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New energy and exergy parameters for geothermal district heating systems

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ABSTRACT

This paper introduces four new parameters, namely energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for geothermal district energy systems. These parameters are applied to Edremit Geothermal District Heating System (GDHS) in Balikesir, Turkey for daily, monthly and yearly assessments and their variations are studied. In addition, the actual data are regressed to obtain some applied correlations for practical use. Some results follow: (i) Both energetic and exergetic renewability ratios decrease with decreasing temperature in heating season and increasing temperature in the summer. (ii) Both energetic and exergetic reinjection ratios increase with decreasing temperature for heating season and increase with increasing temperature for summer season.

1. Introduction

District heating is one of the most common and widespread direct uses of geothermal resources, and such systems are employed to provide space heating and/or cooling to multiple consumers from a single well or multiple wells/fields. The development of geothermal energy, 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 [1]. Recently, geothermal district heating has been successfully implemented in many countries, such as USA, Canada, Italy, Iceland, and more recently Japan, New Zealand, China, and Turkey [2,3]. Turkey has also installed large geothermal district heating systems. Turkey's share of geothermal energy use worldwide is about 12.1% (e.g., [4,5]).

Although there have been many investigations on energy analysis, exergy analysis, sources evaluation and classification, performance assessment, and exergoeconomic analysis of various types of geothermal energy systems and applications, there have been only a few studies on some general parameters, namely specific exergy index, fuel depletion ratio, relative irreversibility, productivity lack, and exergetic factor as introduced [6–9] and applied to geothermal district heating systems by several researchers (e.g., [10,12,15–18]). Van Gool [7] has proposed the parameter of exergetic improvement potential as the maximum improvement in exergy efficiency for a process or system. Lee [8] has proposed the parameter of specific exergy index for some degree of classification and evaluation of geothermal resources using their exergy. Fuel depletion ratio, relative irreversibility, productivity lack, and exergetic factor are defined by Ref. [9] for thermodynamic analysis of some systems.

In this study, we aim to develop four new, applied parameters, namely energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for geothermal district energy systems and to validate these parameters using actual thermal data (in terms of temperatures, pressures, and flow rates) as taken from the Edremit Geothermal District Heating System (GDHS) in Balikesir, Turkey. It is also aimed to study how these parameters change daily, monthly and yearly and how these are used to assess geothermal district heating systems.

2. System description

The Edremit geothermal field is located 87 km west of the city of Balikesir which is in the northwest Anatolia. There is a 3–4 km distance between geothermal source and the center of the Edremit. As of November 2007, 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 and EDJ-3) are currently in use for production. One well (ED-2) is closed because of its insufficient mass flow rate. Other three (EDJ-4, ED-5, EDJ-7) wells have a pump but not yet connected to system. Wellhead

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Nomenclature

$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
$Rein_E$	energetic reinjection (-)
$Rein_{Ex}$	exergetic reinjection (-)
Ren_E	energetic renewability (-)
Ren_{Ex}	exergetic renewability (-)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
s	specific entropy (kJ/kgK)
T	temperature (°C or K)
$\dot{W}$	work rate (or power) (kW)
$\dot{I}$	irreversibility (exergy destruction) rate (kW)
$\dot{P}$	exergy rate of the product (kW)
$\dot{F}$	exergy rate of the fuel (kW)
f	exergetic factor (%)
Greek letters	
ψ	specific exergy (kJ/kg)
η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)
δ	fuel depletion rate (%)
ξ	productivity lack (%)
χ	relative irreversibility (%)
Subscripts	
nd	natural direct discharge
usf	useful
gw	geothermal water
sys	system
in	inlet
out	outlet
e	energy
ex	exergy
HE	heat exchanger
dest	destroyed
pipe	pipe line
gw	geothermal water
0	reference (dead) stead
i	successive number of elements

production temperature is 60 °C. Mass flow rates of operating wells chance from 18 to 86 kg/s. Potential of the Edremit GDHS is 9.815 MWt. Edremit GDHS' wells extend over of nearly 0.3 km^2. As of November 2007, Edremit GDHS was reached 1648 dwelling equivalence. The average area and height of a common dwelling are about 100 m^2 and 2.8 m, respectively, corresponding to a residence volume of 280 m^3. The total heat load for such a dwelling is described as dwelling equivalence, and the equivalent dwelling values for the Edremit GDHS is 8.37 kW.

Generally, heating systems become operational when the outdoor temperature falls below 15 °C. On this temperature basis, according to average temperature, there are 191 "colder" (or heat-requiring) days between October 23 and April 30 annually in the Edremit area. In summer or warmer season, during an average of 174 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 the 5 °C. Under 5 °C, the peaking system, which uses the fuel-oil as a fuel, is activated.

Table 1
Explanation of the wells in Edremit geothermal field.

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

The Edremit GDHS was designed for three stages with the total capacity ultimately corresponding to 7500 dwelling equivalences. In the first stage, heat demand was compensated to 1648 dwelling equivalence. In the second stage, 5000 and in the last stage, 7500 dwelling equivalences will be constructed. In Fig. 1, a schematic diagram of the system is shown. On January 20, 2008, Edremit GDHS supplied the heat requirement of one religious facility, one dormitory, one college, two hospitals and 1345 residences. The essential components of the Edremit GDHS are pumps and heat exchangers as constructed under each building, as well as one under the peaking station. The peaking station is kept for emergency heat requirements, in case the current systems cannot meet the requirements due to extremely low outdoor temperatures and somehow high demand. It is also reserved for system breakdown or natural disaster. The system is designed to have at least one heat exchanger for each building. So now, each building has a heat exchanger to supply its heat requirement. There are 62 buildings, covering 1648 equivalent dwellings in the system. In calculations, it is very difficult to take a fixed value for each heat exchanger. That's why a group of 62 heat exchangers are represented by "HE" in Fig. 1 as a single heat exchanger. Same plate-type heat exchangers are used throughout the system. Inlet and outlet heat exchanger liquid temperatures are measured for both working fluids, namely circulating network water for heating and geothermal fluid. The temperature readings were taken from the farthest building as considered a critical point. It was observed that the difference between critical point and geothermal field is not much, so the effect of elevation is considered negligible in the calculations. The geothermal fluid collected from three production wells, at an average wellhead temperature of 60 °C, is pumped to heat exchangers under the buildings after passing through a peaking station. It was measured that geothermal fluid enters the heat exchangers at an average temperature of 58–59 °C and hence, heat is transferred to the circulating network water for use. After this, geothermal fluid is discharged to the Edremit river at 40–42 °C. No pump is needed for the main distribution pipelines or discharge sections. The pressure supplied from the well pumps is enough for circulation.

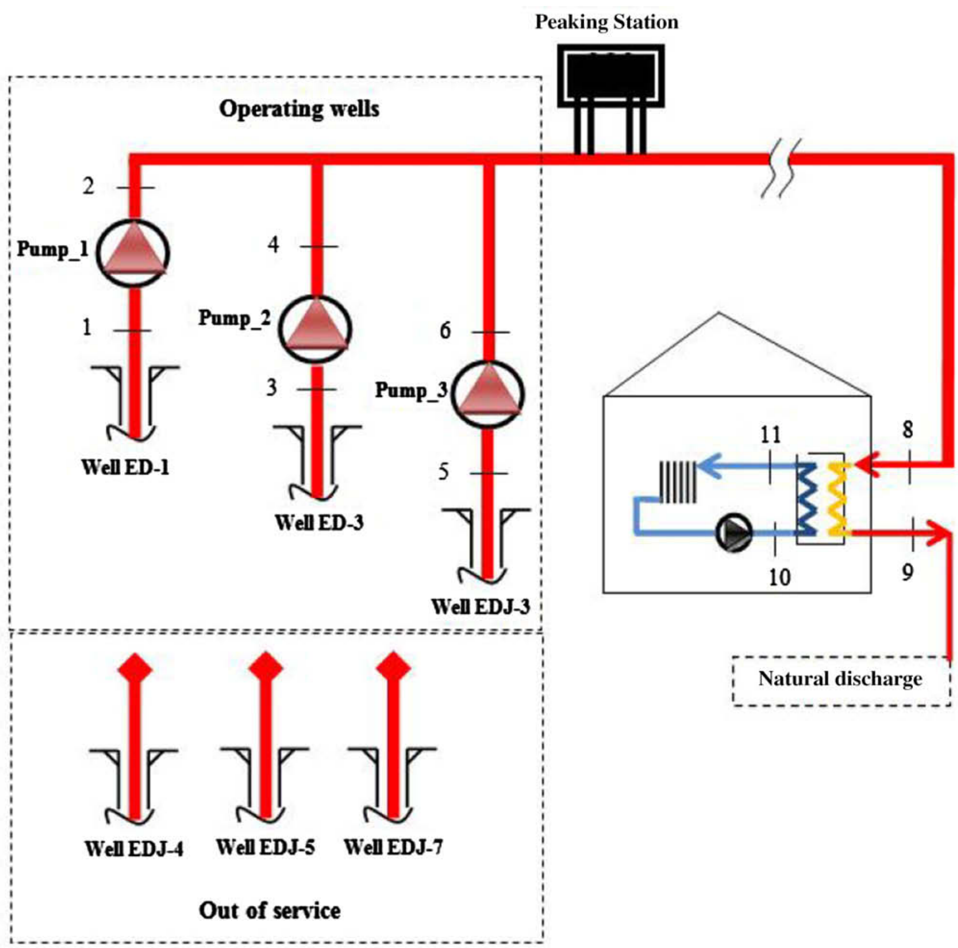

Fig. 1. Flow chart of the GDHS.

3. Modeling

3.1. Balance equations

Here, the balance equations are written for mass, energy and exergy flows for a steady-state and steady-flow system and are applied to the GDHS.

In this regard, the mass balance equation for the overall geothermal system can be written as

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

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

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

$$\dot{E}_{\text{Total}} = \dot{E}_{\text{gw}} + \dot{W}_{\text{pump}} \tag{3}$$

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

$$\dot{E}x_{\text{gw}} = \dot{m}_{\text{gw}}[(h_{\text{gw}} - h_0) - T_0(s_{\text{gw}} - s_0)] \tag{4}$$

$$\dot{E}x_{\text{Total}} = \dot{E}x_{\text{gw}} + \dot{W}_{\text{pump}} \tag{5}$$

The useful exergy, system exergy destruction and total exergy loss are calculated through

$$\dot{E}x_{\text{usf}} = \dot{E}x_{\text{gw}} - \dot{E}x_{\text{Total, loss}} \tag{6}$$

$$\dot{E}x_{\text{Total, loss}} = \dot{E}x_{\text{dest, Sys}} + \dot{E}x_{\text{nd}} \tag{7}$$

$$\dot{E}x_{\text{dest, Sys}} = \sum \dot{E}x_{\text{dest, Pump}} + \sum \dot{E}x_{\text{dest, Pipe}} + \sum \dot{E}x_{\text{dest, HE}} \tag{8}$$

The exergy destructions in the heat exchanger, pump and system itself are calculated as

$$\dot{E}x_{\text{dest, HE}} = \dot{E}x_{\text{in}} - \dot{E}x_{\text{out}} \tag{9}$$

$$\dot{E}x_{\text{dest, Pump}} = \dot{W}_{\text{pump}} - (\dot{E}x_{\text{out}} - \dot{E}x_{\text{in}}) \tag{10}$$

$$\dot{E}x_{\text{dest, Pipe}} = \sum_{i=1}^{n} \dot{E}x_n - \dot{E}x_{n+1} \tag{11}$$

The energy efficiency of the system is written as

$$\eta_{\text{sys}} = \frac{\dot{E}_{\text{usf}}}{\dot{E}_{\text{gw}}} \tag{12}$$

The exergy efficiency of the system then becomes

$$\varepsilon_{\text{sys}} = \frac{\dot{E}x_{\text{usf}}}{\dot{E}x_{\text{gw}}} = 1 - \frac{\dot{E}x_{\text{dest, syst}} + \dot{E}x_{\text{nd}}}{\dot{E}x_{\text{gw}}} \tag{13}$$

3.2. Some literature parameters for GDHS

In the open literature there are a few thermodynamic parameters defined by Ref. [9] for geothermal district energy systems in terms of relative irreversibility, exergetic factor, fuel depletion ratio, and productivity lack as follows:

- *Relative irreversibility:* This parameter describes the ratio of exergy destruction (irreversibility) rate to total exergy destruction for each system element as given in Eq. (14). For example, if the relative irreversibility of a device is found to be 0.15, this means that 15% of the total exergy destruction takes place in that particular device.

$$\chi_i = \frac{\dot{I}_i}{\dot{I}_{tot}} \tag{14}$$

- *Exergetic factor:* This parameter is described as exergetic distribution for each system element as given in Eq. (15). For example, if the value is calculated as 0.15, this means that 15% of the total exergy input is delivered to that particular device.

$$f_i = \frac{\dot{F}_i}{\dot{F}_{tot}} \tag{15}$$

- *Fuel depletion ratio:* This gives the the ratio of exergy destruction of each system element to the total exergy content of the entire system as follows:

$$\delta_i = \frac{\dot{I}_i}{\dot{F}_{tot}} \tag{16}$$

- *Productivity lack:* This is defined as the ratio of exergy destruction of each system element to the total useful exergy obtained from the entire system.

$$\xi_i = \frac{\dot{I}_i}{\dot{P}_{tot}} \tag{17}$$

3.3. Parameter development and analysis

Here, in this section we introduce some system related renewable energy and exergy parameters, namely energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for geothermal systems as to be applied to Edremit GDHS, as follows:

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

$$R_{Ren_E} = \frac{\dot{E}_{usf}}{\dot{E}_{total}} \tag{18}$$

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

$$R_{Ren_{Ex}} = \frac{\dot{E}x_{usf}}{\dot{E}x_{total}} \tag{19}$$

Here, total energy and exergy input terms include the wellhead geothermal water energy only in energy and exergy efficiencies. But in the above equations for energetic and exergetic renewability ratios, all renewable and non-renewable energy and exergy inputs are considered for input.

- *Energetic reinjection ratio:* This is defined as the ratio of renewable energy discharged to environment or reinjected to the well from the system to the total geothermal energy supplied to the system.

$$R_{Rein_E} = \frac{\dot{E}_{nd}}{\dot{E}_{gw}} \tag{20}$$

- *Exergetic reinjection ratio:* This is defined as the ratio of renewable exergy discharged to environment or reinjected to the well from the system to the total geothermal exergy supplied to the system.

$$R_{Rein_{Ex}} = \frac{\dot{E}x_{nd}}{\dot{E}x_{gw}} \tag{21}$$

4. Results and discussion

In this study, the Edremit GDHS is described and investigated from the energetic and exergetic performance point of view. Table 2, based on the thermodynamic states indicated in Fig. 1, lists the state temperatures and pressures, mass flow rates, specific enthalpies, entropies and exergies, and energy and exergy rates of the geothermal fluid, for a chosen day. The state 0 shows dead state for both the geothermal fluid and hot water. For geothermal fluid, the thermodynamic properties of water are used. By doing so, any possible effects of salts and non-condensable gases that might be present in the geothermal fluid are neglected [2,10–18]. The thermodynamic properties of water are obtained from software of Engineering Equation Solver (EES) and the general thermodynamic tables.

The Edremit GDHS do not have automatic temperature control system for outdoor temperature. As the mass flow rates of

Table 2
Exergy rates and other properties at various system locations for one representative unit of the system for 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 ψ (kJ/kg)	Exergy Rate $\dot{E}x$ (kW)	Energy rate $\dot{E}$ (kW)
0	TW	4.9	101.32	20.66	0.0746	–	–	–	–
1	TW	60	55.5	251.1	0.831	40	20.2364	809.456	10044
2	TW	60.15	435	252.1	0.8327	40	20.764	830.56	10084
3	TW	60	55.5	251.1	0.831	45.6	20.2364	922.78	11450
4	TW	60.15	435	252.1	0.8327	45.6	20.764	946.838	11495
5	TW	59	55.5	247	0.8185	15	19.6102	294.15	3705
6	TW	59.14	435	247.9	0.8202	15	20.0378	300.567	3718
7	TW	60.02	435	251.46	0.8312	100.6	20.655	2077.94	25310.9
8	TW	59.5	390	249.52	0.8256	100.6	20.1515	2027.24	25101.7
9	TW	42.5	250	178.5	0.6070	100.6	9.8805	993.978	17957.1
10	W	54.5	190	228.7	0.7628	111.92	16.7837	2130.14	25596.1
11	W	39.5	130	166.1	0.5672	111.92	8.54	1083.87	18589.9

Note: Point zero shows reference state W, water; TW, thermal water.

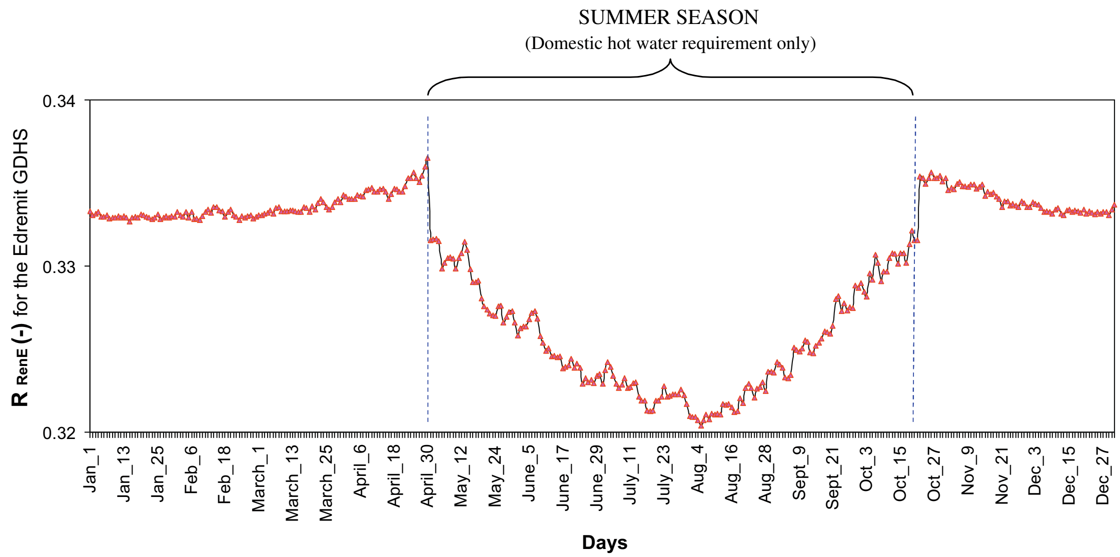

Fig. 2. Change of energetic renewability ratio for the Edremit GDHS annually.

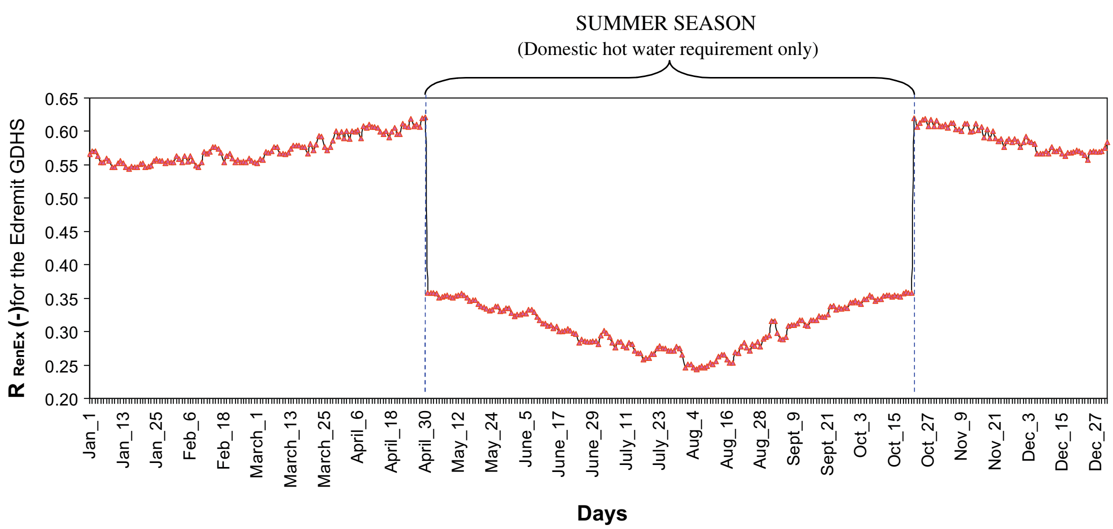

Fig. 3. Change of exergetic renewability ratio for the Edremit GDHS annually.

the systems are changed manually without controlling of outdoor temperatures, the technical managements of system face some problems in many residences. Such problems are now enforcing the managements to implement automatic mass flow rate control systems to GDHS as expected to be completed within one or two years. In this paper, at first we have found the mass flow rates according to heat demand, changing with outdoor temperatures, and then evaluated the systems for future conditions/projections.

We have developed and focused on four new parameters, namely exergetic renewability ratio, energetic renewability ratio, reinjection exergy rate and reinjection energy rate for geothermal district energy systems. Using actual energy data, an application of these parameters is conducted, to the Edremit GDHS for daily, monthly and yearly assessments. These parameters are calculated for each day in each month and then given graphically. The evaluation results of the parameters are given below for summer and winter seasons.

Using Eqs. (18) and (19) energetic and exergetic renewability ratios are calculated for the Edremit GDHS annually and given in Figs. 2 and 3. In the "summer" (or warmer season) (when there is no need to heat the dwellings), only domestic hot water is supplied to the residences. The total domestic hot water load over the summer season is found firstly and then used to find the changes in energetic and exergetic parameters. As seen in Figs. 2 and 3, both energetic and exergetic renewability ratios decrease with increasing temperature in the summer season. Here, one can extract the following:

- The energetic renewability ratio varies between 0.32 and 0.33 for the Edremit GDHS during summer when heating is not required.
- The exergetic renewability ratio varies between 0.25 and 0.35 for the Edremit GDHS during the summer when heating is not required.

It was observed that the outdoor reference ambient temperatures do not have a direct affect on both mass flow rate and energy/exergy losses as a result of no heating requirement for summer season. Domestic hot water requirement is one important

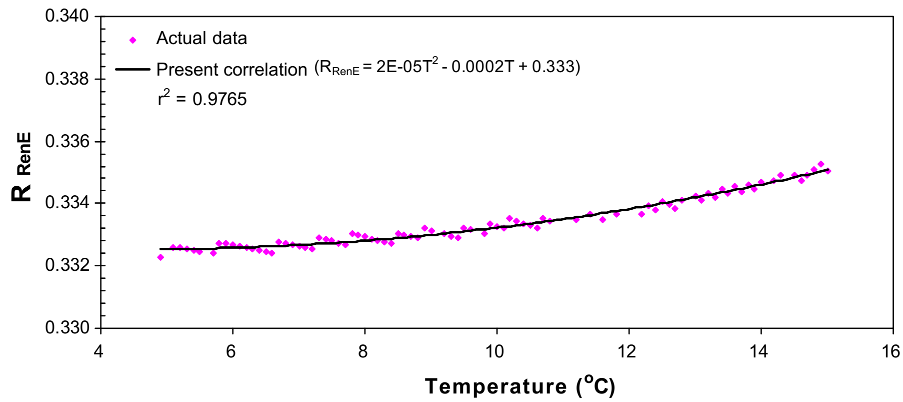

Fig. 4. Change of energetic renewability ratio versus different outdoor temperature for heating season in Edremit GDHS.

parameter for summer season. Domestic hot water requirement increases for hot days. Because of the increase in domestic hot water requirement, pump energy consumption in total energy input increases. Moreover, calculations show that total exergy loss/destruction tended to increase in summer season. For instant, pump exergy destruction increases in summer season as a result of the increase in the required domestic mass flow rate.

In heating season, total "winter" heat demand is the sum of the domestic hot water + heating proper. The mass flow rates for the network water and geothermal water vary during the season dependent on the average useful energy demand. The demand is the highest in January, declines until May and begins increasing until the end of December. It is obvious that based on the demand the mass flow rates proportionally change. The energetic and exergetic renewability ratios become the lowest in January, increasing until May, and begin decreasing until the end of December. We have understood from these results; heat demand and renewability ratio values are opposite characteristic properties. The renewability values are given for heating season as below:

- The energetic renewability ratio varies between 0.33 and 0.34 for the Edremit GDHS.
- The exergetic renewability ratio varies between 0.53 and 0.63 for the Edremit GDHS.

As shown in Fig. 4, the energetic renewability ratios, dependent upon outdoor temperatures, are given as calculated and correlated for the system. While the outdoor temperatures are changing from 5 to 15 °C, the energetic renewability ratio ranges are increased range of 0.2%. Energy consumption of the pumps becomes a key role for increasing or decreasing energetic renewability ratio and it is an effective parameter in total energy input. In the system, pump energy consumption increase with rational base in total energy input with decreasing the reference ambient temperature. So, in heating season, it is found that energetic renewability ratio decreases with decreasing temperatures.

As apparent in Fig. 5, the exergetic renewability ratios, dependent upon outdoor temperatures, are given as calculated and correlated for the GDHS. While the outdoor temperatures are changing from 5 to 15 °C, exergetic renewability ratio ranges are increased range of 6%. In heating season, exergetic renewability ratio decreases with decreasing temperatures, similarly energetic renewability ratios. Useful exergy decreases in lower temperatures as a result of increase in total exergy loss in rational base. Decrease in useful exergy results in decreasing of exergetic renewability ratios.

Both energetic and exergetic reinjection ratios are calculated using Eqs. (20) and (21) for the Edremit GDHS annually as given in Figs. 6 and 7, respectively. These figures can be explained for summer and winter seasons as follows. The energetic reinjection ratio increases in higher temperatures with effect of pump energy consumption. They vary between 0.59 and 0.62 for the Edremit GDHS during summer season when heating is not required (Fig. 6). Variation of the exergetic reinjection ratio depends on outdoor temperature and has similar characteristic with average annually temperature (see Fig. 7). Used geothermal water exergy rate decreases as a result of increase in reference ambient temperature in summer season. Used geothermal exergy rate decreases through the middle of summer, at the highest temperature. Exergetic reinjection ratio varies between 0.10

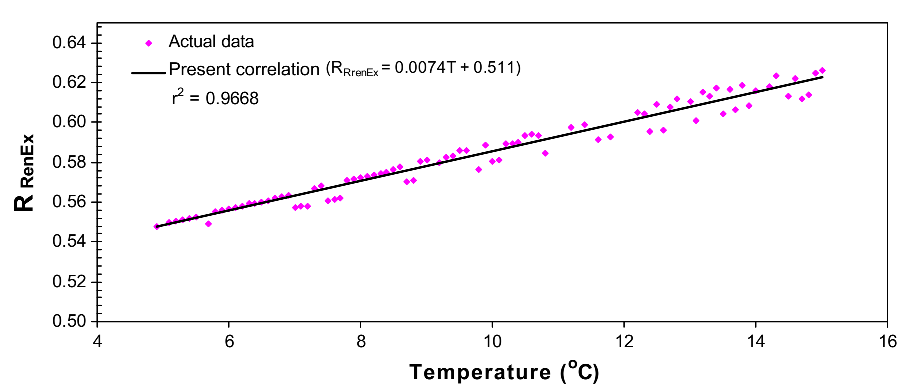

Fig. 5. Change of exergetic renewability ratio versus different outdoor temperature for heating season in Edremit GDHS.

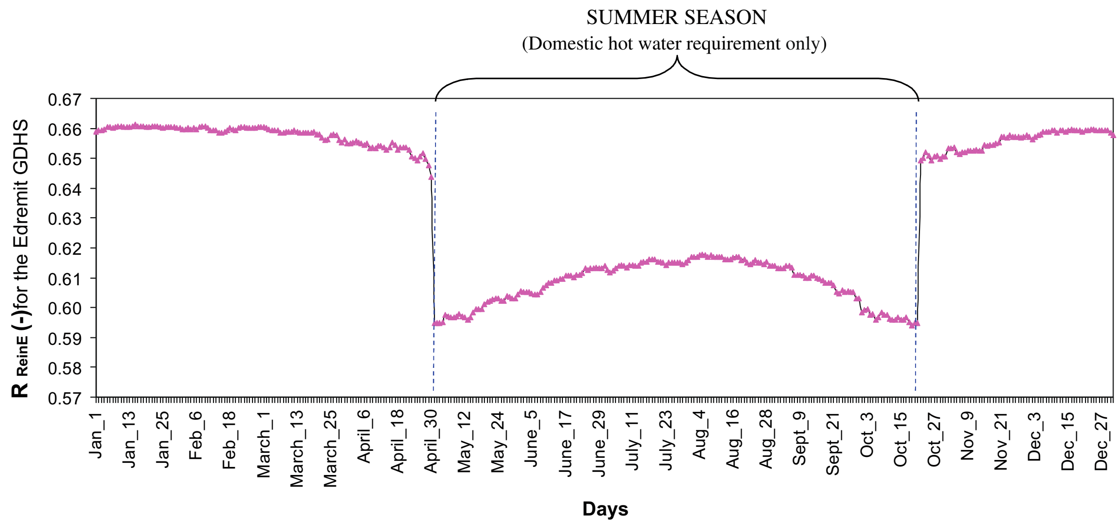

Fig. 6. Change of energetic reinjection ratio for Edremit GDHS annually.

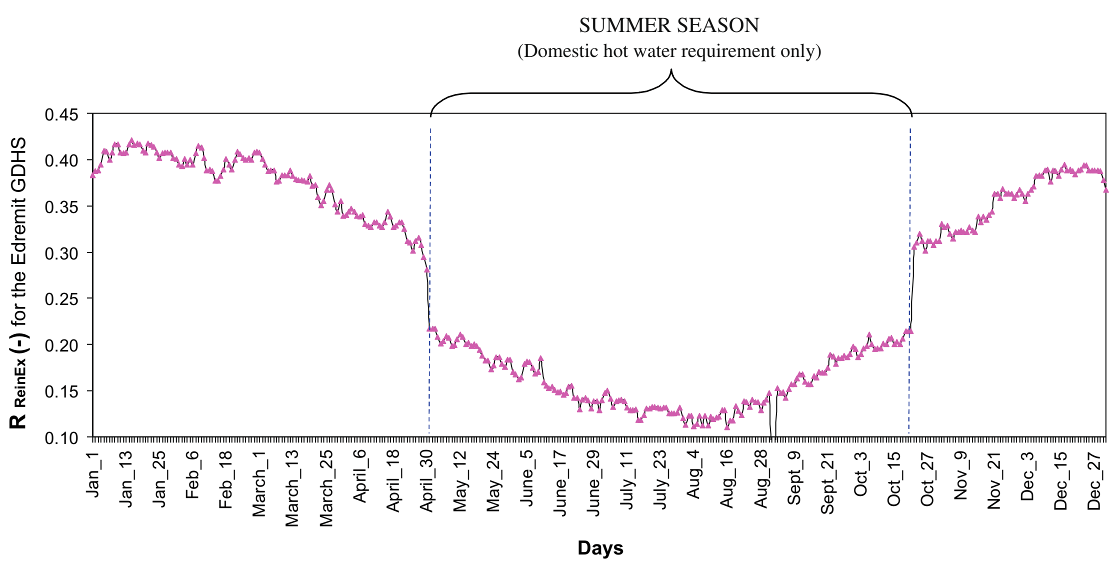

Fig. 7. Change of exergetic reinjection ratio for Edremit GDHS annually.

and 0.20 for the Edremit GDHS during summer season (see Fig. 7).

The pipeline energy losses have a great effect on temperature of the geothermal fluid reaching the heat center. Reinjected geothermal fluid temperature increases in lower temperatures. Increases in geothermal fluid temperature result in increase of reinjection energy loss. As a result of increase in reinjection energy loss, reinjection energy rate increase in colder days. In heating season, the change of energetic reinjection ratios as depending on outdoor temperature is shown in Fig. 8. It shows that energetic reinjection ratio varies between 0.65 and 0.66 for the Edremit GDHS. Calculations show that reinjection exergy loss has the greatest effect on the total exergy loss. It was figured out that governing function for total exergy loss was the reinjection exergy loss. Mass flow of reinjected geothermal water and its exergy rate increases in colder days. As a result of increase in two factors, reinjection exergy rate increase in colder days. Change of exergetic reinjection ratio for different outdoor temperature is shown in Fig. 9. According to these, the exergetic reinjection ratio varies between 0.30 and 0.43 for the Edremit GDHS during the heating season.

5. Conclusions

In this paper we have studied the performance of the Edremit GDHS through some new parameters as energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio. These parameters appear to be key indicators to show how much the system is renewable and apparently sustainable. Of course, higher renewability ratio and lower reinjection ratio are needed for the better performance of the system. Renewability ratio can be also used to evaluation another renewable energy source. Thus, all renewable energy sources are to be possible for comparison each other.

There are three potential problems here such as (i) huge amount of energy loss, (ii) thermal pollution in the river due to discharge water at ~40–45 °C, which will eventually affect the aquatic life and ecology, and (iii) to discharge geothermal fluid directly

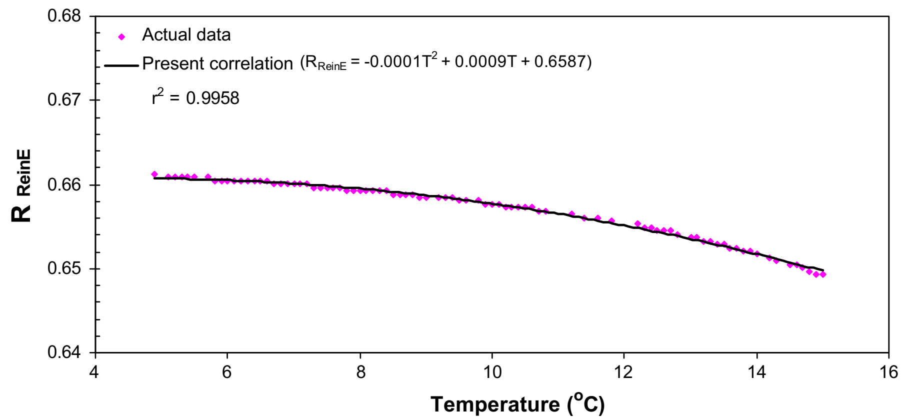

Fig. 8. Change of energetic reinjection ratio versus different outdoor temperature for heating season in Edremit GDHS.

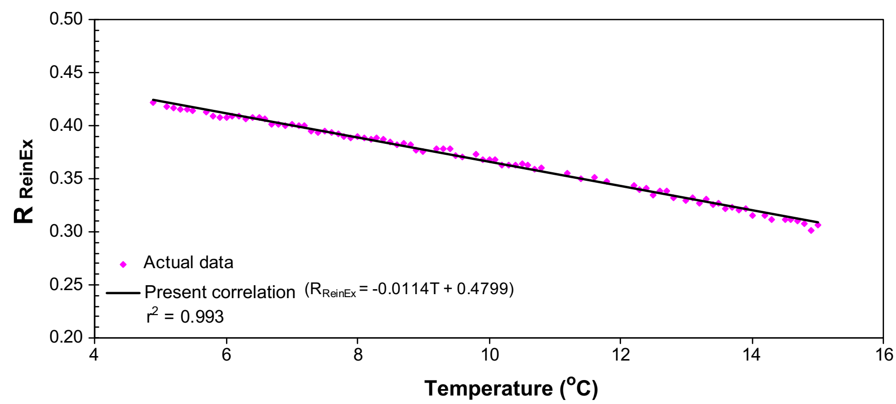

Fig. 9. Change of exergetic reinjection ratio versus different outdoor temperature for heating season in Edremit GDHS.

in the river may also lead to chemical pollution. Therefore, geothermal plants should discharge geothermal fluid to a separate discharge well. Thus, the negative effects of the higher reinjected energy and exergy ratios will also be decreased. Determining of optimum mass flow rate is very crucial to achieve less heat exchanger exergy destruction and less electrical energy for pumping station. Exergy destruction of heat exchangers and electrical energy requirement for pumping station has a direct effect on system energy and exergy efficiency.

The applied results are expected to guide the designers, engineers and policy makers for better implementation of geothermal district heating systems.

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