T_\mathrm{i} = 20$ °C, $T_\mathrm{o} = -6$ °C were considered.

In the calculations of optimum insulation thickness, XPS, EPS, glass wool and rock wool were used due to their wide usage in building applications in Turkey. In Gonen, while XPS and EPS ($\rho \geq 20$ kg/m^3) are mainly used in the exterior insulation of external walls, EPS ($\rho = 10$ kg/m^3) is more often used in the applications of the sandwich wall insulation. Furthermore, the glass wool and the rock wool as ceiling, EPS ($\rho = 16$ kg/m^3) as floor insulation material

Table 2
No or little insulated and optimum insulated constructions, U values and the total surface areas of the external walls.

External wall	Existing (no or little insulated) situation		Optimum insulated situation		Area (m^2)	
	Thickness (m)	Thermal conductivity (W/mK)	Thickness (m)	Thermal conductivity (W/mK)	Old[a]	New[b]
Wall 1						
Interior plaster	0.02	0.87	0.02	0.87	131,936	–
Hollow brick	0.19	0.45	0.19	0.45		
Insulation (XPS, EPS)	–	–	x_{opt}	0.028–0.034		
Exterior plaster	0.03	1.4	0.03	1.4		
	$U_{cal} = 1.571$ W/m^2 K		$U = 1/(R_{ins} + 0.637)$			
Wall 2						
Interior plaster	0.02	0.87	0.02	0.87	8915	8915
Hollow brick	0.19	0.45	0.19	0.45		
Insulation (XPS, EPS)	0.03–0.04	0.028–0.034	x_{opt}	0.028–0.034		
Exterior plaster	0.03	1.4	0.03	1.4		
	$U_{cal} = 0.585 - 0.552$ W/m^2 K		$U = 1/(R_{ins} + 0.637)$			
Wall 3						
Interior plaster	0.02	0.87	0.02	0.87	21,395	3566
Gas concrete	0.2	0.22	0.2	0.22		
Insulation (XPS, EPS)	–	–	x_{opt}	0.028–0.034		
Exterior plaster	0.03	1.4	0.03	1.4		
	$U_{cal} = 0.890$ W/m^2 K		$U = 1/(R_{ins} + 1.124)$			
Wall 4						
Interior plaster	0.02	0.87	0.02	0.87	–	3566
Hollow brick	0.085	0.45	0.085	0.45		
Insulation (EPS)	0.02	0.040	x_{opt}	0.040		
Hollow brick	0.135	0.45	0.135	0.45		
Exterior plaster	0.03	1.4	0.03	1.4		
	$U_{cal} = 0.831$ W/m^2 K		$U = 1/(R_{ins}+0.703)$			

[a] The buildings built before the year 2000.
[b] The buildings built after the year 2000.

are widely used in Gonen. Table 6 gives the properties of insulation materials used in the calculations.

3.1. Calculation of the heat load

The heat losses in buildings generally occur through external walls, windows, ceiling, floor and air infiltration. The heat loss from windows due to the air infiltration is not taken into account in this study since the insulation does not affect that heat loss.

The heat loss per unit area of a structure component is,

$$q = U\Delta T \tag{4}$$

where U is the overall heat transfer coefficient. The annual heat losses from a unit area of a structural component can be approximately calculated depending on the degree-days number as the following:

$$q_A = 86400\, k\, \mathrm{DD}\, U \tag{5}$$

Table 3
No or little insulated and optimum insulated constructions, U values and the total surface areas of the ceilings.

Ceiling	Existing (no or little insulated) situation		Optimum insulated situation		Area (m^2)	
	Thickness (m)	Thermal conductivity (W/mK)	Thickness (m)	Thermal conductivity (W/mK)	Old[a]	New[b]
Ceiling 1						
Insulation (glass wool)	–	–	x_{opt}	0.043	38,110	–
Reinforced concrete	0.12	2.1	0.12	2.1		
Ceiling plaster	0.02	0.87	0.02	0.87		
	$U_{cal} = 3.447$ W/m^2 K		$U = 1/(R_{ins} + 0.290)$			
Ceiling 2						
Waterproofing	–	–	0.002	0.19	7456	–
Insulation (rock wool)	–	–	x_{opt}	0.040		
Alum	0.05	1.4	0.05	1.4		
Reinforced concrete	0.12	2.1	0.12	2.1		
Ceiling plaster	0.02	0.87	0.02	0.87		
	$U_{cal} = 3.498$ W/m^2 K		$U = 1/(R_{ins} + 0.286)$			
Ceiling 3						
Insulation (glass wool)	0.05	0.043	x_{opt}	0.043	29,826	7456
Reinforced concrete	0.12	2.1	0.12	2.1		
Ceiling plaster	0.02	0.87	0.02	0.87		
	$U_{cal} = 0.688$ W/m^2 K		$U = 1/(R_{ins} + 0.290)$			

[a] The buildings built before the year 2000.
[b] The buildings built after the year 2000.

Table 4
No or little insulated and optimum insulated constructions, *U* values and the total surface areas of the floors.

Floor	Existing (no or little insulated) situation		Optimum insulated situation		Area (m^2)	
	Thickness (m)	Thermal conductivity (W/mK)	Thickness (m)	Thermal conductivity (W/mK)	Old[a]	New[b]
Floor 1						
Coating (ceramic)	0.01	0.85	0.01	0.85	45,567	–
Alum	0.05	1.4	0.05	1.4		
Insulation (EPS)	–	–	x_{opt}	0.039		
Waterproofing	–	–	0.002	0.19		
Blinding concrete	0.1	1.1	0.1	1.1		
Sand. gravel	0.15	1.4	0.15	1.4		
Clay. hard soil	0.35	2.1	0.35	2.1		
Concrete foundation	0.5	1.74	0.5	1.74		
Blinding concrete	0.05	1.1	0.05	1.1		
	$U_{cal} = 1.093\ W/m^2\ K$		$U = 1/(R_{ins} + 0.915)$			
Floor 2						
Coating (ceramic)	0.01	0.85	0.01	0.85	29,825	–
Alum	0.05	1.4	0.05	1.4		
Insulation (EPS)	–	–	x_{opt}	0.039		
Reinforced concrete	0.12	2.1	0.12	2.1		
Ceiling plaster	0.02	0.87	0.02	0.87		
	$U_{cal} = 2.962\ W/m^2\ K$		$U = 1/(R_{ins} + 0.338)$			
Floor 3						
Coating (ceramic)	0.01	0.85	0.01	0.85	–	1657
Alum	0.05	1.4	0.05	1.4		
Insulation (EPS)	0.03	0.039	x_{opt}	0.039		
Waterproofing	0.002	0.19	0.002	0.19		
Blinding concrete	0.1	1.1	0.1	1.1		
Sand. gravel	0.15	1.4	0.15	1.4		
Clay. hard soil	0.35	2.1	0.35	2.1		
Concrete foundation	0.5	1.74	0.5	1.74		
Blinding concrete	0.05	1.1	0.05	1.1		
	$U_{cal} = 0.594\ W/m^2\ K$		$U = 1/(R_{ins} + 0.915)$			
Floor 4						
Coating (ceramic)	0.01	0.85	0.01	0.85	–	5799
Alum	0.05	1.4	0.05	1.4		
Insulation (EPS)	0.03	0.039	x_{opt}	0.039		
Reinforced concrete	0.12	2.1	0.12	2.1		
Ceiling plaster	0.02	0.87	0.02	0.87		
	$U_{cal} = 0.903\ W/m^2\ K$		$U = 1/(R_{ins} + 0.338)$			

[a] The buildings built before the year 2000.
[b] The buildings built after the year 2000.

where k is the surface multiplication coefficient and is given in Turkish Standard Number 825. This value is equal to 1 for external walls and terraced roofs, which are in contact with the outside air, while it is equal to 0.8 and 0.5 for ceilings (with pitched roof) and floors (ground floors), respectively. The change of k value is due to the change of outside air temperature used in the calculations [18].

The annual energy requirement for heating (E_A) can be obtained approximately by dividing the annual heat loss to the efficiency of the heating system (η_s).

$$E_A = \frac{86400k\ \mathrm{DD}\ U}{\eta_s} \tag{6}$$

The heat transfer coefficient of a structural component that includes a layer of insulation is given by:

$$U = \frac{1}{R_i + R_{sc} + R_{ins} + R_o} \tag{7}$$

where R_i and R_o are the inner and outer air-film thermal resistances, respectively. R_{sc} is the total thermal resistance of layers of the structural component without insulation. The thermal resistance of the insulation layer R_{ins} is given by:

$$R_{ins} = \frac{x}{\lambda} \tag{8}$$

where x and λ are the thickness and the thermal conductivity of the insulation material, respectively. If R_{sct} is the total component thermal resistance excluding the insulation layer resistance, Eq. (7) can be rewritten as

Table 5
The price of fuel, lower heating value and efficiency of heating systems (October 2009) [15–17].

	Cost	H_u	(%)
Geothermal energy	0.4482 US\$/kg	36.000×10^6 J/kg	98
Natural gas	0.3540 US\$/m^3	34.542×10^6 J/m^3	93
Coal	0.2767 US\$/kg	25.122×10^6 J/kg	65

Table 6
Characteristics of insulation materials.

Insulation material	Density (ρ) (kg/m^3)	Thermal conductivity (λ) (W/mK)	Cost (US\$)
XPS (extruded polystyrene)	≥30	0.028	144
EPS (expanded polystyrene)	≥20	0.034	85
	16	0.039	55
	10	0.040	40
Glass wool mattress	11	0.043	37
Rock wool	150–170	0.040	132

Table 7
Calculated optimum insulation thicknesses of structural components (external wall, ceiling, floor) with respect to different energy sources and insulation materials.

	Geothermal energy		Natural gas		Coal	
External wall	XPS	EPS	XPS	EPS	XPS	EPS
Wall 1	0.039	0.060	0.035	0.055	0.048	0.073
Wall 2	0.039	0.060	0.035	0.055	0.048	0.073
Wall 3	0.026	0.044	0.022	0.038	0.035	0.057
Wall 4	–	0.102	–	0.093	–	0.122
Ceiling	Glass wool	Rock wool	Glass wool	Rock wool	Glass wool	Rock wool
Ceiling 1	0.113	–	0.104	–	0.133	–
Ceiling 2	–	0.060	–	0.055	–	0.071
Ceiling 3	0.113	–	0.104	–	0.133	–
Floor	–	EPS	–	EPS	–	EPS
Floor 1	–	0.042	–	0.036	–	0.054
Floor 2	–	0.064	–	0.059	–	0.076
Floor 3	–	0.042	–	0.036	–	0.054
Floor 4	–	0.064	–	0.059	–	0.076

$$U = \frac{1}{R_{\mathrm{sct}} + R_{\mathrm{ins}}} \tag{9}$$

The annual heating load is then given by:

$$E_{\mathrm{A}} = \frac{86400k\ \mathrm{DD}}{\left(R_{\mathrm{sct}} + \frac{x}{\lambda}\right)\eta_{\mathrm{s}}} \tag{10}$$

and the annual fuel consumption is

$$m_{\mathrm{fA}} = \frac{86400k\ \mathrm{DD}}{\left(R_{\mathrm{sct}} + \frac{x}{\lambda}\right)H_{\mathrm{u}}\eta_{\mathrm{s}}} \tag{11}$$

where H_{u} is lower heating value of the fuel given usually in J/kg, J/m^3 depending on the fuel type.

3.2. Determination of the optimum insulation thickness

The lifetime cost analysis (LCCA) is one of the methods to calculating the optimum insulation thickness. Total heating cost is evaluated together with the present-worth factor PWF for the lifetime of N years. The PWF depends on the inflation rate (g), and the interest rate (i). According to the interest and inflation rates, PWF is defined as below:

If $i > g$ then,

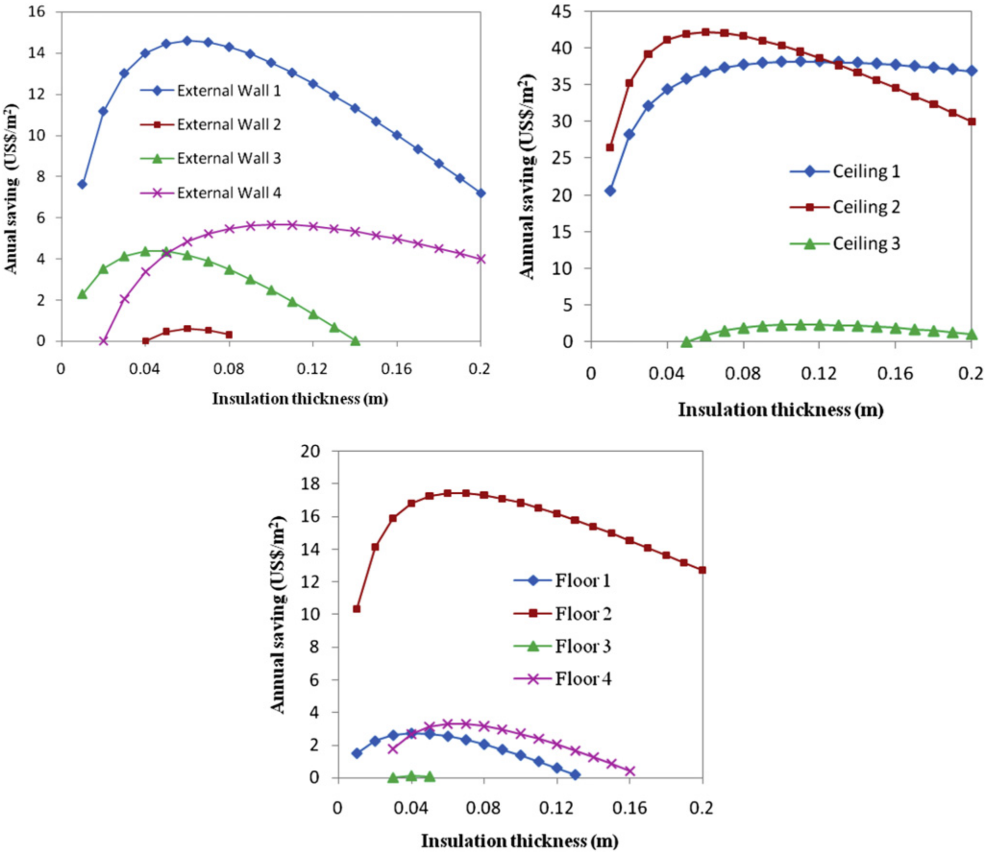

Fig. 1. Effect of insulation thickness on annual savings for mainly used constructions of each component in GDHS buildings.

Table 8
Total annual savings achieved by the optimum insulation thickness for total surface area of Gonen GDHS buildings (US$).

	Geothermal energy		Natural gas		Coal	
External wall	XPS	EPS	XPS	EPS	XPS	EPS
Wall 1	1,686,641	1,926,454	1,367,982	1,584,747	2,528,247	2,820,069
Wall 2	5135	10,819	1822	5759	18,782	28,049
Wall 3	78,124	109,615	56,281	83,412	140,548	181,879
Wall 4	–	20,174	–	16,026	–	31,284
Ceiling	Glass wool	Rock wool	Glass wool	Rock wool	Glass wool	Rock wool
Ceiling 1	1,455,785	–	1,242,398	–	1,999,445	–
Ceiling 2	–	314,866	–	265,563	–	441,545
Ceiling 3	89,003	–	66,411	–	152,121	–
Floor	–	EPS	–	EPS	–	EPS
Floor 1	–	124,491	–	94,915	–	205,951
Floor 2	–	520,248	–	437,821	–	732,368
Floor 3	–	203	–	63	–	809
Floor 4	–	8856	–	6334	–	16,094

$$r = \frac{i-g}{1+g}$$

If $i < g$ then,

$$r = \frac{g-i}{1+i}$$

and

$$\mathrm{PWF} = \frac{(1+r)^{\mathrm{N}}-1}{r(1+r)^{\mathrm{N}}} \tag{12}$$

where N is the lifetime, and it is assumed to be 10 years. According to the published records of the Central Bank of the Republic of Turkey [19] and the State Institute of Statistics [20], the annual interest rate (i) and inflation rate (g) were taken as 9.25% and 5.08%, respectively, for October 2009.

If $i = g$ then,

$$\mathrm{PWF} = \frac{\mathrm{N}}{1+i} \tag{13}$$

The annual heating cost per unit area may be determined from:

$$C_{\mathrm{A}} = \frac{86400k\ \mathrm{DD}\ C_{\mathrm{f}}}{\left(R_{\mathrm{sct}} + \frac{x}{\lambda}\right) H_{\mathrm{u}} \eta_{\mathrm{s}}} \tag{14}$$

where, C_{f} is the fuel cost in US$/kg or US$/m^3 depending on the fuel type.

The cost of insulation is given by:

$$C_{\mathrm{ins}} = C_{\mathrm{I}} x \tag{15}$$

where C_{I} is the cost of insulation material in US$/m^3 and x is the insulation thickness in m.

The total heating cost of the insulated building in present dollars is given by:

$$C_{\mathrm{t}} = C_{\mathrm{A}}\mathrm{PWF} + C_{\mathrm{I}} x \tag{16}$$

$$C_t = \frac{86400\ k\ \mathrm{DD}\ C_{\mathrm{f}}\mathrm{PWF}}{\left(R_{\mathrm{sct}} + \frac{x}{\lambda}\right) H_{\mathrm{u}} \eta_{\mathrm{s}}} + C_{\mathrm{I}} x \tag{17}$$

The optimum insulation thickness is obtained by minimizing Eq. (17). Hence, the derivative of C_{t} with respect to x is taken and set equal to zero from which the optimum insulation thickness x_{opt} is obtained as:

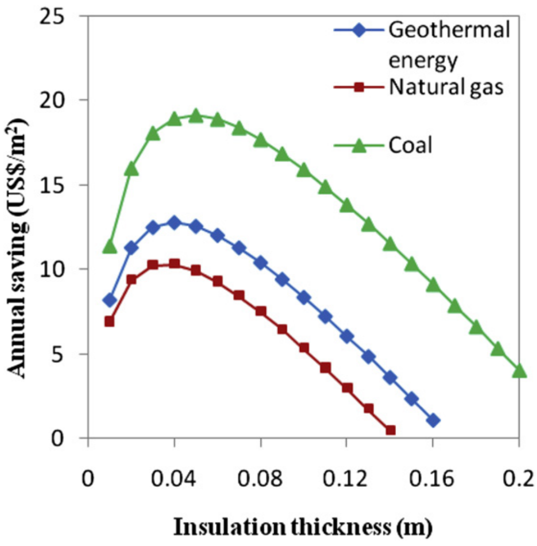

Fig. 2. Annual savings in Wall 1 versus XPS thickness for different energy sources.

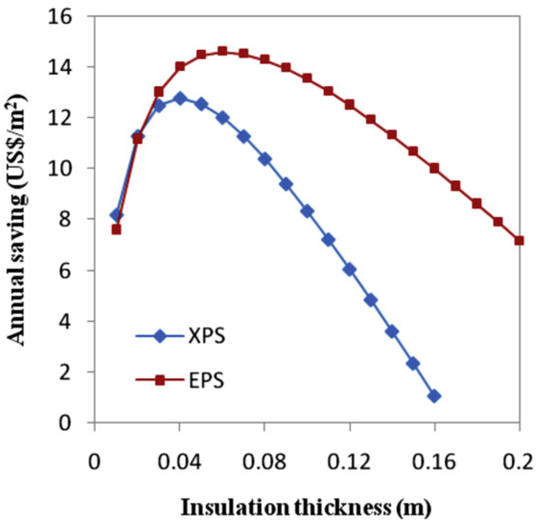

Fig. 3. Annual savings in Wall 1 versus XPS and EPS thickness for geothermal energy.

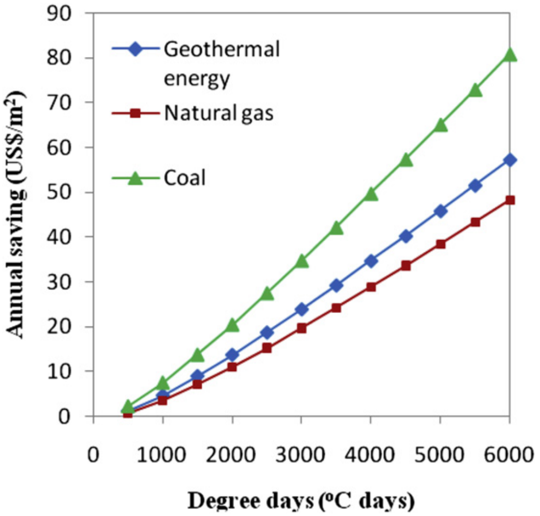

Fig. 4. Annual savings in Wall 1 versus degree-days for different energy sources.

$$x_{\text{opt}} = 293.94\left(\frac{k\,\text{DD}\,C_{\text{f}}\text{PWF}\lambda}{H_{\text{u}}C_{\text{l}}\eta_{\text{s}}}\right)^{1/2} - \lambda R_{\text{sct}} \qquad (18)$$

4. Results and discussion

In this study, optimum insulation thicknesses of the structural components (external walls, ceilings and floors) of the buildings heated by Gonen GDHS were calculated. The amount of savings resulting from optimum insulation thicknesses and the number of the residences which consume coal for heating and can be added to the Gonen GDHS owing to the savings were also determined.

Depending on the type of the energy and the insulation material, the calculated optimum insulation thicknesses for different building components are given in Table 7.

The effect of insulation thickness on the annual savings per unit area for general constructions of each component in GDHS buildings is shown in the form of graphs in Fig. 1. The graphs were obtained considering the use of EPS ($\rho \geq 20$ kg/m^3) in Wall 1, 2 and 3, EPS ($\rho \geq 10$ kg/m^3) in Wall 4; glass wool in Ceiling 1, 3, rock wool in Ceiling 2 and EPS ($\rho \geq 16$ kg/m^3) in Floors 1, 2, 3 and 4 and the use of geothermal energy. By applying optimum insulation thickness on the external walls, while the maximum annual savings per unit area is obtained in Wall 1 (without insulation), the minimum is in Wall 2 (Fig. 1).

As for ceilings, the maximum annual savings per unit area is obtained in Ceiling 2 (terraced roof without insulation). The amount of savings is only given for the thickness range of 0.05–2 m for Ceiling 3 due to the existing insulation with the thickness of 0.05 m in it. Also, the maximum annual savings per unit area is obtained in Floor 2 (over unheated places and without insulation) when the optimum insulation thickness is applied. Similarly, in Fig. 1, the amount of savings is given after the thickness of 0.03 m for Floors 3 and 4 due to the existing 0.03 m insulation in both constructions.

As the components are evaluated in terms of their existing thermal quality, it can be normally said that the less thermal quality causes the savings to increase when the optimum thickness is considered.

Table 8 gives the total annual savings that can be obtained from the total surface area of Gonen GDHS buildings by using the optimum thicknesses for each component, depending on the type of insulation material. The amount of annual savings depending on the natural gas and the coal were also calculated and given in Table 8 to make the study more comprehensive. The total annual savings were calculated by multiplying the annual savings obtained per unit area by the total area of each construction given in Tables 2–4.

As seen in Table 8, among the wall constructions, maximum total annual savings is obtained in Wall 1, which contains no insulation and exists in the most (74%) of the Gonen GDHS buildings.

Similarly, among the ceiling constructions, maximum total annual savings is in Ceiling 1 (with pitched roof), which has no insulation and exists in the most (46%) of the system buildings. As for floor constructions, maximum total annual savings is in Floor 2 (over unheated places), which has no insulation and exists in 36% of the system buildings.

Fig. 2 shows the comparison of annual savings per unit area in Wall 1 versus the thickness of XPS for different energy sources (geothermal energy, natural gas and coal). While the maximum savings is obtained by using coal, the minimum is obtained by using natural gas. The least amount of savings are achieved by using natural gas.

Fig. 3 gives the comparison of the annual savings per unit area in Wall 1 versus the thickness of XPS and EPS for geothermal energy. It is clearly seen in the figure that more saving is achieved by using EPS.

Fig. 4 gives the comparison of annual savings per unit area in Wall 1 versus the degree-days for different energy sources. The amount of savings increases when degree-days rise.

Table 9
Payback periods of building constructions (year).

	Geothermal energy		Natural gas		Coal	
External wall	XPS	EPS	XPS	EPS	XPS	EPS
Wall 1	2.09	1.83	2.24	1.93	1.86	1.67
Wall 2	Neglect	Neglect	Neglect	Neglect	Neglect	Neglect
Wall 3	4.85	3.45	5.84	3.94	3.59	2.78
Wall 4	–	2.64	–	2.91	–	2.24
Ceiling	Glass wool	Rock wool	Glass wool	Rock wool	Glass wool	Rock wool
Ceiling 1	1.23	–	1.25	–	1.19	–
Ceiling 2	–	1.41	–	1.45	–	1.34
Ceiling 3	4.71	–	5.61	–	3.52	–
Floor	–	EPS	–	EPS	–	EPS
Floor 1	–	3.41	–	3.88	–	2.75
Floor 2	–	1.44	–	1.49	–	1.37
Floor 3	–	Neglect	–	Neglect	–	Neglect
Floor 4	–	6.12	–	7.63	–	4.29

Table 9 gives the payback periods of the optimum insulation investments for each construction depending on the insulation materials and the energy types used. Naturally, the shortest payback periods occurs in the components in which the maximum total annual savings are obtained. These constructions are, namely, Wall 1, Ceiling 1 and Floor 2. The payback periods over 12 years are not considered since they are not economical.

With the application of thermal insulation on walls, ceilings and floor components of Gonen GDHS buildings, a considerable increase in the number of the residences heated by Gonen GDHS will be possible due to the energy saving. Thermal insulation on walls and ceilings is easy to apply even on an existing building.

The calculations show that additional 913 and 975 residences will be able to be heated by Gonen GDHS if the optimum insulation thickness of XPS and EPS are respectively applied on the external walls of old Gonen GDHS buildings in which Wall 1 construction (uninsulated, with potential of maximum savings) exists.

Besides, additional 604 residences will be able to be heated by Gonen GDHS if the optimum insulation thickness of glass wool is applied on the ceilings of old Gonen GDHS buildings in which Ceiling 1 construction (uninsulated, with potential of maximum savings) exists.

Furthermore, while additional 2165 residences will be possible to be heated by Gonen GDHS when applying optimum insulation thickness of EPS on the walls and floors and glass wool and rock wool on the ceilings in all old Gonen GDHS buildings, it is 2210 residences when both old and new buildings are considered.

The additional residences are assumed to have double-glazing windows, the walls and the floors with the optimum insulation thickness of EPS and the ceilings with the optimum insulation thickness of glass wool.

5. Conclusions

In this paper, the residential buildings in Gonen GDHS have been investigated to minimize their energy consumption. For simplicity in the analyses, sample buildings which characterize Gonen GDHS buildings were selected considering the structural diversity and the number of the buildings. The investigations conducted in the sample buildings showed that the four different types of the external walls and floors and the three different types of ceiling constructions were mainly used in Gonen GDHS buildings. Using data collected from the sample buildings a reasonable estimation for the whole system buildings was made. The optimum insulation thicknesses, energy savings and payback periods of the building components (external walls, ceilings and floors) were calculated for the four different insulation materials applied commonly on building components. The optimization was based on LCCA and the calculations were also extended including coal and natural gas considering their wide usage for heating in the rest of the buildings in Gonen. The results proved that depending on the type of the energy and the insulation material optimum insulation thickness of the external walls, ceilings and floors varied between 2.2–12.2, 5.5–13.3 and 3.6–7.6 cm, respectively. In case of using optimum insulation thicknesses for all Gonen GDHS buildings the highest annual savings and the shortest payback periods for external walls, ceilings and floors were calculated as 1,926,454, 1,455,785 and 520,248 US$; 1.83, 1.23, and 1.44 years, respectively. The calculations show that an increase of 2210 residences will be possible in the number of the residences heated by Gonen GDHS when applying optimum insulation thickness of EPS on walls and floors and glass wool and rock wool on ceilings in all Gonen GDHS buildings.

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