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Exergoeconomic analysis of the Gonen geothermal district heating system for buildings

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ABSTRACT

This paper presents an application of an exergoeconomic model, through exergy and cost accounting analyses, to the Gonen geothermal district heating system (GDHS) in Balikesir, Turkey for the entire system and its components. This exergoeconomic model is used to reveal the cost formation process and the productive interaction between components. The exergy destructions in the overall Gonen GDHS are quantified and illustrated for a reference temperature of 4 °C. The results indicate that the exergy destructions in the system occur primarily as a result of losses in the cooled geothermal water injected back into the reservoir, pumps, heat exchangers, and pipelines. Total exergy destruction and reinjection exergy of the cooled geothermal water result in 1010 kW (accounting for 32.49%), 320.3 kW (accounting for 10%) of the total exergy input to the Gonen GDHS, respectively. Both energy and exergy efficiencies of the overall Gonen GDHS are also investigated to analyze the system performance, as these efficiencies are determined to be 42% and 50%, respectively. It is found that an increase of the load condition leads to a decrease in the overall thermal costs, which will result in more cost-effective energy systems for buildings.

1. Introduction

Problems with energy supply and use are related not only to global warming, but also to such environmental concerns as air pollution, ozone depletion, forest destruction, and emission of radioactive substances. These issues must be taken into consideration simultaneously if humanity is to achieve a bright energy future with minimal environmental impacts. Much evidence exists, which suggests that the future will be negatively impacted if humans keep degrading the environment. There is an intimate connection between energy, the environment and sustainable development. A society seeking sustainable development ideally must utilize only energy resources which cause no or minimum environmental impact (e.g., which release no or minimum emissions to the environment). In this regard, both residential and commercial sectors become a kind of focal point because of their high energy consumption rates (roughly more than one-third of the world total energy production) in buildings for HVAC&R applications. Of course the essential source of energy is fossil fuels. The potential danger behind this is unavoidable environmental problems, including global warming, due to the excessive use fossil fuels. There are essentially two key solutions to the current energy and environmental problems (technically caused by the building energy systems for HVAC&R) namely renewable energies and efficient energy use. First, renewable energies may cover a broad spectrum from solar to geothermal energy. In this particular paper the energy source is geothermal and the way it is supplied to the buildings is through district heating systems. The latter is efficient energy use which requires exergy analysis in addition to energy analysis. Exergy analysis is an effective thermodynamic method of using the conservation of mass and conservation of energy principles together with the second-law of thermodynamics for design, analysis and performance improvement of building energy (thermal) systems, and is an efficient technique for revealing whether and by how much it is possible to design and use more efficient power systems by reducing the inefficiencies.

The other significant point is that the builders and users want to go for green buildings. This sometimes brings a degree of debate on how this is perceived. Some may see it in a way that putting a couple plants and making the building green are sufficient exercise

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Nomenclature

c	unit cost (\$/kWh)
$\dot{C}$	monetary flow rate (\$/year or \$/h)
C_f	specific heat of the fluid (kJ/kg °C)
CRF	capital recovery factor
DH	degree–hour (°C–h)
E	energy (kWh)
$\dot{E}$	energy rate (kW)
E_{smr}	heat requirement for hot water during warmer or “summer” months (MWh)
Ex	exergy (kWh)
$\dot{Ex}$	exergy rate (kW)
h	enthalpy per unit mass (kJ/kg)
i	interest rate
$\dot{m}$	mass flow rate (kg/s)
n	year
N_{dw}	number of (average) dwellings
N_{per}	number of persons per average dwelling
P	pressure (kPa)
PW	present worth
PWF	present worth factor
s	specific entropy (kJ/kgK)
S	average daily usage of sanitary hot water [kg/(person–day)]
$\dot{S}$	entropy rate (kW)
$S_{k,n}$	salvage value of the kth component
T	temperature (°C or K)
UA	overall heat transfer coefficient (W/m^2 °C)
$\dot{W}$	work rate (kW)
$\dot{Z}$	capital cost rate of the kth unit (\$/s)

Greek letters

ε	exergy or exergetic or second-law efficiency (%)
ϕ	maintenance factor
η	energy or first law efficiency (%)
ΔT_w	difference in water temperatures (°C)

Subscripts

b	base
bound	boundary system
cv	control volume
d	destroyed, destruction
he	heat exchanger
k	kth component
nd	natural discharge
o	outdoor
pi	pipe
pu	pump
P	mechanical
Q	heat
s	entropy production
sys	system
tw	thermal water
T	thermal
T, input	total input
T, outlet	total outlet
usf	useful
w	water
0	dead state

Superscripts

P	mechanical
Q	heat
T	thermal
W	work or electricity

to claim the greenity. Our view is that one cannot make buildings green unless he/she deals with the building energy systems by switching to green energies and minimizing the losses and irreversibilities through a true exergy analysis.

Recently, there has been increasing interest in using exergy analysis as a potential tool for individual or district building energy systems, and some are devoted to low-exergy buildings concept. The collective research alliance resulted in the international cooperation, namely “Annex 49: Low Exergy Systems for High Performance Buildings and Communities” lately concluded under IEA ECBCS Annex 37 “Low-Exergy Systems for Heating and Cooling of Buildings” and to the established a network for “Low-Exergy Systems in Buildings – LowExNet”. Some details are available elsewhere [1,2]. There have been some further works on various aspects of building energy systems and applications and their improvement through exergy. Such studies (e.g., [3–7]) have covered a broad range of investigations ranging from thermal energy storage implementation to mechanical ventilation, from thermal comfort to building insulation, and from ground-source heat pumps to solar heating systems.

In this paper we go one step ahead of exergy to include cost accounting to lead us to exergoeconomic analysis and its application to the Gonen geothermal district heating system. Exergoeconomic analysis is therefore considered a method combining both exergy analysis and cost accounting in order to provide a technique for evaluating the costs of inefficiencies and/or the costs of individual process streams, including intermediate and final products. Exergoeconomic analysis is nowadays considered a powerful tool to study and optimize a power system. The field application is the evaluation of utility costs as products or supplies of production plants, the energy costs between process operations or of an energy converter. Those costs are applicable in feasibility studies, in investment decisions, on comparing alternative techniques and operating conditions, in a cost-effective section of equipment during an installation, an exchange or expansion of an energy system. Furthermore, exergoeconomic analysis estimates the unit cost of products and quantifies monetary loss due to irreversibility. Also, such analysis provides a potential tool for the optimum design and operation of simple and advanced thermal systems. Exergoeconomic analyses are made by many investigators, but recently their studies have intensified for power plants (e.g., [7–10]), cogeneration systems (e.g., [11,12] and on a number of other subjects (e.g., [13,14]).As far as geothermal energy systems are concerned, exergy and exergoeconomic related studies may be classified into five main groups as follows: (i) exergy analysis of geothermal power plants (e.g., [15,16]); (ii) evaluation of geothermal fields using exergy analysis (e.g., [17,18]); (iii) classification of geothermal resources by exergy (e.g., [19,20]); (iv) energy and exergy analysis geothermal district heating systems (GDHSs) (e.g., [6,21]); and (v) exergoeconomic analysis and cost accounting aspects of GDHSs (e.g., [22]).

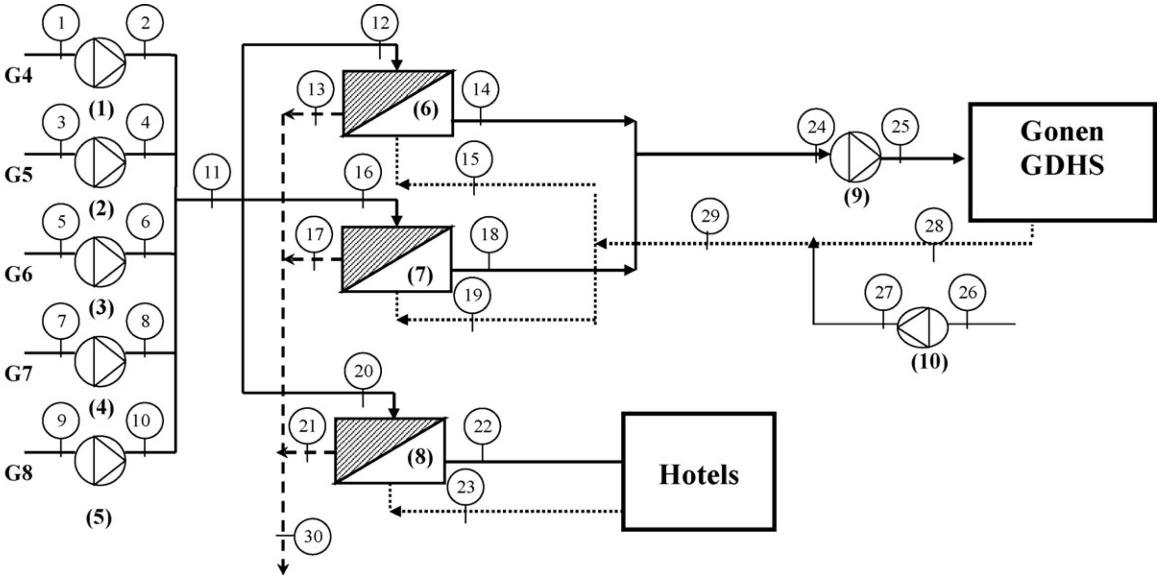

Fig. 1. Schematic diagram of the Gonen GDHS.

As indicated above, the studies of the GDHSs concentrated on exergy analysis intensively and some very limited exergoeconomic analysis studies (particularly on some exergoeconomic parameters) exist in the area. Some studies on energy and exergy analysis of Edremit and Bigadic GDHSs [6] and Gonen GDHS [23] are available elsewhere. Here, in this study, it is aimed to conduct an exergoeconomic analysis of the Gonen GDHS using actual data collected at the plant by the technical staff of the project. The objective of this work is therefore to find unit exergy costs of the Gonen GDHS. Therefore, exergetic and cost accounting analyses are performed for the Gonen GDHS with a capacity of 15.34 MW. In the specific analyses, mass, energy, exergy and cost accounting balances are written for the system and its components. The exergy–cost-balance equations, developed by Oh et al. [24] and Kim et al. [25], are employed here in the analyses first time for a GDHS. Applying the cost-balance equation to each component of the system and to each junction, a set of equations for the unit costs of various exergies is obtained. The monetary valuations of various exergy (thermal, mechanical, etc.) costs, are found by solving the set of equations. The lost cost of each component of the system was obtained by this method. This exergy and cost accounting study will provide comprehensive information about the design and operation of the Gonen GDHS.

2. Case study: the Gonen GDHS

The first space heating application of geothermal energy in Turkey was at the Gonen Park Hotel in 1964. The Gonen GDHS (with an installed capacity of 15 MW), as shown in Fig. 1, was installed in Gonen, Balikesir in 1987. As of January 2008, the number of subscribers to the Gonen GDHS has reached 2985 equivalent dwellings: residences (80.3%; corresponding to 2397 residences), hotels (13.4%), office buildings (4.39%), tanneries (1.5%) and schools (0.17%), respectively. Every state point shown in the Fig. 1 is included in the analysis. The figure also shows 10 components: well pumps (1–5), heat exchangers (6–8), circulation pump for network water (9), circulation pump for tap water (10), respectively. The system was operated with a loading of 80% on the day that the thermal data such as temperatures, pressures and mass flow rates were collected, as listed in Table 1.

3. Analysis

3.1. Balance equations

Here the balance equations are written for mass, energy and exergy flows for the system and its components by considering the steady-state and steady-flow process in engineering thermodynamics.

Table 1
Property values; thermal and mechanical exergy flows; and entropy production rates at various state points in the Gonen GDHS

States	$\dot{m}$ (kg/s)	P (kPa)	T (°C)	$\dot{E}x^{T}$ (kW)	$\dot{E}x^{P}$ (kW)	$\dot{S}$ (kW)
0	–	101.3	4	–	–	–
1	28	119	57.5	539.8	0.495	22.39
2	28	304.1	57.52	540.1	5.678	22.39
3	22	120.3	59.2	449.8	0.4176	18.06
4	22	293.5	59.22	450	4.228	18.07
5	21	131.1	68.2	569.8	0.6254	19.59
6	21	315.1	68.22	570.1	4.489	19.59
7	21	132.8	71.2	620.5	0.6611	20.36
8	21	260	71.21	620.7	3.332	20.36
9	20	148.1	81	760.8	0.9356	21.74
10	20	313	81.02	761.1	4.233	21.74
11	110	304	67.83	2953	22.29	102.1
12	62	304	67.83	1664	12.56	57.55
13	62	202.7	40	563.3	6.282	35.48
14	172	150	52	2702	8.373	125.5
15	172	200	40	1733	16.97	103
16	38	304	67.83	1020	7.7	35.27
17	38	203	40	345.2	3.864	21.74
18	100	150	52	1571	4.868	72.95
19	100	200	40	1007	9.868	59.88
20	10	304	67.83	268.4	2.026	9.283
21	10	203	40	90.85	1.017	5.722
22	45	150	52	706.8	2.191	32.83
23	45	200	40	453.3	4.441	26.95
24	272	150	52	4272	13.24	198.4
25	272	556	52.04	4278	123.7	198.5
26	2.1	450	8	0.2707	0.7322	0.2546
27	2.1	550	8.007	0.2716	0.9421	0.2548
28	269.9	203.1	42	2719	27.47	161.6
29	272	203.1	42	2740	27.68	162.9
30	110	202.8	40	999.3	11.16	62.94

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

$$\dot{m}_{\mathrm{T,input}} = \dot{m}_{\mathrm{T,outlet}} \tag{1}$$

where $\dot{m}_{\mathrm{T}}$ = total mass flow rate (kg/s).

The energetic and exergetic values of working fluid (e.g., geothermal water) are determined using

$$\dot{E}_{\mathrm{T,input}} = \dot{m}_{\mathrm{tw}} h_{\mathrm{tw}} \cong \sum_{i=1}^{n} \dot{m}_{\mathrm{tw},i} h_{\mathrm{tw},i} \tag{2}$$

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,input}} = \sum_{i=1}^{n} \dot{m}_{\mathrm{tw},i}[(h_{\mathrm{tw},i} - h_0) - T_0(s_{\mathrm{tw},i} - s_0)] \tag{3}$$

where the subscript i denotes the working wells.

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

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{d,he}} = \dot{\mathrm{E}}\mathrm{x}_{\mathrm{input,\ he}} - \dot{\mathrm{E}}\mathrm{x}_{\mathrm{outlet,\ he}} \quad \text{for heat exchanger} \tag{4}$$

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{d,Pu}} = \dot{W}_{\mathrm{pu}} - (\dot{\mathrm{E}}\mathrm{x}_{\mathrm{outlet,pu}} - \dot{\mathrm{E}}\mathrm{x}_{\mathrm{input,pu}}) \quad \text{for pumps} \tag{5}$$

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{d,Pi}} = \dot{\mathrm{E}}\mathrm{x}_{\mathrm{input,pi}} - \dot{\mathrm{E}}\mathrm{x}_{\mathrm{outlet,pi}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Q}}_{\mathrm{pi}} \quad \text{for pipes/pipelines} \tag{6}$$

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,d}} = \dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,d,he}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,d,pu}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,d,pi}} \tag{7}$$

The energy efficiency of the system is written as

$$\eta_{\mathrm{sys}} = \frac{\dot{E}_{\mathrm{T,outlet}}}{\dot{E}_{\mathrm{T,input}}} \tag{8}$$

where $\dot{E}_{\mathrm{T,outlet}}$ is the total energy output (useful heat) and $\dot{E}_{\mathrm{T,input}}$ is the total energy input.

The exergy efficiency of the system is also written as

$$\varepsilon_{\mathrm{sys}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,outlet}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,input}}} = 1 - \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{d,sys}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{nd}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T,in}}} \tag{9}$$

3.2. The average total residential heat demand

Building structures and materials: Wall structures vary from one region to another. The materials used in the construction of buildings consist of stones, concrete, bricks, and reinforcement iron bars. In Gonen, brick walls and polystyrene of 2 cm thickness is commonly used as insulating material. Table 2 lists commonly used wall structures for buildings in Gonen and its thermal characteristics, including the conductance U-value, thermal resistance, heat losses, infiltration information, etc.

3.2.1. For summer season

In the "summer" or warm seasons (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 ($\dot{E}_{\mathrm{smr}}$) is *given* by:

$$\dot{E}_{\mathrm{smr}} = N_{\mathrm{dw}} N_{\mathrm{per}} S \Delta T_{\mathrm{w}} C_{\mathrm{f}} \tag{10}$$

where N_{dw} is the number of dwellings (in total 2397), N_{per} is the average number of people in each dwelling (4), S is the average daily usage of sanitary hot water (50 L/(person–day or 50 kg/(person–day), and ΔT_{w} is the difference in temperature between that of the sanitary hot water as 60 °C and that of the tap water from the city distribution network at 10 °C. Thus:

$$\dot{E}_{\mathrm{smr}} = (2397 \times 4 \times 50)\,\mathrm{kg} \times (50\,^{\circ}\mathrm{C}) \times (4.18\,\mathrm{kJ/kg}\,^{\circ}\mathrm{C}) = 1160\ \mathrm{kW}$$

Table 2
Some properties of the model dwelling

Element types	Area (m^2)	U (W/m^2 °C)	UA (W/°C)
Outside Wall			
3 cm external plaster layer, 20 cm brick layer, 3 cm internal plaster, 2 cm insulation	96	0.52	49.92
Windows with two glass	24	2.70	64.8
Roof (8 cm insulation)	100	0.38	38
	K_{total} (W/°C)	152.72	

3.2.2. For winter season

Turkey normally has four climate regions (from mild to severe winter conditions). The Gonen area needs heating for about 7 months every year. The average inner room temperature T_{h} is 20 °C and the average environment temperature T_{e} *is* 15 °C for design and calculations. One of the methods for estimating the energy requirements for heating purposes in a building over a specified period is the degree–time method. The method assumes that the energy needs for a building are proportional to the difference between the outdoor temperature and the base temperature. The total number of heating degree–h (DH) for a heating season can be calculated as

$$\mathrm{DH} = \sum_{j=1}^{N} (T_{\mathrm{b}} - T_{\mathrm{o}})_j, \quad \text{for } (T_{\mathrm{b}} \le T_{\mathrm{o}})_j \tag{11}$$

where T_{o} and T_{b} are the outdoor air and the base temperatures, N is the number of hours providing a condition of $T < T_{\mathrm{b}}$. Here, DH values only take on positive values. If the base temperature is less than the outdoor temperature, heating is needed. In this study, the base temperature is taken as 15 °C. The actual weather data over 20 years as taken from the State Meteorological Affairs General Directorate are used in the energy analyses to have realistic results.

The total energy demand and exergy demand for sanitary hot water and heating purposes in the winter season are calculated using the following equations:

$$E = UA \cdot DH \cdot N_{\mathrm{dw}} \tag{12}$$

$$\mathrm{Ex} = E\left(1 - \frac{T_{\mathrm{outdoor}}}{T_{\mathrm{supply}} - T_{\mathrm{outdoor}}} \ln \frac{T_{\mathrm{supply}}}{T_{\mathrm{outdoor}}}\right) \tag{13}$$

Using actual data in Eqs. (12) and (13) we study daily energy and exergy requirements for the buildings in Gonen using the current system to investigate how their variations take place seasonally and show in Fig. 2. As expected, the energy requirement is more than the exergy requirement due to the fact that energy consists of two parts: exergy (useable one) and anergy (unusable one). So, the energy requirement meets these two parts.

3.3. Exergy–cost-balance equations

The exergy-balance equation for the non-adiabatic components was modified to reflect the exergy losses due to heat transfer. The general exergy-balance equation applicable to cost equation is written as:

$$\dot{\mathrm{E}}\mathrm{x}^{\mathrm{Q}}_{\mathrm{tw}} + \dot{\mathrm{E}}\mathrm{x}^{\mathrm{W}} + \Big(\sum_{\mathrm{input}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_i - \sum_{\mathrm{outlet}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_j\Big) + \Big(\sum_{\mathrm{input}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_i - \sum_{\mathrm{outlet}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_j\Big) + T_0\left(\sum_{\mathrm{input}} \dot{S}_i - \sum_{\mathrm{outlet}} \dot{S}_j + \frac{\dot{Q}_{\mathrm{cv}}}{T_0}\right) = \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Q}}_{\mathrm{usf}} \tag{14}$$

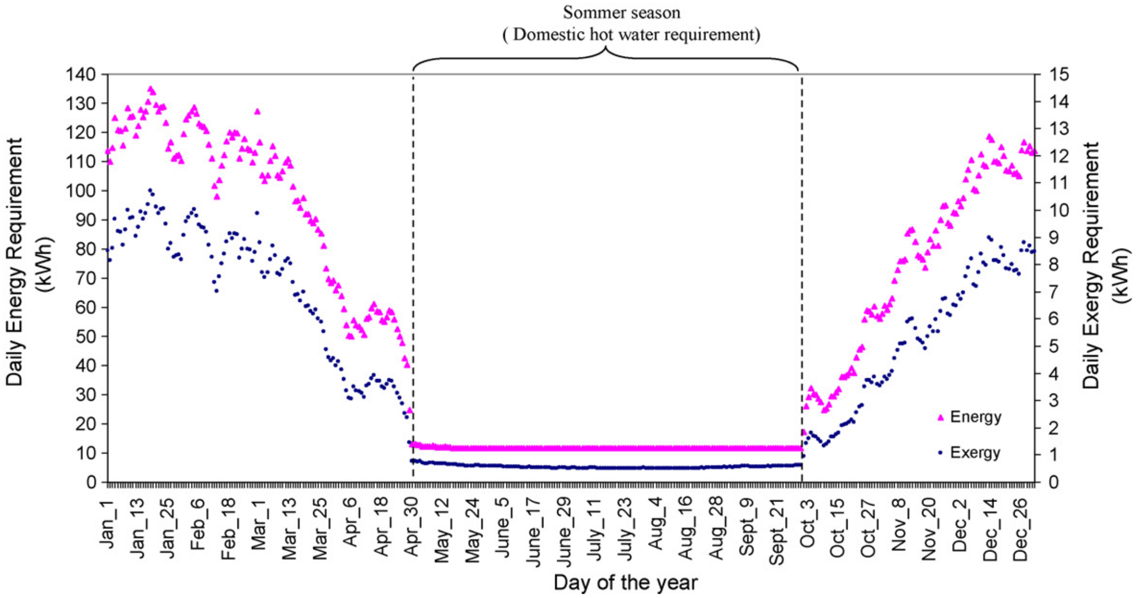

Fig. 2. Annual energy and exergy load of a building.

where $\dot{Q}_{\mathrm{cv}}$ denotes the heat transfer interaction between a component and environment. Considering a unit exergy cost to every separated exergy stream, the exergetic cost-balance equation can be written, according to the exergy-balance equation as given above, as:

$$\dot{\mathrm{E}}\mathrm{x}^{\mathrm{Q}}_{\mathrm{tw}}c_{\mathrm{tw}} + \dot{\mathrm{E}}\mathrm{x}^{\mathrm{W}}\mathrm{c}_{\mathrm{W}} + (\sum_{\text{input}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{i} - \sum_{\text{outlet}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{j})c_{\mathrm{T}} + (\sum_{\text{input}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{i} - \sum_{\text{outlet}} \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{j})c_{\mathrm{P}} + T_0\left(\sum_{\text{input}} \dot{S}_i - \sum_{\text{outlet}} \dot{S}_j + \frac{\dot{Q}_{\mathrm{cv}}}{T_0}\right)c_{\mathrm{s}} + \dot{Z}_{(k)} = \dot{E}x^{\mathrm{Q}}_{\mathrm{usf}}c_{\mathrm{Q}} \tag{15}$$

In this equation, $\dot{Z}_{(k)}$ stands for all financial charges associated with owning and operating the *k*th plant component. The stream exergy is also separated into thermal and mechanical exergies. Here, the exergy-costing method based on the above given equations MOPSA (modified productive structure analysis), developed by Lozano and Valero [26] and Torres et al. [27], is employed.

3.4. Cost equation for the GDHS

All costs as result of owning and operating a plant depend on the type of financing, the required capital, the expected lifetime of a component, and so on [28]. In order to calculate annualized cost of the equipment ($\dot{Z}_{(k)}$), inside the control volume, the annualized (or levelized) cost method is employed, as presented in Bejan et al. [29], to calculate the capital costs of system components. The algorithm of this method is presented in four steps by Kwak et al. [7] and is used in the same way. First, the present worth (PW) of the system is calculated by substituting the effect of salvage value, $S_{k,n}$. In this regard, the salvage values are taken as 10% of the capital cost. Information for the assumption of the salvage values is obtained from the board of directors of the GDHS.

The amortization cost for any particular plant component may be written as

$$\mathrm{PW}_k = c_k - S_{k,n}\mathrm{PWF}(i,n) \tag{16}$$

The present worth of the component is converted to annualized cost using the capital recovery factor CRF(*i*,*n*) as

$$\dot{C}_k(\$/\mathrm{year}) = \mathrm{PW}_k \cdot \mathrm{CRF}(i,n) \tag{17}$$

Using CRF as a function of the lifetime [*n* (*years*)] and interest ratio (*i*), the annual capital cost is found. Dividing the levelized cost by 8000 annual operating hours per year one can obtain the following capital cost for the *k*th component of the system.

$$\dot{Z}_{(k)} = \frac{\phi_k \cdot \dot{C}_k}{(3600 \times 8000)} \tag{18}$$

The maintenance cost is taken into consideration through the factor $\phi_k = 1.06$ for each of the system components whose average expected life is assumed to be 15 years.

4. Model application

The cost-balance equations for each component of the GDHS, as shown in Fig. 1, can be derived from the general cost-balance equation as given in Eq. (15). When the cost-balance equation is applied to each component, a new unit cost must be assigned to the component's principal product, whose unit cost is expressed as Gothic letter. Assigning a new unit cost is crucial in the exergy-costing method based on the productive structure analysis (e.g., [7]). For example, a pump is a component that uses electricity to increase the mechanical exergy of water; the method assigns a new unit cost of c_{P} to the mechanical exergy of water as the component's main product. After unit costs are assigned to the respective principal products of components, the cost-balance equations are written accordingly for each component of the system as follows:

- Well Pump 1 (#1):

  $$(\dot{E}x^{\mathrm{T}}_1 - \dot{E}x^{\mathrm{T}}_2)c_{\mathrm{T}} + (\dot{E}x^{\mathrm{P}}_1 - \dot{E}x^{\mathrm{P}}_2)\mathbf{c_{1P}} + T_0(\dot{S}_1 - \dot{S}_2)c_{\mathrm{s}} + \dot{Z}_{(1)} = \dot{W}_{(1)}c_{\mathrm{W}} \tag{19}$$

  with $\dot{K}^{\mathrm{T}}_{(\text{inlet,outlet})}c_{\mathrm{T}} + \dot{K}^{\mathrm{P}}_{(\text{inlet,outlet})}\mathbf{c_{n\,p}} - \dot{E}^{\mathrm{Lost}}_{x(n)}c_{\mathrm{s}} + \dot{Z}_{(n)} = \dot{E}_x c_{\mathrm{W}}$.These can also be applied to other well pumps (Pump-2, Pump-3, Pump-4 and Pump-5).
- Heat exchanger (#6):

$$(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{12} + \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{15} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{14} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{13})\mathbf{c_{6T}} + (\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{12} + \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{15} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{p}}_{14} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{13})c_{\mathrm{p}} + T_0\left(\frac{\dot{S}_{12} - \dot{S}_{13} + \dot{S}_{15} - \dot{S}_{14} + \dot{Q}_{(6)}}{T_0}\right) \cdot c_{\mathrm{s}} + \dot{Z}_6 = 0 \tag{20}$$

with $\dot{A}^{\mathrm{T}}_{(n,n)}c_{6\mathrm{T}} + \dot{A}^{\mathrm{P}}_{(n,n)}\mathbf{c_{6T}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Lost}}_{(n)}c_{\mathrm{s}} + \dot{Z}_{(n)} = 0$.which can also be applied to the other heat exchangers [HE-2 (#7) and HE-3 (#8)].

Circulation pumps for network water (#9) and fresh water pump (#10):

$$(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{24} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{25})c_{\mathrm{T}} + (\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{24} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{25})\mathbf{c_{9P}} + T_0(\dot{S}_{24} - \dot{S}_{25})c_{\mathrm{s}} + \dot{Z}_{(9)} = \dot{W}_{(9)}c_{\mathrm{W}} \tag{21}$$

$$(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{26} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{27})c_{\mathrm{T}} + (\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{26} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{27})\mathbf{c_{10P}} + T_0(\dot{S}_{26} - \dot{S}_{27})c_{\mathrm{s}} + \dot{Z}_{(10)} = \dot{W}_{(10)}c_{\mathrm{W}} \tag{22}$$

with $\dot{K}^{\mathrm{T}}_{(\mathrm{inlet,\ outlet})}c_{\mathrm{T}} + \dot{K}^{\mathrm{P}}_{(\mathrm{inlet,\ outlet})}\mathbf{c_{nP}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Lost}}_{(n)}c_{\mathrm{s}} + \dot{Z}_{(n)} = \dot{\mathrm{E}}\mathrm{x}^{\mathrm{W}}_{(n)}c_{\mathrm{W}}$.

Geothermal water pipes (#11) and network pipes (#12):

$$\sum_{\mathrm{geopipes}}^{\mathrm{cycle}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{i} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{j})\mathbf{c_{11T}} + \sum_{\mathrm{geopipes}}^{\mathrm{cycle}}(\dot{\mathrm{E}}^{\mathrm{P}}_{x,i} - \dot{\mathrm{E}}^{\mathrm{P}}_{x,j})c_{\mathrm{P}} + T_0\left(\Sigma(\dot{S}_i - \dot{S}_j) + \frac{\dot{Q}_{11}}{T_0}\right)c_{\mathrm{s}} + \dot{Z}_{11} = 0 \tag{23}$$

$$\sum_{\mathrm{network}}^{\mathrm{cycle}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{i} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{j})\mathbf{c_{12T}} + \sum_{\mathrm{network}}^{\mathrm{cycle}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{i} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{j})c_{\mathrm{P}} + T_0\left(\Sigma(\dot{S}_i - \dot{S}_j) + \frac{\dot{Q}_{12}}{T_0}\right)c_{\mathrm{s}} + \dot{Z}_{12} = 0 \tag{24}$$

with $\dot{K}^{\mathrm{T}}_{(n,n)}c_{n\mathrm{T}} + \dot{K}^{\mathrm{P}}_{(n,n)}c_{\mathrm{P}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Lost}}_{(n)}c_{\mathrm{s}} + \dot{Z}_{(n)} = 0$.

Therefore, the 12 cost-balance equations for 12 components of the GDHS are formed, with 15 unknown unit exergy costs $c_{1\mathrm{P}}$, $c_{2\mathrm{P}}$, $c_{3\mathrm{P}}$, $c_{4\mathrm{P}}$, $c_{5\mathrm{P}}$, $c_{6\mathrm{T}}$, $c_{7\mathrm{T}}$, $c_{8\mathrm{T}}$, $c_{9\mathrm{P}}$, $c_{10\mathrm{P}}$, $c_{11\mathrm{T}}$, $c_{12\mathrm{T}}$, c_{P}, c_{T}, and c_{S}. We can obtain two more cost-balance equations for the junctions of thermal and mechanical exergies of the stream as:

$$\sum_{\mathrm{system}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{outlet}})\mathbf{c_P} = \sum_{n=1}^{5}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{outlet}})c_{n\mathrm{P}} + \sum_{n=9}^{10}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{outlet}})c_{n\mathrm{P}} \tag{25}$$

with $\dot{A}_{(n,n)}\mathbf{c_P} = \sum_{n=1}^{5}\dot{K}^{\mathrm{P}}_{(\mathrm{inlet,\ outlet})}c_{n\mathrm{P}} + \sum_{n=9}^{10}\dot{K}^{\mathrm{P}}_{(\mathrm{inlet,\ outlet})}c_{n\mathrm{P}}$ and

$$\sum_{\mathrm{system}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{outlet}})\mathbf{c_T} = \sum_{n=6}^{8}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{outlet}})c_{n\mathrm{T}} + \sum_{n=11}^{12}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{outlet}}) \cdot c_{n\mathrm{T}} \tag{26}$$

with $\dot{A}_{(n,n)}\mathbf{c_P} = \sum_{n=6}^{8}\dot{K}^{\mathrm{T}}_{(\mathrm{inlet,\ outlet})}c_{n\mathrm{T}} + \sum_{n=11}^{12}\dot{K}^{\mathrm{T}}_{(\mathrm{inlet,\ outlet})}c_{n\mathrm{T}}$.

Another cost-balance equation corresponding to the exergy balance for the system boundary of the GDHS can also be obtained. The residual exergies of the stream, leaving the system through the boundary, are due to the entropy production of the system. The cost-balance equation for the system boundary is written as

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{tw}}c_{\mathrm{O}} + \sum_{\mathrm{system}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{T}}_{\mathrm{outlet}})c_{\mathrm{T}} + \sum_{\mathrm{system}}(\dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{inlet}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{P}}_{\mathrm{outlet}})c_{\mathrm{P}} + \left[T_0\left(\frac{\sum_{\mathrm{inlet}}\dot{S}_i - \dot{S}_j + \dot{Q}_{(k)}}{T_0}\right)\right]\mathbf{c_S} + \dot{Z}_{(\mathrm{bound})} = 0 \tag{27}$$

With $\dot{K}^{\mathrm{T}}_{\mathrm{G}}c_{\mathrm{T}} + \dot{K}^{\mathrm{P}}_{\mathrm{G}}c_{\mathrm{P}} - \dot{\mathrm{E}}\mathrm{x}^{\mathrm{Lost}}_{(\mathrm{bound})}c_{\mathrm{s}} + \dot{Z}_{(\mathrm{bound})} = 0$.

To deduce the cost-balance equation for each component, a unit cost is assigned to each component as c_{S}, referring to entropy production cost. We now have sufficient number of cost-balance equations enough to calculate the unit cost of all exergies and products. The GDHS construction cost is represented by the term $Z_{(\mathrm{bound})}$. Entropy production cost is obtained through the boundary of the system, where the exergy losses to environment are important in determining the production costs.

The terms for the exergy unit costs, such as the unit cost of mechanical exergy c_{P} and thermal exergy c_{T} and entropy production c_{S}, are important in determining the production costs. These exergy unit costs may be considered as internal parameters for cost accounting processes. This consideration is evident from the matrix representation of the all cost-balance equations for the system as shown in Fig. 3. Each row in the matrix represents the exergy-balance equation for a component or junction. This is done as suggested by Kwak et al. [7]. So, the exergy value shown in each column of a given row (equation for a component) is the rate of exergy produced or consumed in the component. While each column in the matrix shows how an exergy produced in a component (diagonal element) is distributed to or consumed in other components (off diagonal elements).

Geothermal projects are basically characterized by their high initial investments and relatively low operation and maintenance costs. For example, the cost of drilling and developing production and reinjection wells may vary from US$ 500 to US$4000/kW [30,31].

Under the conditions prevailing in Turkey, the pipeline network represents about 70% of the investment cost of a geothermal district heating project, followed by the wells (10%), building modifications (10%), construction of the heating center (5%), and engineering design (5%) [32]. With appropriate design and implementation, the investment per residence for a GDHS is in the range US$ 1500–2500, excluding radiator installation. In Turkey, the payback time for investment in a geothermal district heating project ranges from 5 to 8 years [33].

5. Results and discussion

The actual pressures, temperatures, and mass flow rates were measured at various points on January 13, 2007 to calculate various aspects of mass, energy, entropy, exergy and cost accounting parameters in terms of exergy flow rates and entropy generation rates (or exergy destruction rates) using Engineering Equation Solver (EES) software package. Therefore, all these actual data and calculated mechanical and thermal exergy flow rates and entropy production rates at various state points of the system as shown in Fig. 1 are given in Table 1.

In Table 3 we tabulate the net flow rates of mechanical, thermal and work related exergies for each component in the GDHS, based upon the 80% loading condition in order to represent the actual operation of the system. Negative values of the work exergies represent that work was done on the components, simply work inputs to the pumps. Thermal water coming from the wells is treated as input, and useful exergy appears as output, based on the conversion from the resource to the product, respectively. The product terms can be classified into the exergy lost through reinjection water, destructed exergies within the system, and useful exergy as needed for heating and sanitary water and are included in the exergy-balance equations. As shown in Table 3, about 10.3 % of the resource exergy is lost through destructed exergy (or irreversibilities) within the components, and 80% of this is destroyed in the heat exchangers, 8.75% in the pumps and the remaining in the pipes as 11.25%, respectively. This shows that the most considerable entropy production (exergy destruction) occurs in the heat exchangers as there is an urgent need for improvement.

Fig. 4 illustrates the exergy flow diagram, as sketched through the exergy-balance equation, consisting of five key exergy flows of the system. The exergy output as useful product accounts for 48%

$$\begin{vmatrix}
\dot{K}^P_{(1,2)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(1,2)} & -\dot{E}x^{Lost}_{(1)} \\
0 & \dot{K}^P_{(3,4)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(3,4)} & -\dot{E}x^{Lost}_{(2)} \\
0 & 0 & \dot{K}^P_{(5,6)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(5,6)} & -\dot{E}x^{Lost}_{(3)} \\
0 & 0 & 0 & \dot{K}^P_{(7,8)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(7,8)} & -\dot{E}x^{Lost}_{(4)} \\
0 & 0 & 0 & 0 & \dot{K}^P_{(9,10)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(9,10)} & -\dot{E}x^{Lost}_{(5)} \\
0 & 0 & 0 & 0 & 0 & \dot{A}^T_{(6,6)} & 0 & 0 & 0 & 0 & 0 & 0 & \dot{A}^P_{(6,6)} & 0 & -\dot{E}x^{Lost}_{(6)} \\
0 & 0 & 0 & 0 & 0 & 0 & \dot{A}^T_{(7,7)} & 0 & 0 & 0 & 0 & 0 & \dot{A}^P_{(7,7)} & 0 & -\dot{E}x^{Lost}_{(7)} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{A}^T_{(8,8)} & 0 & 0 & 0 & 0 & \dot{A}^P_{(8,8)} & 0 & -\dot{E}x^{Lost}_{(8)} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^P_{(24,25)} & 0 & 0 & 0 & 0 & 0 & -\dot{E}x^{Lost}_{(9)} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^P_{(26,27)} & 0 & 0 & 0 & 0 & -\dot{E}x^{Lost}_{(10)} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(11,11)} & 0 & \dot{K}^P_{(11,11)} & 0 & -\dot{E}x^{Lost}_{(11)} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{K}^T_{(12,12)} & \dot{K}^P_{(12,12)} & 0 & -\dot{E}x^{Lost}_{(12)} \\
-\dot{K}^P_{(1,2)} & -\dot{K}^P_{(3,4)} & -\dot{K}^P_{(5,6)} & -\dot{K}^P_{(7,8)} & -\dot{K}^P_{(9,10)} & 0 & 0 & 0 & -\dot{K}^P_{(24,25)} & -\dot{K}^P_{(26,27)} & 0 & 0 & \dot{A}^T_{(13,13)} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\dot{A}^T_{(6,6)} & -\dot{A}^T_{(7,7)} & -\dot{A}^T_{(8,8)} & 0 & 0 & -\dot{K}^T_{(11,11)} & -\dot{K}^T_{(12,12)} & 0 & \dot{A}^T_{(14,14)} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\dot{K}^P_{(G)} & -\dot{K}^T_{(G)} & \dot{E}x^{Lost}_{(bound)}
\end{vmatrix}
\times
\begin{vmatrix}
C_{1P} \\ C_{2P} \\ C_{3P} \\ C_{4P} \\ C_{5P} \\ C_{6T} \\ C_{7T} \\ C_{8T} \\ C_{9P} \\ C_{10P} \\ C_{11T} \\ C_{12T} \\ C_{P} \\ C_{T} \\ C_{S}
\end{vmatrix}
=
\begin{vmatrix}
-\dot{Z}^T_{(1)} - \dot{E}x^W_{(1)} C_W \\
-\dot{Z}^T_{(2)} - \dot{E}x^W_{(2)} C_W \\
-\dot{Z}^T_{(3)} - \dot{E}x^W_{(3)} C_W \\
-\dot{Z}^T_{(4)} - \dot{E}x^W_{(4)} C_W \\
-\dot{Z}^T_{(5)} - \dot{E}x^W_{(5)} C_W \\
-\dot{Z}_{(6)} \\
-\dot{Z}_{(7)} \\
-\dot{Z}_{(8)} \\
-\dot{Z}^T_{(9)} - \dot{E}x^W_{(9)} C_W \\
-\dot{Z}^T_{(10)} - \dot{E}x^W_{(10)} C_W \\
-\dot{Z}_{(11)} \\
-\dot{Z}_{(12)} \\
0 \\
0 \\
-\dot{Z}_{(bound)}
\end{vmatrix}$$

Fig. 3. Cost accounting structure in a matrix form of the Gonen GDHS for analysis.

accordingly. It is also obvious that the performance can be improved drastically if the reinjection exergy flow rate is recovered accordingly and used in the system. In Table 4, the initial investments, the annuity including the maintenance cost, and the corresponding monetary flow rates for each component are given. In this analysis, the total construction cost includes the costs of well opening, plant preparation and building construction. Kwak et al [11] pointed out that the construction cost, which is one-third or two-thirds of the equipment costs, is not negligible. For the Gonen GDHS the construction cost is found to be about 48% of the total cost. So, the cost of network pipes and others (pumps and heat exchangers) is found as 43% and 9% of the total investment cost, respectively.

Table 3
Exergy balances of each component in the Gonen GDHS (at 80% loading condition for January 13, 2007)

Component	Net exergy flow rate (kW)			Entropy production rate (kW)
	$\dot{E}x^W_{(k)}$	$\dot{E}x^T$	$\dot{E}x^P$	
Well pumps				
Pump-1	−6.581	0.2954	5.183	1.103
Pump-2	−4.838	0.2241	3.81	0.8038
Pump-3	−4.906	0.2645	3.864	0.7779
Pump-4	−3.392	0.1913	2.671	0.5293
Pump-5	−4.188	0.2704	3.298	0.6194
Heat exchanger				
HE-1	00.00	−132.1	−14.88	109.1
HE-2	00.00	−111.5	−8.836	95
HE-3	00.00	−75.91	−3.26	55
Network pumps				
Pump-6	−140.2	5.644	110.4	24.15
Pump-7	−0.2666	0.0008608	0.21	0.05582
Pipes				
TW pipes	0.00	−30	0	6.939E−3
NW pipes	0.00	−40	−0.8432	33.09
Total	−164.4	−382.7	96.75	−320.3

TW: thermal water, NW: network water.

The cost flow rates corresponding to each component's exergy flow rate and the construction cost are given in Table 5. The monetary flow rates of products are also given. The cost flow rates connected to the products and resources is used as the case of the exergy balances as listed in Table 3. The lost cost is not counted to evaluate the cost of the final product as consistent with the reference [32]. The cost apparently results from the entropy production in each component as the consumed cost. Sum of the cost flow rates of each component in the GDHS equals zero, as tabulated in Table 4, and shows that cost balances for the each component are suitable. In the total system, the sum of the cost flow rates of electricity and capital expenditures of the GDHS equals zero, which is in fact a content of Eq. (14). Such result confirms that the overall cost balance as given in Eq. (14) is fully correct.

In Table 6 the cost flow rates of exergies without considering the construction costs are given. Comparing the results given in Tables 4 and 5 makes one thing clear that how the cost structure of the system will change by adding the construction cost. Therefore, the cost flow rate of entropy production or the loss cost at each component is increased significantly when the construction cost is added. The unit costs of the thermal and mechanical exergies and of the entropy production are deliberately considered to be internal parameters for the costing processes as consistent with the reference [29]. The internal parameters such as c_P, c_t and c_s, found by solving cost-balance equations, are used to calculate the

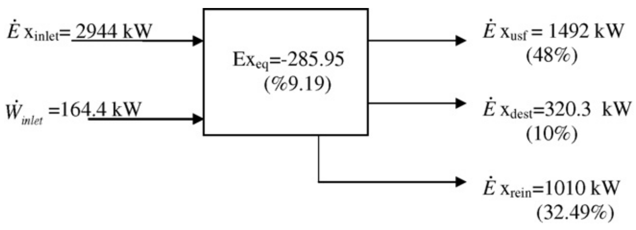

Fig. 4. Exergy-balance flowchart of the GDHS system.

Table 4
Initial investments, annualized costs and corresponding monetary flow rates of each component in the Gonen GDHS

Component	Initial investment cost (US$ 10^3)	Annualized cost (US$/year)	Monetary flow rate (US$/h)
Well pumps			
Pump-1	11.017	429.1	0.057
Pump-2	8.161	317.8	0.042
Pump-3	9.385	365.5	0.049
Pump-4	9.385	365.5	0.049
Pump-5	8.633	336.2	0.045
Heat exchangers			
HE-1	145.064	5650	0.750
HE-2	164.704	6415	0.851
HE-3	46.845	1824	0.242
Network pumps			
Pump-6	14.235	554.4	0.073
Pump-7	0.500	19.47	0.003
Pipes			
TW pipes	611.388	23812	3.203
NW pipes	5653	220154	29.198
Construction	6221	242273	32.135
Total	12903.32	502516	66.695

Table 5
Cost flow rates of thermal, mechanical and entropy production of each component in the Gonen GDHS with construction cost

Component	$\dot{C}_W$ (US$/h)	$\dot{C}_T$ (US$/h)	$\dot{C}_P$ (US$/h)	$\dot{C}_S$ (US$/h)	$\dot{Z}$ (US$/h)
Well pumps					
Pump-1	−0.7436	−0.03758	0.7993	0.03876	−0.057
Pump-2	−0.5467	−0.02851	0.5891	0.02825	−0.042
Pump-3	−0.5544	−0.03364	0.6091	0.02735	−0.049
Pump-4	−0.3833	−0.02434	0.4374	0.0186	−0.049
Pump-5	−0.4732	−0.03439	0.5304	0.02177	−0.045
Heat exchangers					
HE-1	0.00	−0.9358	1.893	3.836	−0.750
HE-2	0.00	−1.212	1.124	3.34	−0.851
HE-3	0.00	−11.71	0.4146	1.933	−0.242
Network pumps					
Pump-6	−15.84	−0.7179	15.79	0.8491	−0.073
Pump-7	−0.03013	−0.0001095	0.03086	0.001962	−0.003
Pipes					
TW pipes	0.00	3.155	0.03086	2.439E-19	−3.203
NW pipes	0.00	30.46	2.824E−4	1.163	−29.198
Boundary	0.00	−18.88	−22.24	−11.26	−32.135
Total	−18.58	0.00	0.00	0.00	−66.695

Table 6
Cost flow rates of thermal, mechanical and entropy production of each component in the Gonen GDHS without construction cost

Component	$\dot{C}_W$ (US$/h)	$\dot{C}_T$ (US$/h)	$\dot{C}_P$ (US$/h)	$\dot{C}_S$ (US$/h)	$\dot{Z}$ (US$/h)
Well pumps					
Pump-1	−0.7436	−0.02132	0.7212	0.03350	−0.057
Pump-2	−0.5467	−0.01618	0.5317	0.02443	−0.042
Pump-3	−0.5544	−0.01909	0.551	0.02364	−0.049
Pump-4	−0.3833	−0.01381	0.3972	0.01609	−0.049
Pump-5	−0.4732	−0.01951	0.4808	0.01882	−0.045
Heat exchangers					
HE-1	0.00	−7.274	1.074	3.31700	−0.750
HE-2	0.00	−6.667	0.6377	2.88733	−0.851
HE-3	0.00	10.56	0.2352	1.67167	−0.242
Network pumps					
Pump-6	−15.84	−0.4073	14.12	0.73400	−0.073
Pump-7	−0.03013	−0.00006213	0.02768	0.00170	−0.003
Pipes					
TW pipes	0.00	3.155	1.603E-16	0.00000	−3.203
NW pipes	0.00	32.3	0.06085	1.00567	−29.198
Boundary	0.00	−31.58	−18.84	−9.73333	0.000
Total	−18.58	0.00	0.00	0.00000	−34.560

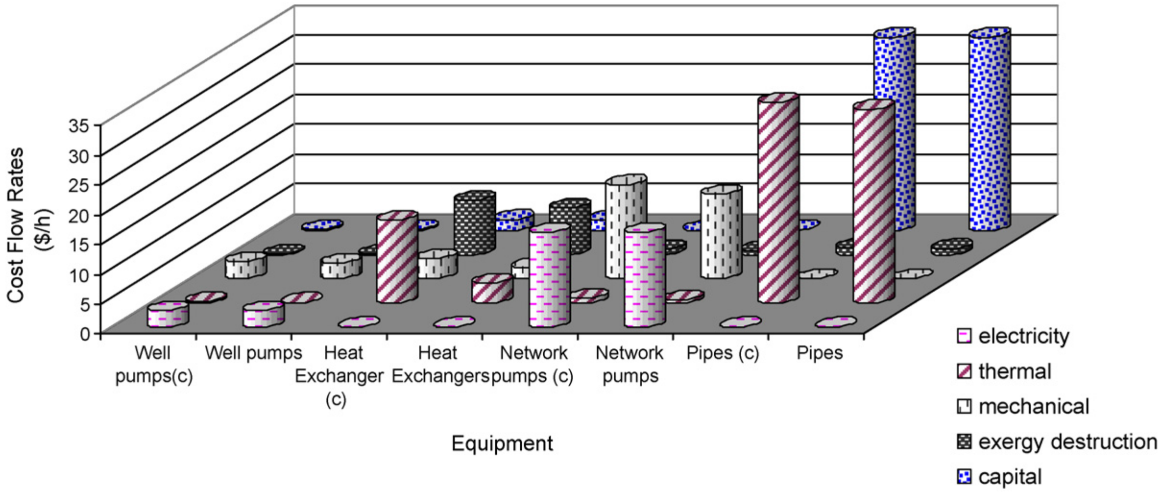

Fig. 5. Cost Flow Rates for all system devices, including exergy destructions.

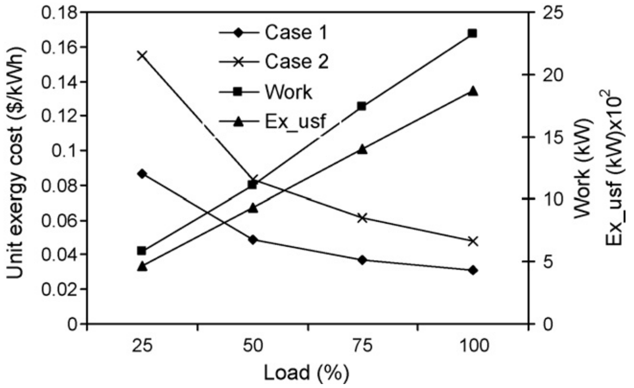

Fig. 6. Unit exergy costs for various load conditions for two cases (Case 1: with construction cost; Case 2: without construction cost).

exergy values consumed by each component. The system is operated at 80% load with an exergy output of 1492 kW and the unit electricity cost was $ 0.113 per kWh at that date. The unit exergy costs are found as $c_P > c_t > c_s > c_Q$ for the studied actual data. The cost structure discussed is a result of the expensive mechanical exergy which is derived from electricity. Adding construction cost changed internal parameters, as shown in Tables 4 and 5, as the results cost flow rates are increased. Here, in order to better illustrate the cost flow rates for all devices employed in the GDHS, Fig. 5 is presented. Exergy destructions are also included to show how much losses take place within the system. Of course, the bar charts are drawn based upon the data tabulated in the above tables.

Furthermore, the unit exergy cost values according to various load conditions are given in Fig. 6. At the high load conditions, although work exergy values are higher, unit exergy costs are decreased. In case of the without of the construction cost, unit exergy costs are found as 0.0864/0.0489/0.0371/0.0309 and adding construction cost, they are found as 0.155/0.083/0.061/0.048 at 25%, 50%, 75% and 100% load conditions. In Fig. 7a and b, based on the unit of $/h, a comparison is made for without and with construction costs as found to be 40.28/45.60/51.87/57.63 and 72.26/77.40/85.28/89.52, respectively, at 25%, 50%, 75% and 100% load conditions, respectively.

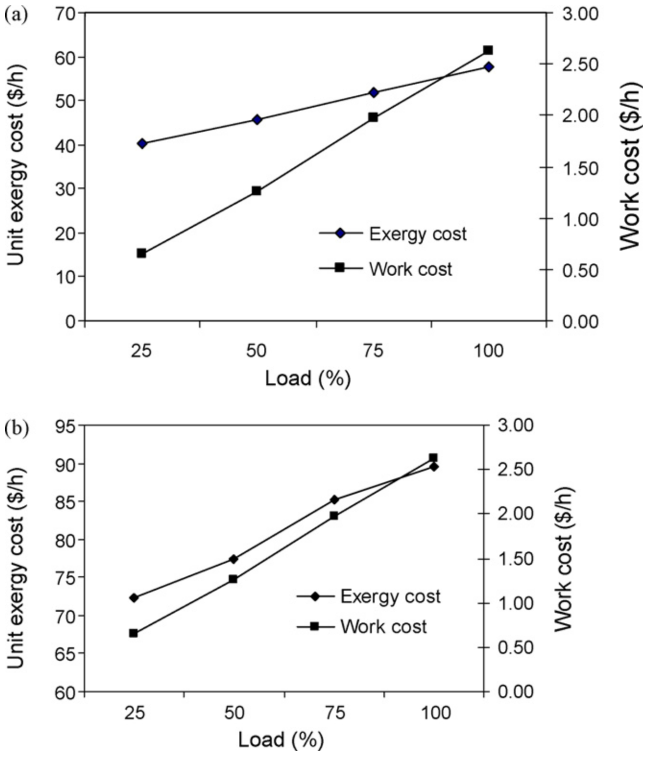

Fig. 7. Unit exergy costs per hour of the system for various load conditions. (a) Without construction cost. (b) With construction cost.

6. Conclusions

In this comprehensive paper we have conducted an exergoeconomic analysis of the Gonen GDHS through mass, energy, entropy, exergy and cost accounting balances for each component of the system. Using this methodology, the cost-balance equation is applied to each component of the system and to each junction. Thus a set of equations for the unit costs of various exergies is obtained for solution. Solving such equations provides the monetary evaluations of various exergy (thermal, mechanical, etc.) costs, as well as the unit cost of useful heat of the thermal system. Some possible configurations for the Gonen GDHS are considered and compared in a detailed analysis that used appropriate exergy and cost-balance equations for the system boundary. The lost cost of each component of the system is obtained through the method applied. The cost accounting results, for example, show that the unit cost of heating from geothermal water in the Gonen GDHS is US$ 0.048/kWh (or US$89.52/h) at 100% load conditions. Finally, this exergoeconomic study provides some key information for the people working in the area for better design, analysis, performance improvement, and operation of the GDHS.

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References

[1] D. Schmidt, Methodology for the modeling of thermally activated building components in low-exergy design, PhD Thesis, The Royal Institute of Technology, Department of Civil and Architectural Engineering, Division of Building Technology, Stockholm, Sweden, May 2004.
[2] Annex 49. Low Exergy Systems for High Performance Buildings and Communities, Website: www.annex49.com. (accessed in 2008).
[3] M. Shukuya, K. Tokunaga, M. Nishiuchi, T. Iwamatsu, H. Yamada, Thermal radiant exergy in naturally-ventilated room space and its role on thermal comfort, Proceedings of Healthy Buildings (2006) 257–262, IV.
[4] I. Dincer, On thermal energy storage systems and applications in buildings, Energy and Buildings 3 (4) (2002) 377–388.
[5] H. Gunerhan, A. Hepbasli, Exergetic modeling and performance evaluation of solar water heating systems for building applications, Energy and Buildings 39 (5) (2007) 509–516.
[6] Z. Oktay, C. Coskun, I. Dincer, Energetic and exergetic performance investigation of the Bigadic geothermal district heating system in Turkey, Energy and Buildings 40 (2008) 702–709.
[7] H.-Y Kwak, D.-J Kim, J.-S. Jeon, Exergetic and thermoeconomic analyses of power plants, Energy 28 (2003) 343–360.
[8] M. Gorji-Bandpy, V. Ebrahimian, Exergoeconomic analysis of gas turbine power plants, International Journal of Energy Journal 7 (2006) 57–67.
[9] M.A. Rosen, I. Dincer, Exergoeconomic analysis of power plants operating on various fuels, Applied Thermal Engineering 23 (2003) 643–658.
[10] F. Cziesla, G. Tsatsaronis, Iterative exergoeconomic evaluation and improvement of thermal power plants using fuzzy inference systems, Energy Conversion and Management 43 (2002) 1537–1548.
[11] L.S. Vieira, J.L. Donatelli, M.E. Cruz, Mathematical exergoeconomic optimization of a complex cogeneration plant aided by a professional process simulator, Applied Thermal Engineering 26 (2006) 654–662.
[12] S. Uhlenbruck, K. Lucas, Exergoeconomically-aided evolution strategy applied to a combined cycle power plant, International Journal of Thermal Sciences 43 (2004) 289–296.

[13] E. Cardona, A. Piacentino, A new approach to exergoeconomic analysis and design of variable demand energy systems, Energy 31 (2006) 490–515.
[14] S.O. Mert, I. Dincer, Z. Ozcelik, Exergoeconomic analysis of a vehicular PEM fuel cell system, Journal of Power Sources 165 (2007) 244–252.
[15] M. Kanoglu, Exergy analysis of a dual-level binary geothermal power plant, Geothermics 31 (2002) 709–724.
[16] R. DiPippo, F. Marcille David, Exergy analysis of geothermal power plants, Transactions – Geothermal Resources Council 8 (1984) 47–52.
[17] J. Quijano, Exergy analysis for the Ahuachapan and Berlin geothermal fields. El Salvador, in: Proceedings of the World Geothermal Congress Kyushu-Tohoku, Japan, 2000, 28 May.
[18] N. Bettagli, G. Bidini, Larderello-Farinello-Valle secolo geothermal area: exergy analysis of the transportation network and of the electric power plants, Geothermics 25 (1996) 3–16.
[19] K.C. Lee, Classification of geothermal resources by exergy, Geothermics 30 (2001) 431–442.
[20] M.P. Hochstein, Classification and assessment of geothermal resources, in: M.H. Dickson, M. Fanelli (Eds.), Small Geothermal Resources, Unitar/Undp Centre for Small Energy Resources, Italy, Rome, Italy, 1990, pp. 1–29.
[21] L. Ozgener, A. Hepbasli, I. Dincer, Energy and exergy analysis of the Gonen geothermal district heating system, Turkey, Geothermics 34 (2005) 632–645.
[22] L. Ozgener, A. Hepbasli, I. Dincer, M.A. Rosen, Exergoeconomic analysis of geothermal district heating systems: a case study, Applied Thermal Engineering 27 (2007) 1303–1310.
[23] Z. Oktay, A. Aslan, Geothermal district heating in Turkey, the Gonen case study, Geothermics 36 (2007) 167–182.
[24] S. Oh, H. Pang, S. Kim, H. Kwak, Exergy analysis for a gas–turbine cogeneration system, Journal of Engineering for Gas Turbines and Power 118 (1996) 782–791.
[25] S. Kim, S. Oh, Y. Kwon, H. Kwak, Exergoeconomic analysis of thermal systems, Energy 23 (1998) 393–406.
[26] M.A. Lozano, A. Valero, Theory of the exergetic cost, Energy 18 (1993) 939–960.
[27] C. Torres, L. Serra, A. Valero, M.A. Lozano, Theories of system optimization, in: R.R. Bittle, K. Herold, A.B. Duncan, D.W. Nutter, J. Fiszdon, D. O'neal, S. Garimella, B.G. Shiva Prasad (Eds.), Proceedings of the ASME Advanced Energy Systems Division, AES, vol. 36, American Society of Mechanical Engineers, New York, 1996 pp. 429–436.
[28] J. Moran, Availability Analysis: a Guide to Efficient Energy Use, Prentice-Hall, NJ, 1982.
[29] A. Bejan, G. Tsasaronis, M. Moran, Thermal Design and Optimization, Wiley, NY, 1996.
[30] M. Kanoglu, Y.A. Cengel, Economic evaluation of geothermal power generation heating and cooling, Energy 24 (1999) 501–509.
[31] BGEI (Bigadic Geothermal Energy Inc.), Reports of Bigadic Geothermal Energy Inc. Unpublished reports, Bigadic, Turkey (in Turkish), 2007.
[32] A. Hepbasli, L. Ozgener, Development of geothermal energy utilization in Turkey: a review, Renewable and Sustainable Energy Reviews 8 (2004) 433–460.
[33] O. Mertoglu, N. Bakir, T. Kaya, Geothermal applications in Turkey, Geothermics 32 (2003) 419–428.