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Energetic, Exergetic and Environmental Assessments of the Edremit Geothermal District Heating System

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ABSTRACT

In this study, we investigate the Edremit Geothermal District Heating System (GDHS) in Balikesir, Turkey through energetic, exergetic, economic and environmental assessments. The actual thermal data taken from the Technical Department of the GDHS are utilized in the analysis to determine the exergy destructions in each component of the system, and the overall energy and exergy efficiencies of the system for a reference temperature taken as 13.4°C for January 20, 2007. The energy and exergy flow diagrams are clearly drawn to illustrate how much destructions/losses take place in addition to the inputs and outputs. The average energy and exergy efficiencies are found to be 32.69 and 54.26%, respectively. It is obtained from the results that the exergy destructions mainly occur in pumps, heat exchangers, transmission pipeline network and discharging sections as 1.66, 6.07, 8.04, and 29.94% respectively. The highest exergy loss occurs in the discharging section since a large amount of exergy is rejected into the river. Some parameters such as energetic and exergetic renewability and reinjection ratios are defined for various systems, particularly for geothermal systems. The energetic and exergetic renewability ratios are found to be 0.34 and 0.52, respectively whereas its energetic and exergetic reinjection ratios are determined to be 0.64 and 0.30, respectively. In addition, both quantity and quality values of the other fossil fuels are studied for comparison purposes for the system. The quality factor for geothermal exergy price of the system is calculated to be 0.178. We finally investigate how much reduction in consumption of traditional fossil fuels and greenhouse gas emissions is possible through the use of the Edremit GDHS.

INTRODUCTION

Humans have used geothermal energy for a variety of purposes in a variety of time periods. For centuries the Romans used exothermally heated water in their bathhouses and to treat illnesses and heat homes. In Iceland and New Zealand, many people cooked their food using geothermal heat. Some North American native tribes also used geothermal heat for both comfort and cooking. Most of these early uses of the Earth's heat were through the exploitation of geothermal vents. Currently, the most common uses of geothermal energy are residential heating and power generation. Heating and cooling buildings using geothermal energy is the primary use of the Earth's heat energy. Much energy is placed into the moderation of temperature inside buildings, especially during times of extreme cold or heat. Using geothermal energy as a way of maintaining temperatures in buildings is one way to continue to provide that comfort while reducing the use of energy sources that are more polluting to the Earth's atmosphere. Geothermal energy can also be used to create electricity and supplement the conventional sources available.

Space heating is one of the most common and widespread direct uses of geothermal resources. District heating networks, and in some cases district cooling, are employed to provide space heating and/or cooling to multiple consumers from a single well or from multiple wells or fields. The development of geothermal district heating, particularly by the Icelanders, has been one of the fastest growing segments of the geothermal space heating industry and now accounts for over 75% of all space heating provided from geothermal resources worldwide (Lund et al. 2005). Recently, geothermal district heating has been successfully implemented in many countries, such as USA, Canada, Italy, Iceland, and more recently Japan, New

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Zealand, China and Turkey (Kanoglu 2002, Mertoglu 1995). Turkey has also installed large geothermal district heating systems. Turkey's share of geothermal energy use worldwide is about 12.1% (Barbier 2002, Hepbasli 2003).

As far as geothermal systems are concerned, these studies may be classified into five main groups as follows:

a. Exergy analysis of geothermal power plants (Kanoglu 2002; Ozturk et al. 2006; Dagdas et al. 2005; Cerci 2003; Kanoglu et al. 1996, 1997, 1998; Kanoglu and Cengel 1997; Bettagli and Bidini 1996; DiPippo and Marcille 1984; Baba et al. 2006; Cadenas 1999),
b. Evaluation of geothermal fields using exergy analysis Baba et al. 2006, Cadenas 1999, Bisio 1998, Bettagli and Bidini 1996, Oszuszky and Szeless 1980, Quijano 2000, Haenel et al. 1988, Dickson and Fanelli 1990),
c. Classification of geothermal resources by exergy (Etemoglu and Can 2007, Lee 2001, Muffler and Cataldi 1978, Hochstein 1990),
d. Energy and exergy analysis geothermal district heating systems (GDHSs) (Ozgener et al. 2007; Ozgener et al. 2007a, 2007b, 2007c; Erdogmus et al. 2006; Ozgener et al. 2005a, 2005b, 2005c; Hepbasli 2005; Ozgener et al. 2004; Ozgener et al. in press) and
e. Exergoeconomic analysis with cost accounting aspects of GDHSs (Ozgener et al. 2007, Benderitter and Cormy 1990).

The main objective of this paper is to conduct an energy and exergy analysis of the Edremit GDHS, to introduce some new parameters as energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for the geothermal systems and apply to the Edremit GDHS, and to discuss performance improvement opportunities. It is also aimed to investigate how much reduction in consumption of traditional fossil fuels and greenhouse gas emissions is possible through the use of the Edremit GDHS.

CASE STUDY: THE EDREMIT GEOTHERMAL DISTRICT HEATING SYSTEM

Geothermal district heating systems are divided into two main groups depending on whether the geothermal water is used directly in the house systems (secondary system) or indirectly by transferring the geothermal heat to the secondary system via the use of heat exchangers. It is generally accepted that hot water at temperatures ranging from 60 to 125°C has been used for space heating and a primary fluid temperature of 60°C is minimum practicable for direct geothermal heating use (Piatti et al. 1992).

Many systems in Turkey have been operating using the principle of the indirect use of the geothermal fluid. On the contrary, Edremit GDHS operates on the principle of direct use and geothermal water is piped directly to the users with a transmission pipeline, like in Iceland.

The Edremit geothermal field is located 87 km in the west of the city of Balikesir in Turkey, knows as the northwest Anatolia. There is a 3 to 4 km distance between geothermal source and the center of the Edremit. As of January 2006; there were seven wells in geothermal field, with depths ranging from 195 to 496 m. Information for the wells opened is shown in Table 1. Three wells (ED-1. ED-3, EDJ-3) were in use for production. One well (ED-2) was closed because of the insufficient mass flow rate. Other three (EDJ-4, ED-5, EDJ-7) wells had a pump, but not yet connected to system. The wellhead production temperature was 60°C. The mass flow rates of operating wells chance from 18 to 86 kg/s (EGEI 2007). The Edremit GDHS' wells extend over of nearly 0.3 km^2. As of January 2007, the number of dwellings for the Edremit GDHS was 1650.

Table 1. Explanation of the Wells

Name	Total Depth (m)	Wellhead Temperature (°C)	Flow Rate (kg/s)	Type/Condition
ED-1	195.60	60.00	75	Production/Operating
ED-2	496.50	55.00	2	Closed
ED-3	495.00	59.00	18	Production/Operating
EDJ-3	266.00	60.00	86	Production/Operating
EDJ-4	296.00	49.00	86	Production/Out of service
EDJ-5	216.00	58.70	45	Production/Out of service
EDJ-7	246.00	58.30	30	Production/Out of service

Generally, heating systems become operational when the outdoor temperature falls below 15°C. On this temperature basis, there are 190 "colder" (or heat-requiring) days annually in the Edremit area. In summer or warmer season, during an average of 175 days, only domestic hot water is supplied from Edremit GDHS. In designated period, outdoor design temperature, while determining the heat demand of a dwelling, had been chosen to be –3°C by project engineers. However the lowest outdoor temperature is about 4.9°C when considering the average outdoor temperature. Energy is generated from geothermal energy when the outdoor temperature is over 5°C. Under 5°C, the auxiliary system, which uses the fuel-oil as a fuel, is activated.

The Edremit geothermal district heating system (Edremit GDHS) was designed for 3 stages with the total capacity ultimately corresponding to 7500 dwelling equivalences. In the first stage, heat demand was compensated to 1650 dwelling equivalence. In the second stage, 5000 and in the last stage, 7500 dwelling equivalences will be constructed. In Figure.1, a schematic diagram of the system is shown. On January 20, 2007, Edremit GDHS supplied the heat requirement of one religious facility, one dormitory, one college, two hospitals and 1345 residences. Equivalent dwelling values of these utilizations are given in Table 2.

The components of the Edremit GDHS are pumps, heat exchangers, constructed under the each building, and a peaking station. Peaking station is activated in case of emergency heat requirements for low outdoor temperatures, when there is

Table 2. Distribution of the Geothermal Energy Usage

Users	Residences Equivalence	%
Religious facilities	6	0.36
Dormitory	9	0.55
College	72	4.36
Hospitals	65	3.94
Residences	1498	90.79

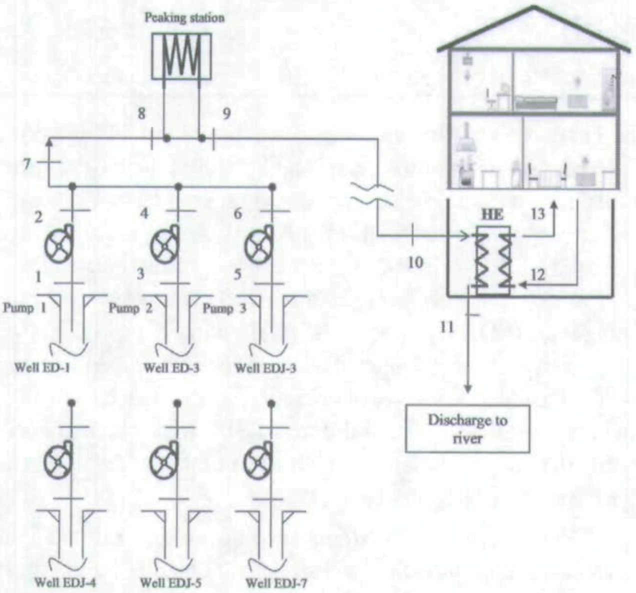

Figure 1 *Flow chart of the Edremit GDHS.*

Table 3. General Characteristic Properties of the Edremit GDHS

Edremit GDHS	
Town	Edremit (Turkey)
Wellhead Temperature (°C)	60
Capacity (MWt)	11,32
Commissioning date	2003
Average inlet/outlet temperature for geothermal water	59/40-42
Average inlet/outlet temperature for fresh water	58/38-40
Actually connected to system/ Maximum capacity	1650/7500
Type of pipes used in the distribution lines.	Fiberglass-reinforced polyester system.

a problem in the energy demand of the system. The system is designed to have one heat exchanger for each building. So now, each building has a heat exchanger to supply its heat requirement. There are 62 buildings which have 1650 equivalent dwellings in the system. In calculations, it is very difficult to take a value for each heat exchanger. Since, those 62 heat exchangers were considered as one heat exchanger which was represented by *HE* in Figure. 1. Same model plate-type heat exchangers are used throughout the system. Inlet and outlet heat exchanger liquid temperatures were measured for both water and geothermal water. Temperature values were taken from the farthest building. This building is taken as a critical point. The difference between critical point and geothermal field is not much, so the effect of elevation is considered negligible in the calculations.

The temperature and pressure data of the system were recorded on January 20, 2007. Geothermal fluid collected from three production wells, at an average wellhead temperature of 60°C, is pumped to heat exchangers constructed under the buildings after passing the peaking station. Geothermal fluid enters the heat exchanger at an average temperature of 58 to 59°C and here, heat is transferred to the fresh water in those heat exchangers At this point used geothermal fluid is discharged to Edremit river at 40 to 42°C. No pump is needed on the main distribution pipeline or discharge section. The pressure supplied from well pumps is enough for circulation. In Table 3, some general characteristic properties of the Edremit GDHS are shown.

ANALYSIS

Balance Equations

The balance equations are written in this paper for mass, energy and exergy flows in the systems which act like the steady-state and steady-flow system. Energy and exergy efficiency equations are also written for performance evaluation of the overall system and its components.

The mass balance equation for the overall geothermal system can be written as

$$\sum_{i=1}^{n} \dot{m}_{in} = \sum_{i=1}^{n} \dot{m}_{out} \tag{1}$$

The geothermal water energy and exergy are calculated from the following equations:

$$\dot{E}_{gw} = \dot{m}_{gw}(h_{gw} - h_0) \tag{2}$$

$$\begin{aligned} \dot{E}x_{gw} &= \dot{m}_{gw}[(h_{gw} - h_0) - T_0(s_{gw} - s_0)] \\ &\cong \sum_{i=1}^{n=3} \dot{m}_{gw,i}[(h_i - h_0) - T_0(s_i - s_0)] \end{aligned} \tag{3}$$

Here h_0 and s_0 depend on the reference (environment) temperature and are considered to be variable for each day.

The exergy destructions in the heat exchanger, pump and system itself are calculated using the following equations:

$$\dot{E}x_{dest,HE} = \dot{E}x_{in} - \dot{E}x_{out} \tag{4}$$

$$\dot{E}x_{dest,Pump} = \dot{W}_{pump} - (\dot{E}x_{out} - \dot{E}x_{in}) \tag{5}$$

$$\dot{E}x_{dest,Pipe} = \sum_{i=1}^{n} \dot{E}x_{n+3} - \dot{E}x_n \tag{6}$$

$$\dot{E}x_{dest,Sys} = \sum \dot{E}x_{dest,HE} + \sum \dot{E}x_{dest,Pump} + \sum \dot{E}x_{dest,Pipe} \tag{7}$$

The energy efficiency of the GDHS system is calculated from

$$\eta_{sys} = \frac{\dot{E}_{usf,HE}}{\dot{E}_{gw}} \tag{8}$$

The exergy efficiency of the system heat exchanger is determined by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream as

$$\varepsilon_{HE} = \frac{\dot{m}_{cold}(\psi_{cold,out} - \psi_{cold,in})}{\dot{m}_{hot}(\psi_{hot,in} - \psi_{hot,out})} \tag{9}$$

with the flow exergy (ψ) as

$$\psi = (h - h_0) - T_0\,(s - s_0) \tag{10}$$

The exergy efficiency of the system is calculated from following equation:

$$\varepsilon_{syst} = \frac{\dot{E}x_{usf,HE}}{\dot{E}x_{gw}} = 1 - \frac{\dot{E}x_{dest,syst} + \dot{E}x_{nd}}{\dot{E}x_{gw}} \tag{11}$$

Many researchers use the specific exergy index as a kind of exergetic rating to classify the geothermal resources as initially introduced by (Lee 2001) in the following form:

1. $SExI < 0.05$ represents the low quality geothermal resources,
2. $0.05 < SExI < 0.5$ represents the medium-quality geothermal resources, and
3. $0.5 < SExI$ represents the high quality geothermal resources.

This index is written as follows as applied commonly (Quijano 2000; Lee 2001):

$$SExI = \frac{h_{geo} - (273.16)s_{geo}}{1192} \tag{12}$$

where 1192 is the reference specific exergy as identified by the researcher (Lee 2001). Therefore, the specific exergy index for any geothermal resource is determined as the ratio of the specific exergy of the geothermal system considered to the reference specific exergy content. The following is the specific geothermal enthalpy equation as required for the above equation:

$$h_{geo} = \frac{\sum_{i=1}^{n=3} \dot{m}_i h_i}{\sum_{i=1}^{n=3} \dot{m}_i} = \frac{(\dot{m}_1 h_1) + (\dot{m}_2 h_2) + (\dot{m}_3 h_3)}{\dot{m}_1 + \dot{m}_2 + \dot{m}_3} \tag{13}$$

which is based on the flow energy balance for an adiabatic mixing process since there are three wells to receive geothermal waters and mix them for the system.

The following is the specific geothermal entropy equation as required for Equation (12):

$$s_{geo} = \frac{\sum_{i=1}^{n=3} \dot{m}_i s_i}{\sum_{i=1}^{n=3} \dot{m}_i} = \frac{(\dot{m}_1 s_1) + (\dot{m}_2 s_2) + (\dot{m}_3 s_3)}{\dot{m}_1 + \dot{m}_2 + \dot{m}_3} \tag{14}$$

which is based on the flow entropy balance for an adiabatic mixing process (with negligible entropy generation term) since there are three wells to receive geothermal waters and mix them for the system.

Furthermore, the rate-basis improvement potential, IP, developed by Hammond and Stapleton (2001) is also employed to show how much improvement potential exists for the system. Here the IP value for the heat exchanger is

$$\mathrm{IP} = (1 - \varepsilon_{HE})(\dot{E}x_{in} - \dot{E}x_{out}) \tag{15}$$

Geothermal sources, apart from fossil fuels, are renewable. In this section we introduce four new parameters, namely energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for the geothermal systems, and apply to the Edremit GDHS. Here, we detail each of these parameters:

- **Energetic renewability ratio:** This is defined as the ratio of total renewable energy obtained from the system to the total energy input (including all renewable and non-renewable energies) to the system.

$$R_{\mathrm{Ren}_E} = \frac{\dot{E}n_{usf}}{\dot{E}n_{total}} \tag{16}$$

- **Exergetic renewability ratio**: This is defined as the ratio of total renewable exergy content obtained from the system to the total exergy input (including all renewable and non-renewable exergies) to the system.

$$R_{\mathrm{Ren}_{Ex}} = \frac{\dot{E}x_{usf}}{\dot{E}x_{total}} \tag{17}$$

- **Energetic reinjection ratio**: This is defined as the ratio of total energy reinjected back from the system to the total geothermal energy supplied to the system.

$$R_{\mathrm{Rein}_E} = \frac{\dot{E}_{\mathrm{Rein}}}{\dot{E}_{gw}} \tag{18}$$

- **Exergetic reinjection ratio**: This is defined as the ratio of total exergy reinjected back from the system to the total geothermal exergy supplied to the system.

$$R_{\mathrm{Rein}_{Ex}} = \frac{\dot{E}x_{\mathrm{Rein}}}{\dot{E}x_{gw}} \tag{19}$$

Table 4. Properties of the System Fluids (Water) and Energy and Exergy Rates at Various Locations in Edremit GDHS

State No.	Fluid Type	Temperature T (°C)	Pressure P (kPa)	Specific Enthalpy h (kJ/kg)	Specific Entropy s (kJ/kg·K)	Mass Flow Rate $\dot{m}$ (kg/s)	Specific Exergy e_x (kJ/kg)	Exergy Rate $\dot{E}x$ (kW)	Energy Rate $\dot{E}$ (kW)
0	GW	13.40	101.32	56.36	0.2011	—	—	—	—
1	GW	60.00	55.50	251.10	0.8310	56.25	14.336	806.43	14,124.38
2	GW	60.15	435.00	252.10	0.8327	56.25	14.849	835.29	14,180.63
3	GW	60.00	55.50	251.10	0.8310	63.75	14.336	913.96	16,007.63
4	GW	60.15	435.00	252.10	0.8327	63.75	14.849	946.67	16,071.38
5	GW	59.00	55.5.00	247.00	0.8185	15.00	13.816	207.24	3705.00
6	GW	59.14	435.00	247.90	0.8202	15.00	14.229	213.44	3718.50
7	GW	60.03	435.00	251.60	0.8312	135.00	14.779	1995.21	33,966.00
8	GW	59.00	390.00	247.20	0.8183	135.00	14.073	1899.97	33,372.00
9	GW	59.00	390.00	247.20	0.8183	135.00	14.073	1899.97	33,372.00
10	GW	58.50	250.00	245.00	0.8121	135.00	13.649	1842.69	33,075.00
11	GW	38.00	180.00	159.30	0.5456	135.00	4.275	577.15	21,505.50
12	W	38.00	130.00	159.30	0.5456	196.00	4.275	837.93	31,222.80
13	W	52.00	190.00	217.80	0.7294	196.00	10.134	1986.43	42,688.80

Note: Point zero shows reference state W: water, GW: geothermal water

Table 5. Calculated Characteristic Properties of the System

The specific exergy index	($SExI$)	0.02
Improvement factor (kW)	(IP_{HE})	10.83
Energetic renewability ratio	R_{RenE}	0.34
Exergetic renewability ratio	R_{RenEx}	0.52
Energetic reinjection ratio	R_{ReinE}	0.64
Exergetic reinjection ratio	R_{ReinEx}	0.30

The results of the above given analysis are given in detail in Table 4 and Table 5.

The Average Total Residential Heat Demand

In the "summer" (or warmer season when there is no need to heat the dwellings), only sanitary hot water is supplied to the residences. The total sanitary hot water load over the summer season ($\dot{E}_{smr}$) is *given* by:

$$\dot{E}_{smr} = N_{dw} N_{per} S \Delta T_w C_p \tag{20}$$

where N_{dw} is the number of average dwellings as 1650, N_{per} is the average number of people in each dwelling as 4, S is the average daily usage of sanitary hot water as 50 L/(person-day or 50 kg/(person-day), and T_w is the difference in temperature between that of the sanitary hot water as 55°C and that of the tab water from the city distribution network as 10°C. Thus, $\dot{E}_{smr}$ = (1650·4·50)kg·(45°C)(4.18kJ/kg·°C) = 718.2 kW.

However, the total "winter" heat demand (sanitary hot water + heating) is expressed as

$$\dot{E}_{design} = \dot{E}_{dw} N_{dw} \tag{21}$$

where $\dot{E}_{dw}$ is the heat load for an average (or equivalent) dwelling. Taking 1650 residences with a maximum load of 6.86 kW per residence, the overall winter heat load becomes 11.319 MW.

Equation (21) can also be written as

$$\dot{E}_{design} = \dot{m} C_p \Delta T_{design} N_{dw} \tag{22}$$

where $\Delta T_{design} = (T_{indoor} - T_{outdoor})_{design}$ is the difference between the indoor and outdoor temperatures and becomes [20 – (–3)].

Since the outdoor temperature changes, we need to take in into consideration through $\Delta T_{average} = (T_{indoor} - T_{outdoor})_{average}$ using average outdoor temperatures while the indoor temperature is kept constant. We can now introduce the temperature ratio as

$$T_R = \frac{\Delta T_{average}}{\Delta T_{design}} \tag{23}$$

in order to determine the average heat loads, as required, below:

$$\dot{E}_{average} = T_R \dot{E}_{design} \tag{24}$$

Table 6 shows the monthly heat demand breakdown for the each month with respect to the average outdoor temperatures.

The annual energy demand can be found through the following equation:

$$\dot{E}_{an} = \sum_{i=1}^{n} \dot{E}(i)_{smr} NDM(i) 24\ \text{h} + \sum_{i=1}^{m} \dot{E}(i)_{average} NDM(i) 24\ \text{h} \tag{25}$$

where n and m stand for the number of the months in summer and winter seasons, and NDM represents the number of days per month.

The exergy of given quantity of district heating can be calculated as (Wall 2006)

$$\dot{E}x = \dot{E}\left(1 - \frac{T_{outdoor}}{T_{\text{supply}} - T_{outdoor}} \ln \frac{T_{\text{supply}}}{T_{outdoor}}\right) \tag{26}$$

Note that the exergy content of the district heating will vary with the outdoor temperature in case that the supply and return temperatures within the district heating system are regulated according to the outdoor temperature. So, an average of the exergy content should be taken into account.

The mass flow rates for the network water and geothermal water can be found as:

$$\dot{m}_{nw} = \frac{\dot{E}_{average}}{C_P(T_{\text{supply}} - T_{return})} \tag{27}$$

$$\dot{m}_{gw} = \frac{\dot{E}_{average}}{C_P \cdot T_{gw} \cdot \eta_{sys}} \tag{28}$$

where C_P shows the specific heat capacity of the water and the supply and return water temperatures for the network are considered constant (according to the constant temperature, various mass flow rates).

The system average energy efficiency is defined as

$$\eta_{sys} = \frac{\dot{E}_{average}}{\dot{E}_{gw}} \tag{29}$$

and Figures 2 and 3 exhibit the variations of the mass flow rates for the network water and geothermal water, and the average useful energy and exergy output, respectively. As seen in the figures, the demand is the highest in January, declines until May, becomes almost constant until September, and begins increasing until the end of December. It is obvious that based on the demand the mass flowrates will proportionally change.

FUEL COST ASPECTS

When geothermal energy is used for district heating, we end up with considerable fuel cost savings compared to the use

Table 6. A Summary of Monthly Energy Requirement from the Edremit GDHS

Months	Average Outdoor Temperature (°C)	Temperature Ratio (T_R)	Total Average Energy (kW) [from Equations (20) and (24)]	Number of Days Requiring Heating (NDM)	Total Monthly Heat Requirement (MWh)
For winter months			*[from Equation (24)]*		
October	14.54	0,2300	2603.37	9	562.328
November	12.40	0.3304	4457.99	30	3209.752
December	8.60	0.4957	6329.03	31	4708.798
January	6.20	0.6000	7509.60	31	5587.142
February	7.00	0.5652	7115.70	28	4781.750
March	9.30	0.4652	5983.80	31	4451.195
April	13.40	0.2869	3965.62	30	2855.246
For summer months			*[from Equation (20)]*		
May	17.20	—	718.20	31	534.340
June	22.60	—	718.20	30	517.104
July	24.20	—	718.20	31	534.340
August	24.90	—	718.20	31	534.340
September	21.70	—	718.20	30	517.104
October	16.30	—	718.20	22	379.209
		Annual Total Energy Demand			*29172.648 MWh*

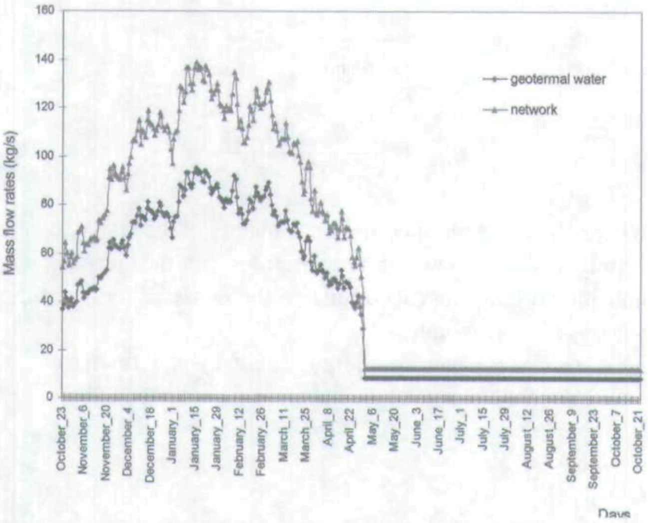

Figure 2 *Daily variation of the mass flow rates geothermal and its network.*

of a conventional fossil-fuel district heating system. In this regard, adding a heat exchanger to a geothermal system instead of a boiler to a conventional system provides financial savings due to the elimination of fuel cost. Annual financial savings become equivalent to the annual fuel cost used to produce the same amount of heat energy in a conventional heating system. The specific fuel consumption (f_s) of a conventional district heating system can be written as (Dagdas 2007, Zhu and Zhang 2004):

$$f_s = \frac{1}{\mathrm{LHV}\eta_h} \tag{30}$$

where LHV is the lower heating value of fuel (kWh/kg or m^3) and η_h is the average heating system efficiency (%). In this regard, the annual fuel consumption can be found as

$$F = \frac{\dot{E}_{an}}{\mathrm{LHV}\eta_h} = f_s\dot{E}_{an} \tag{31}$$

where $\dot{E}_{an}$ is the annual energy demand of the district heating system (kWh/year).

In fact, fuel costs become a major factor in calculating the running costs of schemes and the viability of proposed schemes (e.g., Technical Publication Inc. 2007, Hepbasli and Canakci 2003). For Edremit GDHS annual energy demand is calculated from Equation (25). Table 7 shows typical fuel prices for various types of residential heating systems as of January 18, 2007. For this reason, the prices given in Table 7 can be used for comparison purposes on the basis of fuel costs.

If the elemental composition is known, the chemical exergy of various fuels can be evaluated accurately using the Szargut's correlations in (Szargut et al. 1998). In addition, a correlation formula to estimate chemical exergies of oil fractions and fuel mixtures from enthalpy of combustion and atomic composition developed by Govin et al. (2000) is used.

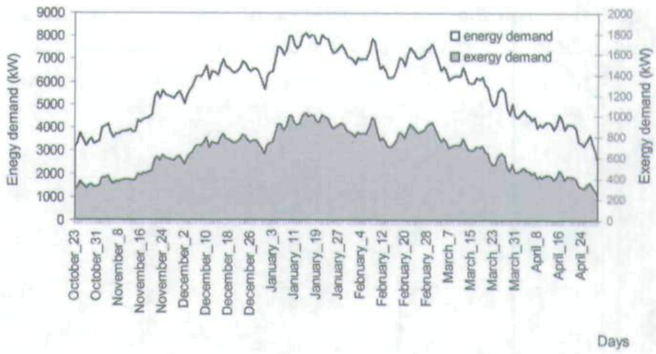

Figure 3 *Daily variation of energy and exergy demand in the Edremit GDHS for a heating season.*

The following equations may be employed for the chemical exergy of fuel:

$$\beta_{\mathrm{LHV}} = \frac{\dot{E}x_{ch}}{\mathrm{LHV}} \quad \text{based on the lover heating value (LHV)} \tag{32}$$

and

$$\beta_{\mathrm{HHV}} = \frac{\dot{E}x_{ch}}{\mathrm{HHV}} \quad \text{based on the higher heating value (HHV)} \tag{33}$$

where β is the proportionality constant (or quality factor or exergy coefficient). Note that LHV is more commonly used due to the combustion reactions types.

Note that exergy content of the useful energy amount can be found from Equation (11). In the present study, exergy content for each month is found as using actual data. Using the values given in Tables 6 and 7, energy and exergy prices of various fuels for the Turkish residential applications are calculated and illustrated in Table 8. The exergy prices for the geothermal district heating have been obtained in two various ways, namely using two various quality factors of 0.29 suggested by various researcher (e.g., Rosen and Dincer 1997, Reistad 1975) and as 0.178 by calculated here.

The highest energy price is that of LPG, while the lowest one is that of the natural gas. The differences between energy and exergy prices may be small for various energy carriers. Besides this, the district heating subscriber pays much more for exergy than other energy user.

ENVIRONMENTAL BENEFITS

Protection of the environment is one of the most important obligations, whose goals were defined during some key United Nation's Summits in Rio (1991), Kyoto (1997) and Johannesburg (2001). Any type of energy production, transportation, transformation, conversion and consumption has some impact on the environment, and the magnitude of such an impact will depend closely on the technologies and methods used. The emission of air pollutants such as nitrogen oxides, sulfur dioxide, and carbon dioxide, will be greatly reduced if we manage to limit our consumption of fossil fuels.

Table 7. Cost Comparisons of Different Energy Sources for Edremit Dwellings as of January 18, 2007

Fuel Type Used for Space Heating	Heating Value of Energy Source a^{I}	Unit Price[a,b] b^{II}	Average Efficiency c (%)	Annual Cost Increase Cost d (%)	Fuel Cost e = [100b/ac] (US$/kWh)	Fuel Requirement for the Year [F from Equation (31)], f (kg)	Annual Cost of Fuel ($g = bf$) (in US$)	Average Monthly Cost of Fuel ($h = g/12$) (in US$) *Tot. Residence*	Average Monthly Cost of Fuel ($h = g/12$) (in US$) *Per Residence*
Domestic coal	4.74 kWh/kg	US$ 0.157 kg^{-1}	60	40	0.0553	10,257,611.81	1,611,910.43	134,325.87	81.41
Natural gas	9.59 kWh/m^3	US$ 0.304 m^{-3}	90	26	0.0353	3,379,984.71	1,028,722.49	85,726.87	51.96
LPG[III]	12.79 Wh/kg	US$ 1.332 kg^{-1}	90	20	0.1157	2,534,327.86	3,375,000.62	281,250.05	170.45
Fuel oil	11.48 kWh/kg	US$ 0.879 kg^{-1}	80	13	0.0957	3,176,464.29	2,790,750.77	232,562.56	140.95
Elect. resistance	1 kWh/kWh	US$ 0.113 kWh^{-1}	99	0.03	0.1142	29,467,321.21	3,331,912.11	277,659.34	168.28

Notes: For geothermal, the annual cost of energy is only US$ 682704 (for 1650 dwelling number) and US$ 413.76 (per dwelling while the monthly fee is US$ 34.48)

[I] Heating value is taken form Turkish cogeneration website(http;//www.kojenerasyon.com)

[II] Assuming 1 US$ = 1.4 [new Turkish Lira (TRY)]

[III] LPG: Liquid Propane Gas

Table 8. Comparison of Energy and Exergy Prices of Commonly Used Fuels for the Residential Sector

Fuel Type	Energy Price		Quality Factor β_{LHV}	Exergy Price				CO_2 Equivalents	
	US$/kWh A	US$/year		US$/kWh	US$/year (Total Residence)	US$/year (Per Residence)	US$/month (Per Residence)	Conversion Factors (kg/kWh) B[a]	CO_2 Emission (US$/kg) (A/B)
Domestic									
Soma coal	0.0553	1,613,247.434	1.08	0.0512	1,493,747.624	905.30	75.44	0.31	0.18
Natural gas	0.0353	1,029,794.474	1.04	0.0339	990,186.9946	600.11	50.01	0.21	0.17
Fuel oil	0.1157	3,375,275.374	1.07	0.1081	3,154,462.966	1911.80	159.32	0.30	0.39
LPG	0.0957	2,791,822.414	1.06	0.0903	2,633,794.730	1596.24	133.02	0.21	0.46
Electric resistance	0.1142	3,331,516.402	1.00	0.1142	3,331,516.402	2019.10	168.26	0.73	0.16
Geothermal district heating	0.0234	682,639.9632	0.29	0.0807	2,353,930.908	1426.62	118.89		
	0.0234	682,639.9632	0.178[a]	0.1315[a]	3,835,055.973[a]	2324.28[a]	193.69[a]		
			0.137*		5,505,620.438*				

[a] Hepbasli (2007).

*Using Equation (26) under the design conditions for the Edremit geothermal district heating system in Turkey

The environmental benefits of exploiting the Edremit geothermal resources for district heating can be quantified by calculating the reduction in pollutant emissions compared to fossil fuels. Through the values for heating systems burning coal, fuel oil and electric resistance for the year as shown in Table 7, using the Edremit GDHS, instead of conventional fossil fuel driven systems, the local emissions of CO_2 and SO_2 would have been reduced annually by 24,059 and 282.86, 8857.19 and 38.66, 110,074 and 1335 tones/year, respectively.

RESULTS AND DISCUSSION

Although this is a comprehensive study, we neglect the effect of salts and other chemical compounds in the geothermal fluid in the analysis, due to their insignificant contribution. So, the thermodynamic properties of the geothermal fluid are treated as water and this is consistent with the results of (Kanoglu 2002) who employed this type of selection in the exergy analysis of geothermal power plants.

For this present study the actual data needed were recorded on January 20, 2007 and used as raw data for analysis. The energy and exergy efficiencies and exergy destructions and losses of the Edremit GDHS were investigated using these actual data. For the geothermal fluid and fresh hot water, the temperature, pressure, mass flow rate data, energy and exergy rates were calculated by using general thermodynamic tables and software programs and given in Table 4. The state 0 shows dead state for both the geothermal fluid and hot water. The dead state conditions are taken as 13.4°C and 101.3 kPa on that particular day. Table 4, based on the thermodynamic states indicated in Figure 1, lists the state temperatures and pressures, mass flowrates, specific enthapies, entropies and exergies, and energy and exergy rates of the geothermal fluid.

Figures 2 and 3 exhibit the daily variations of the mass flow rates for the network water and geothermal water, and the daily average energy and exergy demands for residents. As seen in the figure, the demand is the highest in January and starts declining after this month until May. It later becomes almost constant until September and begins increasing again until the end of December. It is obvious that based on the demand the mass flowrates will proportionally change.

One crucial aspect that we need to highlight is that the used geothermal water (at about a temperature of 42°C), after being circulated through heat exchangers, is discharged to the river nearby with a total heat capacity of 21 506 kW, respectively. It is extremely important to save such high amount of energy by reinjecting the fluid back to the well. This has been communicated to the responsible body for implementation.

In this respect, Figure 4 shows both energy and exergy flow diagrams which is the heart of this study. It is a clear presentation of how exergy is destructed and lost due to internal and external irreversibilities. The energy flow diagram does not account for such destructions and losses since it bases on the first law of thermodynamics (apparently conservation of energy principle) which is applicable for reversible processes only. In practice we know that all processes are irreversible, and energy analysis is insufficient to deal with the problem accordingly. Therefore, it is apparent that exergy is needed as a potential tool to determine how much exergy destructions and losses take place in each component of the system and to require engineers to work on better system efficiency. This can easily be done by doing some system configurations to avoid losses (e.g., insulation) and using heat recovery and reinjection options and more efficient pumps and heat exchangers.

The energy diagram consists of total energy input, pipeline heat losses, useful energy extracted for the dwellings, and the energy discharged to the river. It is clear that 63.56% of the total energy input is not used at all and is lost to the river. There are two problems here such as (1) large amount of energy loss and (2) thermal pollution in the river due to discharge water at ~42ºC, which will eventually affect the aquatic life and ecology. The exergy flow diagram give a better picture of the system, representing true exergy contents and energy quality itself. Here the output exergy (or useful exergy) becomes 54.26% of the total exergy input. Here we also include the exergy destructions in the pumps, heat exchangers, pipelines, and exergy losses through discharged geothermal water. According to Figure 4 most of the energy losses exists as used hot water, discharged to the river, as 97% (i.e., 21 505.5 kW), while the pipeline losses are shown to be 3% (i.e., 865.5 kW) of the total energy losses. However exergy losses result from many components. Distribution losses of each component in the total exergy losses are achieved for pumps, heat exchanger, pipeline and discharge water as 4, 13, 18 and 65%, respectively.

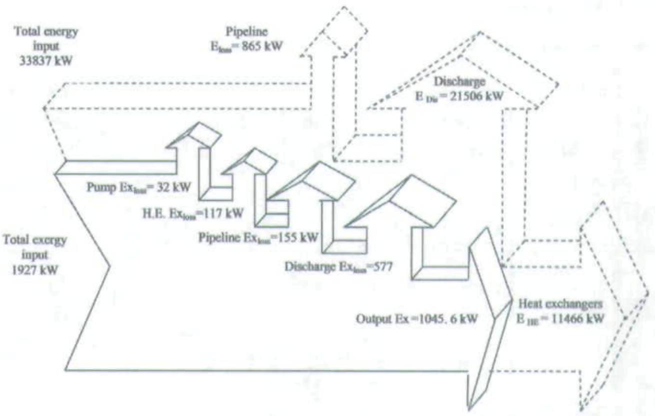

Figure 4 *The flow diagrams of energy and exergy contents for the Edremit GDHS.*

Table 6 presents the monthly energy requirement based on the average outdoor temperatures and the number of days for heating requirement. It is clearly seen that the highest energy demand occurs in January since the average outdoor temperature is the lowest. A comprehensive summary of the study on how the energy cost changes for various energy sources if used for the Edremit dwellings is given in Table 7. In Turkey, the most expensive fuel on the basis of US$/kWh, is liquefied petroleum gas (LPG), which is about 3.5 times more expensive than natural gas. This is basically followed by electricity, fuel oil, the domestic Soma coal and natural gas. The most expensive source appears to be LPG for the residents. Table 8 compares the energy and exergy prices for the commonly used fuels in the residential sector, resulting in that natural gas is the least expensive fuel to use in the residential sector and that the geothermal appears to be the most expensive way per residence since the Edremit GDHS serves just a small percentage of the residences. The unit energy prices evaluated in terms of CO_2 equivalents are also shown in Table 8. Annual CO_2 emission price for electric will be higher than coal, fuel oil and natural gas as US$ 17787019, 4527669, 3881177 and 1558343, respectively.

In regards to the environmental benefits of the Edremit GDHS, we can summarize a couple facts: (1) It is obtained that maximum heating demand for a total of 1650 dwellings is 11.32 MW and the energy savings achieved with this system amounts to 3136.05 tonnes of oil equivalent (TOE) per year (1) TOE is equal to 8,000,000 kcal). (2) The amounts of emissions of CO_2 and SO_2 are reduced drastically. If other fuels, namely coal, fuel oil and electricity were used, the annual emissions of such gases would have been 24,059/282.86, 8857.19/38.66, 110,074/1335 tons/year, respectively. Figure 5 give a summary of these in detail. It is obvious that using electricity causes the biggest environmental problem and hence emissions, due to the fact each kWh of electricity the power plants emit about 1 kg of CO_2 and 7 g of SO_2, respectively.

In regards to the system performance, in the current Edremit GDHS 22% (11 320 kW) of the total capacity (51 450 kW) is used. If the system worked with full capacity, the number of the equivalent of the dwelling would have increased from 1650 to 7500. If this scenario is developed, a total of 14,269 TOE/year will be saved and for coal, fuel oil and electric resistance, leading to a reduction in CO_2/SO_2 emissions will be 109,468/1287, 40,300/175.9 500,836/6074.25 tons annually. The municipality may also benefit by approximately US$ 3,103,200 per year through net cash flow.

Finally, we have also investigated the some new parameters for the system such as energetic and exergetic renewability ratios as 34 and 52%, and energetic and exergetic reinjection ratios as 64 and 30%, respectively. Both energetic and exergetic renewability ratios show that there is room for performance improvement. Both energetic and exergetic reinjection ratios show that there is an opportunity to recover high percentage of energy and exergy for the system to perform better, and the need for reinjection is to be implemented urgently.

CONCLUSIONS

In this study, we have presented an energetic and exergetic performance analysis of the Edremit GDHS situated in Turkey and its all components, such as heat exchangers, pumps, etc. Pipeline distance plays a key role in terms of transmission pipeline exergy and energy losses. In Edremit GDHS, decreasing the transmission pipeline distance will results in a decrease of energy and exergy losses. Furthermore, heat exchanger losses were found in low values because of the fact that there is no main heat exchanger in central heating center. The results show that although the Edremit geothermal field falls into the category of low-quality geothermal resources, the system has high exergy efficiency by affecting the direct usage of the geothermal fluid. Here we can extract some concluding remarks for better efficiency and better operation of the system:

- Pumps should be worked by adding a fully automatic controlling system which regulates the mass flow rate according to outdoor temperature
- Re-injection section should be constructed and an efficient geothermal greenhouse heating options should be added to the system before the re-injection section.
- Water treatment plant and pH-control system should be added to the system in order to prevent corrosion, which causes a decrease in both energy and exergy efficiencies.

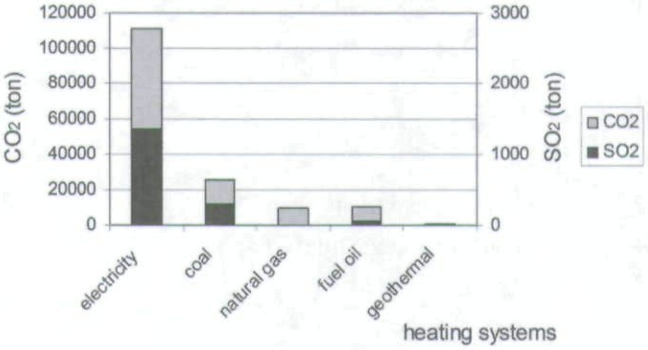

Figure 5 *Comparison of the CO_2 and SO_2 emissions for various fuels for comparison purposes.*

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NOMENCLATURE

C_p = specific heat (kJ/kg °C)
E = energy (kJ)
$\dot{E}$ = energy rate (kW)
$\dot{E}x$ = exergy (kJ)
$\dot{E}x$ = exergy rate (kW)
ex = specific exergy (kJ/kg)
E_{dw} = heat load for an average (or equivalent) dwelling (kW)
E_{smr} = heat requirement for hot water during warmer or "summer" months (MWh)
E_{design} = heat requirement for colder or "winter" months (MWh)
F = annual fuel consumption (kg/year)
f_s = specific fuel consumption (kg/kWh)
h = specific enthalpy (kJ/kg)
IP = improvement potential rate (kW)
LHV = lower heating value (kWh/kg or kWh/m^2)
HHV = higher heating value (kWh/kg or kWh/m^2)
$\dot{m}$ = mass flow rate (kg/s)
N_{dw} = number of (average) dwellings
N_{per} = number of persons per average dwelling
NDM = number of days in each month
P = pressure (kPa)
R = ratio
S = average daily usage of sanitary hot water [kg/(person-day)]

$SExI$ = specific exergy index (dimensionless)
s = specific entropy (kJ/kg·K)
T = temperature (ºC or K)
TW = thermal water
W = water
T_{indoor} = design indoor temperature (°C)
$T_{outdoor}$ = outdoor temperature (°C)
T_R = temperature ratio
$\dot{W}$ = work rate, power (kW)

Greek Letters

ΔT_w = difference in water temperatures (°C)
ΔT_{design} = difference between the indoor and minimum outdoor temperatures
$\Delta T_{average}$ = difference between the indoor and average outdoor temperatures
η = energy or first law efficiency (%)
ε = exergy or exergetic or second law efficiency(%)
ψ = flow exergy (kJ/ kg)
β = proportionality constant or quality factor or exergy coefficient (dimensions)

Subscripts

nd = natural direct discharge
usf = useful
geo = geothermal
sys = system
in = inlet
out = outlet
e = energy
ex = exergy
Rein_E = energetic reinjection
Rein_{Ex} = exergetic reinjection
Ren_E = energetic renewability
Ren_{Ex} = exergetic renewability
HE = heat exchanger
$dest$ = destroyed
$pipe$ = pipe line
gw = geothermal water
ch = chemical
an = annual
nw = network water
0 = dead state

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