Exergy-based Performance Analysis and Assessment of Geothermal District Cooling Systems

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ABSTRACT
Space cooling and heating is responsible for a huge amount of energy consumed worldwide. Based on the recent literature review, there has been a particular interest in renewable energy-based district heating and cooling systems. Considering geothermal energy, the majority of applications are related to district heating while only few installations regard for district cooling. Exergy-based analysis and assessment tools are very useful for detecting the interactions among components of energy-conversion systems and the real potential for improving each component in the system. Exergoeconomic also combines exergy and economics for exergy-aided cost minimization while low exergy (Low-Ex) systems are mostly used for buildings to draw and evaluate energy and exergy flows from the primary energy source to the building envelope (i.e., at various stages such as primary energy transportation, generation, storage, distribution, heating/cooling element, room air and envelope).

The main objectives of this contribution are to exergetically, exergoeconomically and lowexergetically model, analysis and evaluate a geothermal district cooling system (GDCS) along with its main components based on the real measurement values for the first time to the best of the authors’ knowledge. In this regard, the Balcova GDCS, the first geothermal cooling system in Turkey, was considered as an application place. This GDCS was commissioned at the end of May 2018 and since then, the system has been operated successfully. The whole system consists of a heat exchanger, a chiller, a cooling tower and circulating pumps. Space cooling is accomplished from geothermal energy through a LiBr-water absorption cycle. In this study, energy and exergy efficiencies as well as exergy destructions and exergoeconomic factor values of each component and the entire system were determined to present possible improvements first. Next, the GDCS was also evaluated from the energy production to the building envelope stage by stage through the Low-Ex method. The exergy efficiency value of the whole system on the product/fuel basis was then calculated to be 49.4% at a dead (reference) state temperature of 19°C while the minimum and maximum thermodynamic loss rates belonged to the chiller and heat exchanger, respectively. Finally, based on the Low-Ex approach, the total system exergy efficiency of the building was obtained to be 3.56% while the Balcova-Narlidere geothermal field was found to fall into the medium quality geothermal resources in terms of the exergetic classification.

1. INTRODUCTION
Buildings consume huge amount of energy and are responsible for one-third of world greenhouse gas emissions (Soltania et al., 2019). A significant share of this energy consumed has been used for cooling and heating purposes. District cooling systems (DCSs) have been widely in use for providing the necessary cooling comfort in commercial, residential, institutional, and industrial customers from one central source and developed as a very important technology because of their high-quality cooling and high effectiveness. The energy supplied from DCS is used in space cooling and dehumidification. DCSs can also be integrated with renewable energy in an economically feasible manner when compared to conventional cooling systems (Gang et al., 2016; Wang et al., 2017; Inayat and Raza, 2019; Anderson and Rezaie, 2019). In this context, low cost resources for buildings can be provided through geothermal heating and cooling systems, which generally have greater lifespans, temporal consistency, reliability and resilience, compared to other renewable energy sources such as wind and solar (Dincer and Acar, 2015).

Geothermal heat is an energy source, which is local, reliable, resilient, environmentally-friendly, and sustainable. Geothermal energy is independent on weather or climate while it is possible to supply heat and electricity almost continuously throughout the year. of years (Soltania et al., 2019). Depending on the operating temperature of the source, geothermal heat has been used for a long year for various purposes. If low and medium-enthalpy sources are available, geothermal energy is used directly for space heating, domestic hot water, agricultural uses, etc. while heat is more profitably converted to electricity if high-enthalpy geothermal resources exist (Angnisani et al., 2016).

There exists a link between exergy and sustainable development. Exergy can be defined in different ways, as comprehensively explained elsewhere (Hepbasli, 2012). According to one definition, exergy defined as the quality of energy while energy and exergy do not stand for the same meaning. Exergy is evaluated with respect to a dead (or reference) state. Exergy analysis method is employed for detecting and evaluating quantitatively the causes of the thermodynamic imperfection of the process under consideration. It can, therefore, indicate the possibilities of thermodynamic improvement potential of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement (Rosen and Dincer, 2003).

In recent years, exergy analysis (or second-law analysis) has been considered a very powerful tool and widely utilized in the design, simulation, test and performance assessment of energy-related systems. Exergoeconomic (called in Europe) or thermoeconomic (named in the US) analysis, which combines exergy with economics, is considered a meaningful tool to study and optimize various types of energy systems while there are various exergoeconomic analysis methods in the literature. Exergy analysis is used for...
determining exergy destructions and losses while economic analysis gives cost values associated with capital investment, operating and maintenance costs for a considered system.

Low exergy (or the so-called LowEx) systems are defined as heating or cooling systems that allow the use of low valued energy, which is delivered by sustainable energy sources as the energy source. These systems practically provide heating and cooling energy at a temperature close to room temperature while the LowEx approach, which has been and still being successfully used in sustainable buildings design (Hepbasli, 2012).

As far as recent studies conducted on GDCSs are concerned and as also highlighted by Modi et al. (2017), in the last decades, an impressive number of studies have been performed by many researchers to explore various aspects of absorption refrigeration system (ARS), which have become more important because of their fueling by renewable energy other than electricity. In this regard, Ma et al. (2010) explained an absorption refrigeration system, namely a two-stage LiBr/H\textsubscript{2}O absorption chiller driven by hot water, used for exploiting mid low temperature geothermal resources. Based on their experimental data, the COP values for this chiller varied between 0.38 and 0.42 with heat source temperature values of 63-65 °C. This system also reduced the power consumption to 62\% compared to a traditional air-conditioner while the payback period of the investment was less than four years. Karamangil et al. (2010) reviewed absorption refrigeration systems along with the currently used refrigerant–absorbent pairs and their alternatives. They also investigated the effects of operating temperatures, the effectiveness of solution, refrigerant and solution–refrigerant heat exchangers and selection of working fluid pair on the system performance. They concluded that the performances of the cycles were improved as generator and evaporator temperatures increased while reducing with increasing the condenser and absorber temperatures. Sikorska-Bączek (2015) studied a hybrid absorption-compression refrigerator powered by geothermal energy used for the production of ice slurry for air-conditioning refrigeration. It was concluded that absorption refrigerators were particularly economically attractive when there was a free energy source having temperature values between 50 and 200°C. Angrisani et al. (2016) modeled a novel heating and cooling system through a transient simulation package (TRNSYS 17) and evaluated its energy and economic performances based on the coupling between a low or medium-enthalpy geothermal source and an air handling unit, including a desiccant wheel. They reported that the utilization factor of domestic hot water significantly affected the performance of their system. Primary energy saving increased from 77\% to 95\% and pay-back period decreased from 14 years to 1.2 years, respectively. Yugcu et al. (2016) parametrically optimized a single stage geothermal energy assisted absorption refrigeration system using ammonia-water solution under various solution concentrations and design parameters. They investigated the effect of generator, evaporator, condenser and absorber temperatures on the system performance while they made an economic analysis through net present value. For the optimum design, the COP value for the system was determined to be 0.5722, with an exergy efficiency of 0.6201. Yılmaz (2017) considered a geothermal powered absorption cooling system with a liquid geothermal source temperature of 100 °C at a mass flow rate of 100 kg/s for the city of Izmir, Turkey and analyzed it using some thermodynamic performance parameters such as cooling load and coefficient of performance (COP) while performing its economic analysis. He also investigated effect of geothermal water temperature on the annual cooling cost and payback periods. The COP of the ammonia-water absorption cycle was calculated to be 0.441 and the discounted payback periods ranged from 5.684 to 8.816 years. Modi et al. (2017) modeled and analyzed an absorption refrigeration system using LiBr-H\textsubscript{2}O solution through energy and exergy analysis methods while they applied an optimization criterion to the generator temperature for enhancing energy and rational efficiencies and identifying the exergy destruction values of each system component. They proposed that generator and absorber were the essential components from the design point of view while COP and rational efficiency values were fluctuated with respect to the component temperature of the system. The COP value for heating increased with increment in the generator temperature while the circulation ratio indicated the inverse pattern. Inayat and Raza (2019) reviewed possible potential of DCSs with various renewable energy technologies and highlighted that the most suitable renewable energy technologies that could be integrated with DCSs seemed to be biomass energy, solar thermal energy, geothermal energy, surface water energy, solar photovoltaic energy, and waste heat energy. They reported that DCSs had strong budding with these renewable energies for supplying sustainable and clean cooling energy options in the future world. Ozcan et al. (2019) designed a geothermal assisted cooling system with a vapor absorption chiller using water and ammonia as an absorbent and a refrigerant, respectively, for meeting the demand of a 140 m\textsuperscript{2} detached single-family house in the city of Izmir, Turkey. They used energy and exergy analysis methods for evaluating the performance of the whole system along with its main components while undertaking some parametric studies. The system had a coefficient of performance (COP) value of 0.30 with a simple payback period of 6.4 years. The highest exergy destruction was due to the absorber with a rate of 38.2\%, followed by the solution heat exchanger and rectifier. The majority of Low-Ex analyses are based on heating systems (Hepbasli, 2012), with a limited number for a geothermal heating system (Kalinci et al., 2009).

Based on the literature survey done, DCSs have been widely studied using energy analysis methods while exergetic studies performed on geothermal energy-based DCSs are relatively low in numbers. In these exergetic studies, the focus was on the refrigeration system along with its main components. An exergy-based holistic analysis and assessment of a GDCS based on the actual operational data, consisting of mainly these analyses, namely (i) exergetic and exergoeconomic analyses of the GDCS and the Low-Ex analysis of the building the building from the primary energy source to the building envelope, has not appeared in the open literature based on the author’s knowledge. This was the prima motivation in contributing to the literature.

The present contribution differs from the previously conducted ones as follows: (i) It performs exergetic and exergoeconomic analyses of the Balcova GDCS, which is the first GDCS in Turkey, based on the actual operational data for the first time, and (ii) It also applies the Low-Ex approach to the building where the GDCS was installed for investigating the exergetic efficiencies of the overall system from the primary energy source to the building envelope.

2. SYSTEM DESCRIPTION
The Balcova GDCS was commissioned at the end of May 2018 and since then, the system has been operated successfully. The whole system consists of a heat exchanger (I), a chiller (II), a cooling tower (III) and circulating pumps (P1-3), as shown in Figure 1.
In the Balcova geothermal field, there are various wells, which form a ring line. The geothermal water enters the primary loop (state 1) of the heat exchanger (I) and is then reinjected. The geothermal water temperatures vary between 95 °C and 118 °C, keeping at 98 °C during the summer season while the geothermal water is reinjected at 75 °C (state 2) with a pressure of 2.1 bar. On the secondary loop of the heat exchanger, the hot water is circulated at flow and return temperatures of 100 °C (state 3) and 70 °C (state 4), respectively to supply the heat flux to the chiller (II), namely a LiBr-water absorption cycle. It is then routed through the refrigeration circulation to the building where the chilled water enters fan-coils at 7 °C (state 6) and leaves it at 12 °C (state 7) while flow and return cooling water temperatures at the cooling tower (III) are 32 °C (state 9) and 28 °C (11), respectively (Yigit, 2019).

3. EXERGY-BASED ANALYSIS RELATIONS

3.1 Energy, Exergy and Exergoeconomic Relations

General mass, energy and exergy balance equations are given in more detail elsewhere (Hepbasli, 2008, 2010) while the following section includes the relations used for the main components of the Balcova GDCS illustrated in Figure 1.

Mass and energy balances as well as exergy destructions obtained from exergy balances along with exergy efficiencies on the exergetic product/exergetic fuel ($P/E$) basis for each of the Balcova GDCS components are derived as follows:

**Heat Exchanger (I):**

\[
\dot{m}_{in} = \dot{m}_{out} \tag{1a}
\]
\[
\dot{m}_1 = \dot{m}_2 = \dot{m}_{geo} \tag{1b}
\]
\[
\dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_{hw} \tag{1c}
\]

where $\dot{m}$ indicates the mass flow rate while the subscripts $in$, $out$, $geo$ and $hw$ denote inlet, outlet geothermal and hot water, respectively.

\[
\dot{E}_{in} = \dot{E}_{out} \tag{2a}
\]
\[
\dot{Q}_{geo} = \dot{Q}_{hw} \tag{2b}
\]
\[
\dot{m}_{geo}(h_1 - h_2) = \dot{m}_{hw}(h_3 - h_5) \tag{2c}
\]

where $\dot{E}$, $\dot{Q}$ and $h$ stand for the energy rate, the heat transfer rate and the specific enthalpy, respectively.

\[
\dot{E}_{x,in} - \dot{E}_{x,out} = \dot{E}_{x,dest} \tag{3a}
\]
\[
\dot{E}_{x,dest,HE} = \dot{m}_{geo} (\psi_1 - \psi_2) + \dot{m}_{hw} (\psi_5 - \psi_3) \tag{3b}
\]
\[
\psi = (h - h_0) - T_0 (s - s_0) \tag{3c}
\]
\[
\varepsilon_{HE} = \frac{\dot{m}_{hw} (\psi_3 - \psi_5)}{\dot{m}_{geo} (\psi_1 - \psi_2)} \tag{4}
\]

where $\dot{E}_x$, $\psi$, $s$ and $\varepsilon$ are the exergy rate, the specific (or flow) exergy, the specific entropy and the exergy (second law) efficiency, respectively while the subscript $0$ indicates the dead (reference) state.

**Chiller (II):**

\[
\dot{m}_3 = \dot{m}_4 = \dot{m}_{hw} \tag{5a}
\]
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\[ \dot{m}_6 = \dot{m}_8 = \dot{m}_{chw} \quad (5b) \]
\[ \dot{m}_9 = \dot{m}_{11} = \dot{m}_{cw} \quad (5c) \]
\[ \dot{E}_{x,dest,CH} = \dot{m}_{hw}(\psi_3 - \psi_4) + \dot{m}_{chw}(\psi_6 - \psi_5) + \dot{m}_{cw}(\psi_{11} - \psi_9) \quad (6) \]
\[ \varepsilon_{CH} = \dot{m}_{chw}(\psi_6 - \psi_5)/[\dot{m}_{hw}(\psi_3 - \psi_4) + \dot{m}_{cw}(\psi_9 - \psi_{11})] \quad (7) \]

where the subscripts \( chw, cw, dest \) and \( CH \) denote the chilled water, the cooling water, the destruction (or irreversibilities) and the chiller, respectively.

Cooling Tower:

\[ \dot{m}_9 = \dot{m}_{10} = \dot{m}_{11} = \dot{m}_{cw} \quad (8) \]
\[ \dot{m}_{12} = \dot{m}_{13} = \dot{m}_{air} \quad (9) \]
\[ \dot{E}_{x,dest,CT} = \dot{m}_{cw}(\psi_9 - \psi_{11}) + \dot{m}_{air}(\psi_{12} - \psi_{13}) + \dot{W}_{fan} \quad (10) \]
\[ \varepsilon_{CT} = (\dot{m}_{cw}\psi_{11} + \dot{m}_{air}\psi_{13})/ (\dot{m}_{cw}\psi_9 + \dot{m}_{air}\psi_{12} + \dot{W}_{fan}) \quad (11) \]

where the subscript \( CT \) indicates the cooling tower.

Circulating Pumps (P1-P3):

\[ \dot{m}_4 = \dot{m}_5 = \dot{m}_{hw} \quad (12) \]
\[ W_{pump,1} = \dot{m}_{hw}(h_5 - h_4) \quad (13a) \]
\[ W_{pump,1,elec} = \dot{W}_{pump,1}/\eta_{pump,elec} \eta_{pump,mech} \quad (13b) \]
\[ \dot{E}_{x,dest,pump,1} = \dot{m}_{hw}(\psi_4 - \psi_5) + W_{pump,1,elec} \quad (14) \]
\[ \varepsilon_{pump,1} = \dot{m}_{hw}(\psi_5 - \psi_4)/W_{pump,1,elec} \quad (15) \]

where \( \eta \) is the energy (first law) efficiency while the subscripts \( elec \) and \( mech \) denote electrical and mechanical, respectively. Here, the relations for the circulating pump (P1) only are included.

Relative irreversibility (RI) is calculated by

\[ RI = \dot{E}_{x,dest,1}/\dot{E}_{x,dest,\text{total}} \quad (16) \]

There are various exergoeconomic analysis methods such as Exergy Cost Energy Mass (EXCEM) and the Specific Exergy Costing (SPECO). In this study, we used the EXCEM analysis, which dictates mass, energy, exergy and cost balance equations, as explained in more detail elsewhere (Yucer and Hepbasli, 2013). The EXCEM parameter \( \dot{R}_{ex} \), which is defined as the ratio of thermodynamic loss rate \( \dot{L}_{ex} \) to cost \( K \), may be written as follows:

\[ \dot{R}_{ex} = \dot{L}_{ex}/K \quad (17) \]

where the subscript \( ex \) denotes the exergy.

The value of \( \dot{R}_{ex} \) varies in various situations (e.g., technology, time, location, resource costs, knowledge). During periods when energy-resource costs increase, the value of \( \dot{R}_{ex} \) is likely to decrease (i.e., greater capital is invested to reduce losses).

Yucer and Hepbasli (2013) also proposed a new definition “Exergetic Cost Effectiveness (ExCE)” to include both the effects of equipment’s exergy destruction and cost figure to the overall system, as given below:

\[ \text{ExCE} = a \cdot b \quad (18a) \]

where \( a \) is the contribution of a stage or a component to the total cost, as given below:

\[ a = \frac{\text{Cost of a stage or a component}}{\text{Total cost of the system}} \quad (18b) \]

and \( b \) is the contribution of a stage or a component to the total exergy destruction and is expressed as

\[ b = \frac{\text{Exergy destruction of a stage or a component}}{\text{Total exergy destruction of the system}} \quad (18c) \]

Here, the low value of ExCE dictates more cost effective, more appropriate and more efficient component or stage.
3.2 Exergetic Relations for Classification of Geothermal Resources

Lee (2001) proposed the term specific exergy index (SExI) for classification of geothermal resources to reflect their ability to do thermodynamic work, which is more useful than heat because not all the heat can be converted to work, as given below:

\[
S\text{ExI} = \left(h_{\text{brine}} - 273.16 \, s_{\text{brine}}\right) / 1192
\]  

(19a)

with the average values for the specific enthalpy and the specific entropy, respectively (Quijano, 2000)

\[
h_{\text{brine}} = \sum_{i=1}^{n} \dot{m}_i \, h / \sum_{i=1}^{n} \dot{m}_i
\]

(19b)

\[
s_{\text{brine}} = \sum_{i=1}^{n} \dot{m}_i \, s / \sum_{i=1}^{n} \dot{m}_i
\]

(19c)

SExI is a straight line on an h-s plot of the Mollier diagram. Straight lines of SExI = 0.5 and SExI = 0.05 can therefore be drawn on this diagram and used as a map for classifying geothermal resources by considering the following:

\[
S\text{ExI} < 0.05 \text{ for low quality geothermal resources}
\]

(20a)

\[
0.05 \leq S\text{ExI} < 0.5 \text{ for medium quality geothermal resources}
\]

(20b)

\[
S\text{ExI} \geq 0.5 \text{ for high quality geothermal resources}
\]

(20c)

where the demarcation limits for these indices are exergies of saturated water and dry saturated steam at 1 bar absolute.

3.3 Low-Ex Relations

Low exergy (or Low-Ex) systems are defined as heating or cooling systems that allow the use of low valued energy, which is delivered by sustainable energy sources (i.e., through heat pumps, solar collectors, either separate or linked to waste heat, energy storage) as the energy source. These systems practically provide heating and cooling energy at a temperature close to room temperature while the so-called LowEx approach, which has been and still being successfully used in sustainable buildings design (Hepbasli, 2019). The Low-Ex approach divides all processes involved in energy supply in buildings into several blocks or subsystems, from the primary energy conversion to the final heat transfer through the building envelope. For analyzing and optimizing buildings using energy and exergy analysis methods under steady-state conditions and in the heating mode, an Excel tool has been developed within the framework of ECBCS Annex 49 (2019).

The relations used in this approach are given by Hepbasli (2012) in a detailed manner within the framework of a comprehensive review while the following covers two exergy-based efficiency definitions only:

Exergy flexibility factor (ExFF):

\[
\text{ExFF} = \frac{\text{Exergy load of room air}}{\text{Exergy load of heating or cooling device}}
\]

(21a)

where the heating or cooling device means fan-coil, radiator, etc.

Exergy efficiency of the whole system or total system exergy efficiency (ε_{total,lowex}):

\[
\varepsilon_{\text{total,lowex}} = \frac{\text{Exergy demand of room} + \text{DHW}}{\text{Total exergy input}}
\]

(21b)

where DHW stands for the domestic hot water.

4. RESULTS AND DISCUSSION

The system described in Section 2 is evaluated from the exergetic point of view while the relations presented in Section 3 is applied to this system.

The assumptions made for the exergy analysis of the system may be listed as follows:

a) All processes are under steady state and steady flow conditions with negligible potential and kinetic energy effects and no chemical or nuclear reactions.

b) The directions of heat transfer to the system and work transfer from the system are positive.

c) Pressure losses are ignored in all components including pipes.

d) The heat gain to the system components from the surroundings are negligible.

e) The circulating pump mechanical (η_{pump,mech}) and the circulating pump motor electrical (η_{pump,elec}) efficiencies are 82% and 88%, respectively.

f) The exergy content of the air is calculated, assuming ideal gas behavior.

g) The exergy of the make up water at the cooling tower is negligible.

h) The values for the dead (reference) state temperatures are taken 19 °C, 24 °C, 29 °C and 34 °C to undertake a parametric study while the dead state pressure is ε 101.325 kPa.

i) Thermodynamic properties of geothermal fluid are taken to be similar with those of water.

Temperature, pressure and mass flow rate data for one representative unit of the Balcova GDCS at a dead state temperature of 19 °C are shown in Table 1 (following the state numbers specified in Figure 1) where exergy rates calculated for each state are also included in this table.
Table 1: Thermodynamic properties, energy and exergy rates for one representative unit of the Balcova GDCS at a dead state temperature of 19 °C.

<table>
<thead>
<tr>
<th>State no.</th>
<th>Inlet/Outlet</th>
<th>Fluid</th>
<th>Phase</th>
<th>T (°C)</th>
<th>P (kPa)</th>
<th>h (kJ/kg)</th>
<th>s (kJ/kg K)</th>
<th>( \dot{m} ) (kg/s)</th>
<th>( \psi ) (kJ/kg)</th>
<th>( E ) (kW)</th>
<th>( E_x ) (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Water</td>
<td>Dead state</td>
<td>19</td>
<td>101.3</td>
<td>79.82</td>
<td>0.2822</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0'</td>
<td></td>
<td>Air</td>
<td>Dead state</td>
<td>19</td>
<td>101.3</td>
<td>270.7</td>
<td>5.449</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Heat exchanger inlet (primary)</td>
<td>Geo-thermal fluid</td>
<td>Compressed liquid</td>
<td>110</td>
<td>400</td>
<td>461.6</td>
<td>1.419</td>
<td>1.19</td>
<td>49.77</td>
<td>549.3</td>
<td>59.22</td>
</tr>
<tr>
<td>2</td>
<td>Heat exchanger outlet (primary)</td>
<td>Geo-thermal fluid</td>
<td>Compressed liquid</td>
<td>75</td>
<td>250</td>
<td>314.3</td>
<td>1.016</td>
<td>1.19</td>
<td>20.19</td>
<td>374</td>
<td>24.03</td>
</tr>
<tr>
<td>3</td>
<td>Chiller inlet/secondary</td>
<td>Hot water</td>
<td>Compressed liquid</td>
<td>100</td>
<td>330</td>
<td>419.3</td>
<td>1.307</td>
<td>1.392</td>
<td>40.1</td>
<td>583.5</td>
<td>55.8</td>
</tr>
<tr>
<td>4</td>
<td>Chiller outlet</td>
<td>Hot water</td>
<td>Compressed liquid</td>
<td>69.9</td>
<td>300</td>
<td>292.9</td>
<td>0.9538</td>
<td>1.392</td>
<td>16.84</td>
<td>407.5</td>
<td>23.43</td>
</tr>
<tr>
<td>5</td>
<td>Hot water circulating pump (P1) outlet</td>
<td>Hot water</td>
<td>Compressed liquid</td>
<td>70</td>
<td>380</td>
<td>293.4</td>
<td>0.9549</td>
<td>1.392</td>
<td>16.98</td>
<td>408.2</td>
<td>23.63</td>
</tr>
<tr>
<td>6</td>
<td>Chiller outlet</td>
<td>Chilled water</td>
<td>Compressed liquid</td>
<td>7</td>
<td>350</td>
<td>29.77</td>
<td>0.1064</td>
<td>8.58</td>
<td>1.312</td>
<td>255.4</td>
<td>11.25</td>
</tr>
<tr>
<td>7</td>
<td>Chilled water circulating pump inlet (P2)</td>
<td>Chilled water</td>
<td>Compressed liquid</td>
<td>11.95</td>
<td>320</td>
<td>50.51</td>
<td>0.1798</td>
<td>8.58</td>
<td>0.581</td>
<td>433.4</td>
<td>4.986</td>
</tr>
<tr>
<td>8</td>
<td>Chilled water circulating pump outlet (P2)</td>
<td>Chilled water</td>
<td>Compressed liquid</td>
<td>12</td>
<td>370</td>
<td>50.77</td>
<td>0.1806</td>
<td>8.58</td>
<td>0.626</td>
<td>435.6</td>
<td>5.371</td>
</tr>
<tr>
<td>9</td>
<td>Chiller outlet/ Cooling tower inlet</td>
<td>Cooling water</td>
<td>Compressed liquid</td>
<td>32</td>
<td>270</td>
<td>134.3</td>
<td>0.4642</td>
<td>27.6</td>
<td>1.343</td>
<td>3708</td>
<td>37.07</td>
</tr>
<tr>
<td>10</td>
<td>Cooling tower outlet</td>
<td>Cooling water</td>
<td>Compressed liquid</td>
<td>27.9</td>
<td>200</td>
<td>117.1</td>
<td>0.4076</td>
<td>27.6</td>
<td>0.654</td>
<td>3233</td>
<td>18.06</td>
</tr>
<tr>
<td>11</td>
<td>Chiller inlet</td>
<td>Cooling water</td>
<td>Compressed liquid</td>
<td>28</td>
<td>330</td>
<td>117.7</td>
<td>0.409</td>
<td>27.6</td>
<td>0.797</td>
<td>3248</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>Cooling tower inlet</td>
<td>Air</td>
<td>Air</td>
<td>37</td>
<td>101.3</td>
<td>310.6</td>
<td>5.735</td>
<td>1.2</td>
<td>0.519</td>
<td>372.8</td>
<td>0.623</td>
</tr>
<tr>
<td>13</td>
<td>Cooling tower outlet</td>
<td>Air</td>
<td>Air</td>
<td>34</td>
<td>101.3</td>
<td>307.6</td>
<td>5.726</td>
<td>1.2</td>
<td>0.362</td>
<td>369.2</td>
<td>0.434</td>
</tr>
</tbody>
</table>
4.1 Exergy and Exergoeconomic Analysis Results

Using the values given in Table 1 and the equations in Section 3, the values for exergy destruction rates, relative irreversibility rates and exergy efficiencies are calculated at a reference state temperature of 19 °C and listed in Table 2. As can be seen from the table, the greatest exergy destruction (irreversibility) on the main system components of I-III occurs in the cooling tower, followed by the chiller and the heat exchanger. This ranking changes on the whole system basis. The values for circulating pumps were estimated and P3 indicated the biggest irreversibility.

Table 2: Values of exergy destruction rates, relative irreversibility rates and exergy efficiencies for one representative unit of the Balçove GDCS at a dead state temperature of 19 °C.

<table>
<thead>
<tr>
<th>Component no.</th>
<th>$\dot{E}_{x\text{dest}}$ (kW)</th>
<th>$\varepsilon$ (%)</th>
<th>$\dot{\rho}$</th>
<th>$\dot{\rho}_{RI}$</th>
<th>$RI$</th>
<th>$RI_{RI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3.02</td>
<td>91.42</td>
<td>35.21</td>
<td>32.19</td>
<td>6.7</td>
<td>4.7</td>
</tr>
<tr>
<td>II</td>
<td>11.41</td>
<td>12.4</td>
<td>13.03</td>
<td>1.62</td>
<td>25.2</td>
<td>17.7</td>
</tr>
<tr>
<td>III</td>
<td>30</td>
<td>42.6</td>
<td>52.24</td>
<td>22.24</td>
<td>68.1</td>
<td>46.5</td>
</tr>
<tr>
<td>P1</td>
<td>0.74</td>
<td>29.2</td>
<td>1.04</td>
<td>0.30</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>2.69</td>
<td>17.4</td>
<td>3.25</td>
<td>0.56</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>16.61</td>
<td>26.5</td>
<td>22.61</td>
<td>6.00</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Total (I+II+III)</td>
<td>45.19</td>
<td>127.38</td>
<td>62.91</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Grand total</td>
<td>64.47</td>
<td>127.38</td>
<td>62.91</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Irreversibilities in the heat exchanger are due to the temperature differences between the two heat exchanger fluids, pressure losses, flow imbalances and heat transfer with the environment, which is also valid for the cooling tower and chiller. In terms of exergy efficiencies, the heat exchanger has the highest value of 91.42%. The overall exergy efficiency on the exergetic product/exergetic fuel basis is obtained to be 49.4% while it is 46.2% at $T_0 = 24$ °C. A parametric study was undertaken to investigate the effect of varying dead state temperatures on the system components. Figure 2 illustrates this effect at dead state temperatures of 19 °C, 24 °C and 29 °C. Exergy destruction rates for the heat exchanger seem to be very close to each other while those for the chiller increase and those for the cooling tower decrease as the dead state temperatures increase.

**Figure 2: Effect of varying dead state temperatures on the exergy destructions of each of system components.**

It should be noted that the efficiency values differ from each other depending on the exergetic efficiency definition used. Exergy efficiency may be generally defined in two ways: (i) Universal exergy efficiency, which is a ratio between exergy output/exergy input similar to the energy efficiency, and (ii) Functional exergy efficiency, which is defined as a ratio of exergetic product (or benefit or desired effect) to exergetic fuel, which we used in the study. Exergy efficiencies of each of system components are studied in terms of the effect of varying dead state temperatures, as shown in Figure 3. It is obvious from this figure that with the increase in the dead state temperatures, exergy efficiency values are very close to each other for the heat exchanger while those for the chiller increase and those for the cooling tower decrease from 19 °C to 24 °C and then do not change so much at 29 °C.

**Figure 3: Effect of varying dead state temperatures on the exergy efficiencies of each of system components.**
EXCEM analysis is applied to the main components of the Balcova GDCS at different dead state temperatures. The thermodynamic loss rates, capital costs and exergoeconomic results at $T_D = 19^\circ\text{C}$ are presented in Table 3. By comparison, the minimum and maximum thermodynamic loss rates belong to the chiller and heat exchanger on the components I-III basis while those are associated with the chiller and Pump 3 on the whole system basis, respectively. The chiller has the minimum EXCEM ratio as 0.114 W/US$ because its capital cost is higher than that of other components on the components I-III basis.

### Table 3. Exergoeconomic results of the Balcova GDCS.

<table>
<thead>
<tr>
<th>Component no.</th>
<th>$E_{x,dest}$ (kW)</th>
<th>$K$ (US$)</th>
<th>$\dot{R}_{ex}$ (W/US$)</th>
<th>$a$</th>
<th>$B$ (or $R$)</th>
<th>$ExCE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3.02</td>
<td>500</td>
<td>6.04</td>
<td>0.0038</td>
<td>0.047</td>
<td>0.00018</td>
</tr>
<tr>
<td>II</td>
<td>11.41</td>
<td>100,000</td>
<td>0.114</td>
<td>0.7604</td>
<td>0.177</td>
<td>0.13459</td>
</tr>
<tr>
<td>III</td>
<td>30</td>
<td>30,000</td>
<td>1</td>
<td>0.2247</td>
<td>0.465</td>
<td>0.10449</td>
</tr>
<tr>
<td>P1</td>
<td>0.74</td>
<td>300</td>
<td>2.467</td>
<td>0.002</td>
<td>0.011</td>
<td>0.00002</td>
</tr>
<tr>
<td>P2</td>
<td>2.69</td>
<td>500</td>
<td>5.38</td>
<td>0.0038</td>
<td>0.042</td>
<td>0.00016</td>
</tr>
<tr>
<td>P3</td>
<td>16.61</td>
<td>700</td>
<td>23.73</td>
<td>0.0053</td>
<td>0.258</td>
<td>0.00137</td>
</tr>
<tr>
<td>Total</td>
<td>64.47</td>
<td>131,500</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The findings related to the parameter ExCE for comparing the system components are given in Table 3. Each component should be evaluated by comparing its ExCE value with that of other components. One can see from the table that the chiller represents the maximum ExCE value among all components, meaning that it needs to be firstly improved before other components. On the components I-III basis, if one considers the exergy destruction rate or $R$ values, more attention for improvement should be paid to the cooling tower while in case of using the ExCE, the chiller should have a priority. This clearly indicates that exergy analysis needs to be combined with economic analysis tools.

#### 4.2 Exergy-Based Classification Results of Geothermal Resources

The Balcova geothermal field is located 9 km west of the city center of Izmir while it is hosted within the Alpine-Himalayas Orogenic Belt (Alacalı and Savascin, 2015). In the Balcova-Narlidere geothermal field, there are a total of 13 productions wells, of which 2 belong to the Narlidere district, with a total of 5 reinjection wells. Using the data given by Esergül et al. (2019), the values presented in Table 4 are computed first. The $SEx/I$ was then applied to the Balcova-Narlidere geothermal field given in the table. Finally, taking into account the values listed the table and using Equations (19a-c), the $SEx/I$ value was calculated to be 0.074. This represents that this field falls into the medium quality geothermal resources according to the classification of Lee (2001) given by Equation (20b), as also calculated earlier in a study done by Baba et al. (2006) when eight production wells were considered.

### Table 4: Thermodynamic properties of the production wells at the Balcova-Narlidere geothermal field as of 2019

<table>
<thead>
<tr>
<th>ID # of well</th>
<th>Drilling date</th>
<th>$T$ (Â°C)</th>
<th>$m$ (kg/s)</th>
<th>$h$ (kJ/kg)</th>
<th>$s$ (kJ/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1A</td>
<td>2019</td>
<td>102</td>
<td>39.88</td>
<td>427.8</td>
<td>1.330</td>
</tr>
<tr>
<td>B-4A</td>
<td>2019</td>
<td>98</td>
<td>27.99</td>
<td>411</td>
<td>1.284</td>
</tr>
<tr>
<td>B-5A</td>
<td>2018</td>
<td>96</td>
<td>40.05</td>
<td>402.5</td>
<td>1.262</td>
</tr>
<tr>
<td>B-7A</td>
<td>2018</td>
<td>98</td>
<td>38.66</td>
<td>411</td>
<td>1.284</td>
</tr>
<tr>
<td>B-10A</td>
<td>2013</td>
<td>100</td>
<td>45.26</td>
<td>419.4</td>
<td>1.307</td>
</tr>
<tr>
<td>BD-4/BD4A</td>
<td>1998</td>
<td>133</td>
<td>85.46</td>
<td>559.3</td>
<td>1.666</td>
</tr>
<tr>
<td>BD-5</td>
<td>1999</td>
<td>118</td>
<td>26.24</td>
<td>495.5</td>
<td>1.506</td>
</tr>
<tr>
<td>BD-6A</td>
<td>2013</td>
<td>127</td>
<td>91.14</td>
<td>533.7</td>
<td>1.603</td>
</tr>
<tr>
<td>BD-7A</td>
<td>2015</td>
<td>120</td>
<td>39.30</td>
<td>504</td>
<td>1.528</td>
</tr>
<tr>
<td>BD-9</td>
<td>2003</td>
<td>134</td>
<td>93.15</td>
<td>563.5</td>
<td>1.677</td>
</tr>
<tr>
<td>BD-11</td>
<td>2006</td>
<td>141</td>
<td>38.55</td>
<td>593.5</td>
<td>1.75</td>
</tr>
<tr>
<td>BD-12</td>
<td>2006</td>
<td>140</td>
<td>38.59</td>
<td>589.2</td>
<td>1.739</td>
</tr>
<tr>
<td>BD-14</td>
<td>2007</td>
<td>118</td>
<td>32.81</td>
<td>495.5</td>
<td>1.506</td>
</tr>
</tbody>
</table>

By comparison, the well temperatures at the Balcova-Narlidere geothermal field vary between 96 Â°C and 141 Â°C while the weighted average value of the temperature ($T_{mean}$) was calculated to be 129.8 Â°C by using the similar relation given in Equation (19b). This field falls into the intermediate enthalpy resources according to the classifications of Muffler and Cataldi (1978), Benderitter and Cormy (1990) and Hochstein (1990) while it is characterized as low enthalpy resources according to the classification of Haenel et al. (1988), as given in Table 5. This clearly indicates that the classification with reference to SEx/I is more meaningful as there is no general agreement on the arbitrary temperature ranges used in the classification of geothermal resources by temperature.

8
Table 5: Classification of geothermal resources by temperature (Dickson and Fanelli, 1990).

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Low enthalpy</th>
<th>Intermediate</th>
<th>High enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muffler and Cataldi (1978)</td>
<td>&lt; 90 °C</td>
<td>90-150 °C</td>
<td>&gt; 150 °C</td>
</tr>
<tr>
<td>Haenel et al. (1988)</td>
<td>&lt; 150 °C</td>
<td>-</td>
<td>&gt; 150 °C</td>
</tr>
<tr>
<td>Hochstein (1990)</td>
<td>&lt; 125 °C</td>
<td>125-225 °C</td>
<td>&gt; 225 °C</td>
</tr>
<tr>
<td>Benderitter and Corny (1990)</td>
<td>&lt; 100 °C</td>
<td>100-200 °C</td>
<td>&gt; 200 °C</td>
</tr>
</tbody>
</table>

4.3 Low-Ex Analysis Results

The Low-Ex Excel tool has been developed for the heating only, as appeared in the open literature. Considering the heated/cooled floor area of 1800 m², the heating load of the building of 180 kW, indoor and outdoor air temperatures of 22 °C and 0 °C, respectively and using this tool, the exergy flexibility factor was determined to be 71.61% while the total system exergy efficiency was 3.56%. Exergy losses at the various stages of the whole system, from the production to the building envelope has not been given here.

5. CONCLUSIONS

The majority of modelling and analysis of geothermal district systems are based on heating and energetic evaluations while there are very limited studies focusing on exergetic assessment of GDCSs. Especially, no studies using the actual operational data for an exergetic holistic approach have appeared in the open literature. This study contributed to the literature in terms of this approach. The main concluding remarks we have drawn from the results of the present contribution may be listed as follows:

a) Exergy is a way to sustainable development. In this regard, exergy analysis is a very useful tool, which can be successfully used in the performance evaluation of GDCSs as well as all energy-related systems while it helps determine the locations, types and true magnitudes of energy losses, guiding the design of more efficient energy systems.

b) Based on the $SE\tilde{E}$ values calculated for the Balcova-Narlidere geothermal field, this field falls into the medium quality geothermal resources according to the classification of Lee (2001) while it may fall into low or intermediate enthalpy resources according to the classification proposed by various investigators. Therefore, classification of geothermal resources based on the exergetic approach seems to be more meaningful compared to enthalpy (or temperature)-based classifications.

c) The overall exergy efficiency value on the product/fuel basis was determined to be 49.4% at a dead (reference) state temperature of 19°C.

d) Considering exergy efficiencies, the heat exchanger had the highest value of 91.42%.

e) The greatest exergy destruction (irreversibility) on the main system components of I-III were due to the cooling tower, followed by the chiller and the heat exchanger.

f) The minimum and maximum thermodynamic loss rates belong to the chiller and heat exchanger on the components I-III, respectively.

g) The chiller represents the maximum exergetic cost effectiveness value among all components in the system.

h) The total system exergy efficiency of the building geothermally heated was determined to be 3.56%. This means that the performance of geothermal district heating systems should be assessed and optimized as a whole, from the production stage to the building envelope.

i) Exergy analysis along may not be sufficient to assess the performance of the GDCS. Therefore, it needs to be combined with an economic analysis, as indicated in this study.

j) The application of GDCSs should be widespread throughout the country because Turkey has an attractive and huge geothermal energy utilization potential.

k) The results are expected to be beneficial to the researchers, government administration, and engineers working in the field of geothermal energy systems.

l) For future studies, performing the comprehensive transient advanced exergetic, exergoeconomic, and exergoenvironmental analyses of the system is proposed.

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REFERENCES


Hepbasli


