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Modified exergoeconomic modeling of geothermal power plants

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ABSTRACT

In this study, a modified exergoeconomic model is proposed for geothermal power plants using exergy and cost accounting analyses, and a case study is in this regard presented for the Tuzla geothermal power plant system (Tuzla GPPS) in Turkey to illustrate an application of the currently modified exergoeconomic model. Tuzla GPPS has a total installed capacity of 7.5 MW and was recently put into operation. Electricity is generated using a binary cycle. In the analysis, the actual system data are used to assess the power plant system performance through both energy and exergy efficiencies, exergy losses and loss cost rates. Exergy efficiency values vary between 35% and 49% with an average exergy efficiency of 45.2%. The relations between the capital costs and the exergetic loss/destruction for the system components are studied. Six new exergetic cost parameters, e.g., the component annualized cost rate, exergy balance cost, overall unavoidable system exergy destruction/loss cost rate, overall unavoidable system exergy destruction/loss cost rate, overall unavoidable system exergy production cost rate and the overall unavoidable system exergy production cost rate are studied to provide a more comprehensive evaluation of the system.

1. Introduction

Geothermal energy can be used for a large variety of applications, such as electricity generation, heating, cooling, industrial drying, fermentation, balneological utilization, distillation and desalination depending on the temperature of the source [1]. There are various research studies [e.g., 2–12] available in the literature on various aspects of geothermal energy and its utilization. One of them is the electricity production. Electricity generation from geothermal fluid is relatively new in industry dating back to the beginning of the last century. In fact, commercial generation of electricity from geothermal steam began in Larderello, Tuscany, Italy, in 1913, with an installed capacity of 250 kWe. However, the first experiment with natural steam was performed for electricity generation in to 1904, when Prince Piero Ginori Conti coupled a steam-engine to a dynamo to light five bulbs in his boric acid factories in Larderello. Since 1950s, other countries have followed the Italian example, and at present, electricity is generated from geothermal energy in 21 countries all over the world [13]. The total geothermal electricity production in the world was 59.24 TWh in 2006 with the United States leading with 16.58 TWh and followed by Philippines with 10.47 TWh. Other major countries are Mexico, Indonesia, Italy, New Zealand, Japan and Iceland, each with a production capacity varying between 6.69 and 2.63 TWh. Iceland produces 26.5% of its electricity from geothermal sources, while this rate is 20.3%, 18.5% and 14% in El Salvador, Philippines and Costa Rica, respectively. On average, 0.31% of all the electricity in the world is produced from geothermal sources [14]. Today, there are at least 24 countries with geothermal electricity utilization plants.

Turkey is an energy importing country, and more than two-thirds of the energy requirement is supplied through the imports. In this context, geothermal energy appears to be one of the most efficient and effective solutions for sustainable energy development and environmental impact reduction [15]. Electricity production utilizing geothermal energy is around 100 MWe as of the first half of 2010 in Turkey with six running plants. The potential capacity for the generation of electricity from the geothermal sources in Turkey is estimated as 2000 MW (16 TWh/year) and a generation capacity of 550 MW from geothermal sources is expected by the year 2013. Nine locations including Denizli-Kizildere (200–242 °C), Aydin-Germencik (232 °C), Canakkale-Tuzla (174 °C), Aydin-Salavatli (171 °C), Kutahya-Simav (162 °C), Manisa-Salihli (150 °C), and Izmir-Seferihisar (153 °C) are classified as high enthalpy fields that are suitable for the production of electrical power [16].

High temperature geothermal resources such as dry steam and hot water as well as medium temperature geothermal resources

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such as water of moderate temperature can be profitably used to generate electricity using three types of geothermal power plants (GPPs): dry steam, flash and binary power plants. Dry steam geothermal power plants use very hot steam (>235 °C) and limited amounts of water from the geothermal resources. Flash steam power plants (single or double) use hot water (>180 °C), while binary cycle system uses water at moderate temperatures (100–180 °C) coming from geothermal resources [17].

Since 1950s, exergoeconomics has been known and employed in a limited fashion for various systems, applications and processes. More recently, exergoeconomics has become a powerful tool to study, optimize and improve energy systems. Its application field is the evaluation of utility cost in terms of products or supplies of production plants, the energy cost among the process and the operations of an energy converter. Exergoeconomic analysis combines exergy analysis with economic analysis and offers a technique for the evaluation of the inefficiencies or the costs of individual process streams, including intermediate and final products. These costs could be used in feasibility studies, investment decisions, comparison of alternative techniques and operating conditions, cost-effective section of equipment during an installation, and exchange or expansion of an energy system [18,19]

Numerous investigators [20–26] presented different exergoeconomic approaches to analyze and optimize energy systems. Rosen and Scott [27] proposed a comprehensive methodology for the analysis of systems and processes, which was based on the quantities of exergy, cost, energy and mass, and the method was referred to as EXCEM analysis. Subsequently, the method was further developed by Rosen and Dincer [28]. The first law of thermodynamics embodies energy analysis, which identifies only the waste and loss of external energy. Potential improvements for the effective use of resources are not possible with energy, for instance an adiabatic throttling process. However, the second law of thermodynamics, which can be formulated in terms of exergy, takes exergy destructions and losses into consideration and accounts for irreversibilities. Economics is also essential in analysis, and therefore it is incorporated in the EXCEM analysis of costs.

There are a number of methods available in the literature for economic analysis, as they are used to evaluate the cost of geothermal plants. Most of them [29–36] are applied to the district heating systems. However, the number of studies on exergoeconomic analysis of geothermal-based electricity production is rather limited. Some of these studies may be summarized as follows: Arslan and Kose [37] investigated the possibility of electricity generation by a binary cycle and heating the residences and greenhouses by means of waste geothermal fluid. For this purpose, they constructed and analyzed twenty-one different models using exergy and life-cycle-cost (LCC) methods. Their pre-feasibility study indicated that the utilization of this geothermal capacity for multiple uses would be an attractive investment option for Simav region. Arslan [38] studied the optimum-operating conditions for the Kalina Cycle System plant design, taking the exergetic and life-cycle-cost concepts into consideration. In his study, different ranges of working temperatures were taken into account in addition to the ammonia fraction in the working fluid mixture. The energetic and exergetic efficiencies were determined as 14.9% and 36.2%, respectively, using an optimal design criterion.

The novelty that this study brings to forefront is the application of a modified exergoeconomic model for the analysis of a geothermal power plant. The thermodynamic loss rates of the system are studied in detail for assessing the economic performance. In addition, the relations between thermodynamic losses and capital costs are investigated and exhibited through some key parameters. Some practical correlations are developed as well.

2. Description of the Tuzla geothermal power plant (Tuzla GPP)

The geothermal power plant which was investigated in the study is located in Northwestern Anatolia. The first in the plant well was drilled in 1982, and the temperature was determined as 174 °C in a reservoir at a depth of 333–553 m in volcanic rocks with a low permeability. A second well was drilled down to a depth of 1020 m. Two shallow wells at the depths of 81 m and 128 m were drilled, and the fluid temperatures were measured to be 146 and 165 °C, respectively [39].

The GPP, which was analyzed in this study, is designed as a binary plant that generates a gross power of 7.5 MWe. The full power production was started after the tests in February 2010. The brine is extracted from two production wells. The power plant operates on a liquid-dominated resource at 175 °C. The brine passes through the heat exchanger system that consists of a series of counter-flow heat exchangers, where heat is transferred to the working (binary) fluid, isopentane, before the brine is reinjected back to the ground via two reinjection wells (T-10, T-15). The isopentane becomes superheated at the heat exchanger exit. The vapor expands in the turbine, and the mechanical power extracted from the turbine is converted to electrical power in the generator. It utilizes a dry-air condenser to condense the working fluid before being pumped back to the vaporizer to complete the cycle, therefore no fresh water is consumed. The isopentane is then circulated in a closed cycle, based on the Rankine cycle. The schematic representation of the plant is given in Fig. 1.

Two types of inhibitors are utilized in the system. The cost of an inhibitor is $ 3/kg and an inhibitor with a capacity of 7 kg/s is utilized in the system. The daily cost of the inhibitors is about US$ 504. The cost of electricity production ranges between $ 0.033/kW and $ 0.046/kW. The average annual cost of electricity production is $ 0.038/kW. The average cost of capital equipment is about 3 million dollars per each MWe for this system.

3. Energy and exergy analyses

The thermodynamic properties of water were used for the geothermal fluid so that the effects of the salts and the non-condensable gases that might be present in the geothermal brine are considered negligible. This was thought not to cause any significant errors in the calculations since their percentages were estimated to be negligibly small by the plant management [40]. The thermodynamic properties of the working fluid, isopentane, were obtained from the engineering equation solver (EES) software. The exergy rate of the system components are then calculated as follows:

$$\dot{E}x_{\mathrm{i}} = \dot{m}_{\mathrm{i}}[(h_{\mathrm{i}} - h_0) - T_0(s_{\mathrm{i}} - s_0)] \tag{1}$$

Both energy and exergy efficiencies for the overall systems and major components are listed in Table 1. Note that in all plants, there are electrical loads such as the pump fans and the controls, which are necessary to operate the facility. Often these loads are referred to the "parasitic loads". The air-cooled condenser unit was reported to have a great effect on the parasitic load which is constituted about 60–75% of the parasitic loads for the system considered.

3.1. Exergoeconomic analysis

The rate of exergy loss/destruction to capital cost is described as R_{Ex} in the model [28,41]. The formulation is given as follows:

$$R_{\mathrm{Ex}} = \frac{\dot{E}x_{\mathrm{dl.}}}{\dot{Z}} \tag{2}$$

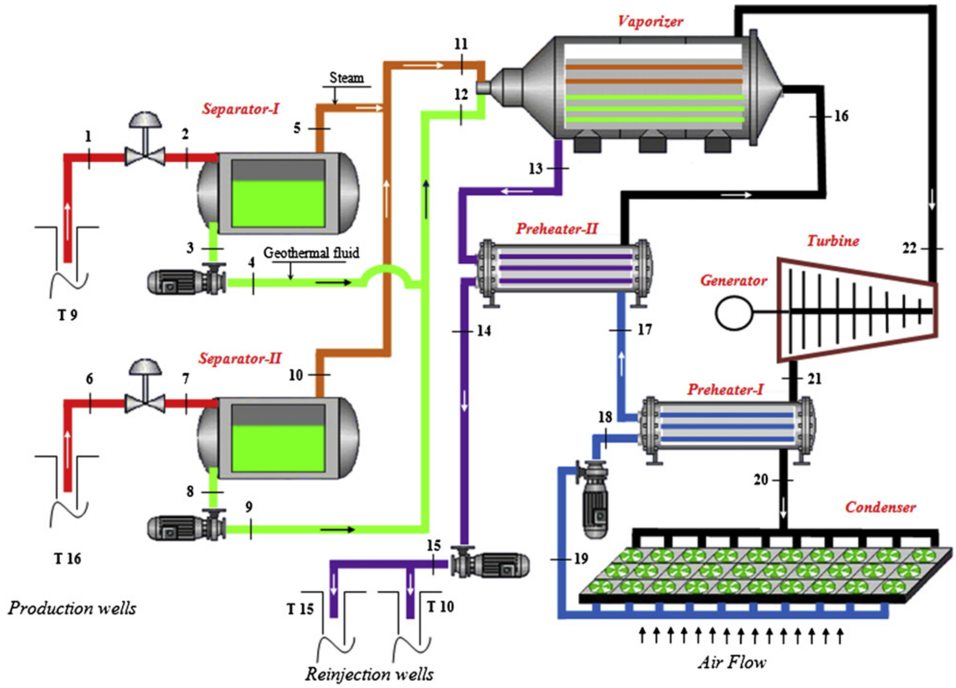

Fig. 1. Schematic layout of the geothermal power plant.

where $\dot{E}x_{\text{dl.}}$ denotes the rate of exergy loss/destruction. The exergy losses can be determined as given in Eq. (3), and they are of two types: external (i.e., the loss associated with the exergy emitted from the system, or waste exergy output) and internal (i.e., the exergy losses within the system due to process irreversibility, or exergy consumption).

$$\dot{E}x_{\text{accum.}} = \dot{E}x_{\text{in}} - \dot{E}x_{\text{out}} - \dot{E}x_{\text{dl.}} \tag{3}$$

The balance equation for cost, a non-conserved quantity, can be written since cost is an increasing and non-conserved quantity. The cost balance equation is reported in Refs. [24,37] as:

$$\dot{Z}_{\text{accum.}} = \dot{Z}_{\text{in}} - \dot{Z}_{\text{out}} \tag{4}$$

where $\dot{Z}$ is the capital cost. Input ($\dot{Z}_{\text{in}}$), output ($\dot{Z}_{\text{out}}$) and accumulation ($\dot{Z}_{\text{accum.}}$) of cost represent, respectively, the cost associated with all inputs, outputs and accumulation for the system. Cost generation corresponds to the applicable capital and other costs associated with the construction and the maintenance of a system.

Table 1
Energy and exergy efficiency equations for system components and overall system.

	Energy efficiency	Exergy efficiency
Heat exchanger	$\eta_{(\text{HE})} = \frac{\dot{E}_{(\text{HE}),\text{in}} - \dot{E}_{(\text{HE}),\text{out}}}{\dot{E}_{(\text{HE}),\text{in}}}$	$\varepsilon_{(\text{Turb})} = \frac{\dot{E}x_{(\text{HE}),\text{in}} - \dot{E}x_{(\text{HE}),\text{out}}}{\dot{E}x_{(\text{HE}),\text{in}}}$
Turbine	$\eta_{(\text{Turb})} = \frac{\dot{W}_{(\text{Turb})}}{\dot{E}_{(\text{Turb}),\text{in}} - \dot{E}_{(\text{Turb}),\text{out}}}$	$\varepsilon_{(\text{Turb})} = \frac{\dot{W}_{(\text{Turb})}}{\dot{E}x_{(\text{Turb}),\text{in}} - \dot{E}x_{(\text{Turb}),\text{out}}}$
Pump	$\eta_{(\text{Pump})} = \frac{\dot{E}_{(\text{Pump}),\text{out}} - \dot{E}_{(\text{Pump}),\text{in}}}{\dot{W}_{(\text{Pump})}}$	$\varepsilon_{\text{Pump}} = \frac{\dot{E}x_{(\text{Pump}),\text{out}} - \dot{E}x_{(\text{Pump}),\text{in}}}{\dot{W}_{(\text{Pump})}}$
The overall net plant	$\eta_{\text{sys}} = \frac{\dot{W}_{(\text{Turb})} - \dot{W}_{(\text{PL})}}{\dot{E}_{(\text{Sys}),\text{in}}}$	$\varepsilon_{\text{sys}} = \frac{\dot{W}_{(\text{Turb})} - \dot{W}_{(\text{PL})}}{\dot{E}x_{(\text{Sys}),\text{in}}}$

Here, subscripts in, out, HE, Turb, Pump, Sys and PL indicate the inlet, outlet, heat exchanger, turbine, pump, overall system, respectively. Also, η, ε, $\dot{E}$, $\dot{E}x$ and $\dot{W}$ stand for energy efficiency, exergy efficiency, energy rate, exergy rate and work rate, respectively.

Tsatsaronis and Park [42] and Cziesla et al. [43] proposed avoidable and unavoidable exergy destructions and investment costs respectively. They applied this concept to various types power generating plants.

3.2. Modified exergoeconomic model

In this study, the model and the assessment methodology developed by Tsatsaronis et al. [42,43] were modified and applied to a geothermal power plant system. The actual local cost data were taken from the plant and used in the calculations. The balance equations were used for the exergy cost in the system and in its components since they were considered to have attained their values for steady-state and steady-flow control volume systems. In the analysis, the capital cost was calculated taking the annualized cost of the equipment into consideration. This method was accomplished using the equation below:

$$\dot{Z}_{(\text{i})} = \frac{\phi_{\text{i}} \cdot \dot{C}_{\text{i}}}{hr \cdot 3600} \tag{5}$$

where ϕ_{k} is a coefficient for the mean total cost, which is the sum of the annualized cost of equipment and the annual maintenance cost. It was taken as 1.05 for each system component. $\dot{C}_{\text{i}}$ (\$/year) is the annualized cost for any system unit. hr is the annual operating hours and taken as 8541. i indicates the system components. $\dot{Z}_{(\text{i})}$ is the annualized total cost of the component. The average life time is given for each system component in Table 2.

A new parameter, so-called the component annualized cost rate, (R_{CAC}) is introduced in this study as

$$R_{\text{CAC}} = \frac{\dot{Z}_{(\text{i})}}{\dot{Z}_{\text{Tot.}}} \tag{6}$$

where R_{CAC} is the component annualized cost rate and it indicates the percent rate of any selected equipment in the overall system total annualized cost ($\dot{Z}_{\text{Tot}}$). It is a very significant parameter for decision-making in the investigation process of the order of

Table 2
Average life time of the system components

Components	Life time (year)
Production wells	40
Wellhead pumps	5
Separators	5
Vaporizer	10
Turbine	5
Preheater I-II	10
Circulating Pump	5
Condenser	10
Reinjection pump	5
Reinjection well	40

exergetic improvement. The total unit exergy cost is comprised of two components in this approach. These are mainly the costs of exergy destruction/loss ($\dot{Z}_{(i),DL}$) and exergy production ($\dot{Z}_{(i),P}$).

$$\dot{Z}_{(i)} = \dot{Z}_{(i),P} + \dot{Z}_{(i),DL} \quad (7)$$

The main difference of the present approach from the one presented in Refs. [42,43] is that the cost of total unit exergy is considered as paid not only for the product exergy but also for the destructed or lost exergy. The reference point for the determination of the total unit exergy cost distribution is the highest exergy efficiency of the system. We considered the total unit exergy cost to be paid for the optimal working condition in terms of the exergetic point of view. The highest exergy efficiency of the system component ($\varepsilon_{(i)}^{highest}$) was determined by analyzing the actual data under the actual working conditions. Then, the costs of exergy destruction/loss ($\dot{Z}_{(i),DL}$) and the exergy production ($\dot{Z}_{(i),P}$) for any component (i) may be calculated as

$$\dot{Z}_{(i),P} = \left(\dot{Z}_{(i),P}^{UA} + \dot{Z}_{(i),P}^{A}\right) = \dot{Z}_{(i)} \cdot \varepsilon_{(i)}^{highest} \quad (8)$$

and

$$\dot{Z}_{(i),DL} = \left(\dot{Z}_{(i),DL}^{UA} + \dot{Z}_{(i),DL}^{A}\right) = \dot{Z}_{(i)} \cdot \left(1 - \varepsilon_{(i)}^{highest}\right), \quad (9)$$

respectively.

The costs of exergy destruction/loss and exergy production were constant in the calculation procedure for any component. Two exergy cost components ($\dot{Z}_{(i),P}$ and $\dot{Z}_{(i),DL}$) may be divided in two subgroups as the cost of unavoidable exergy destruction/loss ($\dot{Z}_{(i),DL}^{UA}$), the cost of avoidable exergy destruction/loss ($\dot{Z}_{(i),DL}^{A}$), the cost of unavoidable exergy production ($\dot{Z}_{(i),P}^{UA}$) and the cost of avoidable exergy production ($\dot{Z}_{(i),P}^{A}$).

$$\dot{Z}_{(i)} = \left(\dot{Z}_{(i),P}^{UA} + \dot{Z}_{(i),P}^{A}\right) + \left(\dot{Z}_{(i),DL}^{UA} + \dot{Z}_{(i),DL}^{A}\right) \quad (10)$$

The four exergetic cost components are written as

$$\dot{Z}_{(i),P}^{UA} = ExBC_{(i)} \cdot \dot{E}x_{(i),P} \quad (11)$$

$$\dot{Z}_{(i),DL}^{UA} = ExBC_{(i)} \cdot \dot{E}x_{(i),DL} \quad (12)$$

$$\dot{Z}_{(i),P}^{UA} = \dot{Z}_{(i),P} - \dot{Z}_{(i),P}^{A} \quad (13)$$

$$\dot{Z}_{(i),DL}^{A} = \dot{Z}_{(i),DL} - \dot{Z}_{(i),DL}^{UA} \quad (14)$$

where $ExBC_{(i)}$ is a new parameter, so-called the cost of exergy balance which is determined by

$$ExBC_{(i)} = \frac{\dot{Z}_{(i)} \cdot \varepsilon_{(i)}^{highest}}{\dot{E}x_{(i),P}^{highest}} = \frac{\dot{Z}_{(i)} \cdot \left(1 - \varepsilon_{(i)}^{highest}\right)}{\dot{E}x_{(i),DL}^{highest}} \quad (15)$$

The cost of exergy balance is determined for the working condition with the highest exergy efficiency where $\dot{E}x_{(i),P}^{highest}$ and $\dot{E}x_{(i),DL}^{highest}$ denote the rates of exergy production and exergy destruction/loss for the working condition with the highest exergy respectively.

Following the calculation of the costs of unavoidable exergy destruction/loss, avoidable exergy destruction/loss, unavoidable exergy production and avoidable exergy production for each system component, the four parameters are calculated for the overall system. This is called the cost of overall system unavoidable exergy destruction/loss ($\dot{Z}_{Tot.,DL}^{UA}$), the cost of avoidable exergy destruction/loss ($\dot{Z}_{Tot.,DL}^{A}$), the cost of unavoidable exergy production ($\dot{Z}_{Tot.,P}^{UA}$) and the cost of avoidable exergy production ($\dot{Z}_{Tot.,P}^{A}$).

$$\dot{Z}_{Tot.,P}^{UA} = \sum_{i=1}^{n} \dot{Z}_{(i),P}^{UA} \quad (16)$$

$$\dot{Z}_{Tot.,P}^{A} = \sum_{i=1}^{n} \dot{Z}_{(i),P}^{A} \quad (17)$$

$$\dot{Z}_{Tot.,DL}^{UA} = \sum_{i=1}^{n} \dot{Z}_{(i),DL}^{UA} \quad (18)$$

$$\dot{Z}_{Tot.,DL}^{A} = \sum_{i=1}^{n} \dot{Z}_{(i),DL}^{A} \quad (19)$$

The cost rates of the overall system unavoidable exergy destruction/loss (R_{DL}^{UA}), the avoidable exergy destruction/loss (R_{DL}^{A}), the unavoidable exergy production (R_{P}^{UA}) and the avoidable exergy production (R_{P}^{A}) were proposed respectively in this study for the determination of the rate of unavoidable exergy destruction/loss cost, avoidable exergy destruction/loss cost, unavoidable exergy production cost and avoidable exergy production cost in to annualized total cost ($\dot{Z}_{Tot.}$). The four overall system exergetic cost rate parameters can be described as

$$R_{DL}^{A} = \frac{\dot{Z}_{Tot.,DL}^{A}}{\dot{Z}_{Tot.}} \quad (20)$$

$$R_{DL}^{UA} = \frac{\dot{Z}_{Tot.,DL}^{UA}}{\dot{Z}_{Tot.}} \quad (21)$$

$$R_{P}^{A} = \frac{\dot{Z}_{Tot.,P}^{A}}{\dot{Z}_{Tot.}} \quad (22)$$

$$R_{P}^{UA} = \frac{\dot{Z}_{Tot.,P}^{UA}}{\dot{Z}_{Tot.}} \quad (23)$$

A sample calculation is therefore conducted to present the calculation procedure for Preheater-I. Exergy production and destruction/loss were determined as $\dot{E}x_{(PH-I),P} = 171$ kW and $\dot{E}x_{(PH-I),DL} = 140$ kW, respectively. The highest exergy efficiency ($\varepsilon_{(PH-I)}^{highest}$) and exergy production ($\dot{E}x_{(PH-I),P}^{highest}$) were determined as 0.793 and 594 kW, respectively. $\dot{Z}_{(PH-I)}$ was calculated as \$ $1.536 \cdot 10^{-4}$/s (or \$ 0.553/h).

$$\dot{Z}_{(PH-I),P} = \dot{Z}_{(PH-I)} \cdot \varepsilon^{highest}_{(PH-I)} = \left(\$\,1.536 \cdot 10^{-4}/s\right) \cdot (0.793)$$

$$\dot{Z}_{(PH-I),P} = \$\,1.218 \cdot 10^{-4}/s = \$\,0.4385/h$$

$$ExBC_{(PH-I)} = \frac{\dot{Z}_{(PH-I)} \cdot \varepsilon^{highest}_{(PH-I)}}{\dot{E}x^{highest}_{(PH-I),P}} = \frac{(1.536 \cdot 10^{-4}\ \$/s) \cdot (0.793)}{594\ kW}$$

$$ExBC_{(PH-I)} = \$\,2.05 \cdot 10^{-7}/kW$$

$$\dot{Z}^{A}_{(PH-I),P} = ExBC_{(PH-I)} \cdot \dot{E}x_{(PH-I),P} = \left(2.05 \cdot 10^{-7}\ \ \$/s\right) \cdot (171\ kW)$$

$$\dot{Z}^{A}_{(PH-I),P} = \$\,0.3506 \cdot 10^{-4}/s = \$\,0.1262/h$$

$$\dot{Z}^{R}_{(PH-I),P} = \dot{Z}_{(PH-I),P} - \dot{Z}^{A}_{(PH-I),P} = (1.218 - 0.3506) \cdot 10^{-4}$$

$$\dot{Z}^{R}_{(PH-I),P} = \$\,0.8674 \cdot 10^{-4}/s = \$\,0.3123/h$$

$$R^{A}_{(PH-I),P} = \frac{\dot{Z}^{A}_{(PH-I),P}}{\dot{Z}_{(PH-I)}} = \frac{0.3506}{1.536} = 0.2283$$

$$R^{R}_{(PH-I),P} = \frac{\dot{Z}^{R}_{(PH-I),P}}{\dot{Z}_{(PH-I)}} = \frac{0.8674}{1.536} = 0.5647$$

$$\dot{Z}_{(PH-I),DL} = \dot{Z}_{(PH-I)} \cdot \left(1 - \varepsilon^{highest}_{(PH-I)}\right) = \left(\$\,1.536 \cdot 10^{-4}/s\right) \cdot (0.207)$$

$$\dot{Z}_{(PH-I),DL} = \$\,0.3179 \cdot 10^{-4}/s = \$\,0.1145/h$$

$$\dot{Z}^{A}_{(PH-I),DL} = ExBC_{(PH-I)} \cdot \dot{E}x_{(PH-I),DL} = \left(\$\,2.05 \cdot 10^{-7}/kW\right) \cdot (140\ kW)$$

$$\dot{Z}^{A}_{(PH-I),DL} = \$\,0.287 \cdot 10^{-4}/s = \$\,0.1033/h$$

$$\dot{Z}^{R}_{(PH-I),DL} = \dot{Z}_{(PH-I),DL} - \dot{Z}^{A}_{(PH-I),DL} = (0.3179 - 0.287) \cdot 10^{-4}$$

$$\dot{Z}^{R}_{(PH-I),DL} = \$\,0.0309 \cdot 10^{-4}/s = \$\,0.0111/h$$

$$R^{A}_{(PH-I),DL} = \frac{\dot{Z}^{A}_{(PH-I),DL}}{\dot{Z}_{(PH-I)}} = \frac{0.287}{1.536} = 0.1868$$

$$R^{R}_{(PH-I),DL} = \frac{\dot{Z}^{R}_{(PH-I),DL}}{\dot{Z}_{(PH-I)}} = \frac{0.0309}{1.536} = 0.020$$

The annualized cost rate for Preheater-I is given as

$$R_{CAC} = \frac{\dot{Z}_{(PH-I)}}{\dot{Z}_{Tot.}} = \frac{\$\,1.536 \cdot 10^{-4}/s}{\$\,2.985 \cdot 10^{-2}/s} = 0.0051\ \ or\ \ 0.51\%$$

4. Utilization of the novel exergoeconomic parameters in design and decision-making process

Six new parameters, which were estimated on the basis of the actual system data, are presented in the paper. The key point is how to use those indicators in order to guide or improve the process system design or operation. In first part of the analysis, the total annualized cost was calculated for each system component. Then component annualized cost rate was determined. This parameter is very important for deciding the order of exergetic improvement investigation process. The component selection should be initiated with the component, which has the highest annualized cost rate. In this article, based on the component annualized cost rate, the generator + turbine unit was determined to have the highest share in the annualized total cost. The equipment selection process was conducted by taking the unit exergy production cost and the exergy destruction/loss cost into consideration based on the order. The equipment selection should be conducted such that equipment with higher unit exergy production cost should be preferred within the range of possibility. Then, the costs of the unavoidable exergy destruction/loss, avoidable exergy destruction/loss, unavoidable exergy production and the avoidable exergy production were determined for every system component and for the overall system. Following the process of system design, the designed system needs to be compared with similar different actual running systems by taking the costs of overall unavoidable exergy destruction/loss, avoidable exergy destruction/loss, unavoidable exergy production and avoidable exergy production into consideration. Exergoeconomic state of the system can be determined among the compared systems. The presented modeling strategy is helpful in the exergoeconomic assessment of low-grade energy conversion systems. The present modified exergoeconomic model would be beneficial for the designers and engineers working in the area of exergoeconomic models.

5. Results and discussion

In this study, the reference state was selected as the outdoor reference temperature at the atmospheric pressure of 101.32 kPa. Tables 3 and 4 tabulate the temperature, pressure, and the mass flow rate data for the geothermal fluid, isopentane as the working fluid and air based on their state numbers specified in Fig. 1 for two different outdoor reference temperatures. Energy and exergy rates were calculated for each state, and are listed in Tables 3 and 4. The state 0 is the dead state for the geothermal fluid, the working fluid and air.

The variations in the efficiencies of energy and exergy with the outdoor temperature were studied and are shown in Fig. 2. It was found that energy and exergy efficiencies of the system decrease with increasing outdoor temperatures. The overall system energy and exergy functions were determined based on the outdoor temperature as a parameter. These relationships are obtained by the following correlations:

$$\varepsilon_i = 47.52 - 0.0465 \cdot T - 0.00448 \cdot T^2 - 0.000079 \cdot T^3 \qquad (24)$$

$$\eta_i = 10.94 - 0.0936 \cdot T - 0.00044 \cdot T^2 - 0.000006 \cdot T^3 \qquad (25)$$

where ε, η and T stand for exergy efficiency (%), energy efficiency (%) and the reference environment temperature (°C), respectively. The system exergy efficiency varied between 37% and 48% at temperatures in a range from 0 °C to 35 °C. The annual average exergy efficiency was calculated for system as 45.2%. The overall system energy efficiency varied between 7% and 11% at temperatures in

Table 3
Thermal properties of the plant state and their energy and exergy rates for first day.

State no	Fluid type	Mass flow rate $\dot{m}$ (kg/s)	Temperature T (°C)	Pressure P (kPa)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg °C)	Energy rate $\dot{E}$ (MW)	Exergy rate $\dot{E}x$ (MW)
0	Isopentane	–	25.4	101	−349.1	−1.687	–	–
0	Water	–	25.4	101	106.6	0.373	–	–
1	G. Water	79.11	156.8	570	692.0	1.959	46.311	8.871
2	GW.+S.	79.11	142.8	391	691.8	1.986	46.295	8.218
3	G. Water	75.75	142.8	391	601.2	1.769	37.466	5.911
4	G. Water	75.75	142.9	772	601.9	1.769	37.519	5.964
5	Steam	3.36	142.8	391	2737	6.903	8.838	2.291
6	G. Water	23.42	164.2	687	794.0	2.214	16.099	3.233
7	GW.+S.	23.42	142.8	391	793.8	2.231	16.094	3.110
8	G. Water	21.31	142.8	391	601.2	1.769	10.540	1.663
9	G. Water	21.31	142.9	728	601.8	1.769	10.553	1.676
10	Steam	2.11	142.8	391	2737	6.903	5.550	1.439
11	Steam	5.47	141.5	377	2735.4	6.915	14.380	3.701
12	G. Water	97.06	142.6	550	600.4	1.766	47.928	7.583
13	G. Water	102.53	116.5	320	489.1	1.490	39.218	5.043
14	G. Water	102.53	90.6	240	379.7	1.200	28.001	2.699
15	G. Water	102.53	90.7	540	380.3	1.201	28.062	2.730
16	Isopentane	77.80	103.5	967	−153.2	−1.111	15.241	1.869
17	Isopentane	77.80	49.0	967	−293.3	−1.512	4.341	0.279
18	Isopentane	77.80	32.8	967	−331.6	−1.633	1.362	0.108
19	Isopentane	77.80	32.7	120	−332.4	−1.632	1.299	0.022
20	Isopentane	77.80	38.4	122	16.2	−0.495	28.420	0.747
21	Isopentane	77.80	60.2	126	55.7	−0.376	31.493	1.058
22	Isopentane	77.80	121.4	967	139.9	−0.353	38.044	7.075

a range from 0 °C to 35 °C while the annual average energy efficiency of system was calculated as 9.5%.

The dry-air condenser unit had a pronounced effect on the total system energy and exergy efficiency. The condenser efficiency increased as the outdoor temperature decreased. The temperature of isopentane that was pumped back to the vaporizer decreased in accordance with the outdoor temperature. The gross electric power production was achieved as 5.935 and 7.507 MW for the first (25.4 °C) and the second (9.8 °C) case investigations respectively. The system theoretically allowed the production of gross electricity power up to 8.2 MW. However, the system did not allow to exceed the net electricity production of (gross power − parasitic load) over 7.5 MW in practice. During the operation, if the outdoor temperature decreased too much, the net electricity production exceeded 7.5 MW, and the system automatically reduced electricity production down to 6.2 MW. The decrease in the outdoor temperature down to around 4 °C is considered acceptable. However, further decreases had less effect on the electricity production. With the increase in outdoor temperature, the total exergy destruction tended to decrease. The outdoor temperature distribution had an indirect effect on the total energy and exergy efficiency. Even if two geothermal power plants had the same geothermal fluid property

Table 4
Thermal properties of the plant state and their energy and exergy rates for second day.

State no	Fluid type	Mass flow rate $\dot{m}$ (kg/s)	Temperature T (°C)	Pressure P (kPa)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg°C)	Energy rate $\dot{E}$ (MW)	Exergy rate $\dot{E}x$ (MW)
0	Isopentane	–	9.8	101	−378.6	−1.780	–	–
0	Water	–	9.8	101	41.1	0.144	–	–
1	GW.	79.90	156.8	570	692.0	1.959	52.008	10.996
2	GW.+S.	79.90	142.8	391	691.8	1.986	51.992	10.370
3	GW.	76.51	142.8	391	601.2	1.769	42.852	7.693
4	GW.	76.51	142.9	772	601.9	1.769	42.905	7.746
5	S.	3.39	142.8	391	2737.0	6.903	9.149	2.662
6	GW.	23.65	164.2	687	794.0	2.214	17.809	3.962
7	GW.+S.	23.65	142.8	391	793.8	2.231	17.805	3.844
8	GW.	21.52	142.8	391	601.2	1.769	12.055	2.164
9	GW.	21.52	142.9	728	601.8	1.769	12.068	2.177
10	S.	2.13	142.8	391	2737.0	6.903	5.745	1.672
11	S.	5.52	141.5	377	2735.4	6.915	14.885	4.306
12	GW.	98.03	142.6	550	600.4	1.766	54.829	9.862
13	GW.	103.56	104.4	320	438.5	1.383	41.153	4.868
14	GW.	103.56	72.0	240	302.4	0.954	27.059	3.338
15	GW.	103.56	72.1	540	302.8	0.955	27.100	3.350
16	Isopentane	77.80	84.0	967	−201.1	−1.247	13.810	2.083
17	Isopentane	77.80	40.4	967	−307.1	−1.555	5.563	0.612
18	Isopentane	77.80	20.1	967	−354.7	−1.704	1.859	0.187
19	Isopentane	77.80	20.0	120	−354.8	−1.705	1.852	0.202
20	Isopentane	77.80	30.0	122	5.9	−0.526	29.914	2.324
21	Isopentane	77.80	57.5	126	55.7	−0.376	33.789	2.898
22	Isopentane	77.80	135.0	967	157.9	−0.347	41.740	10.211

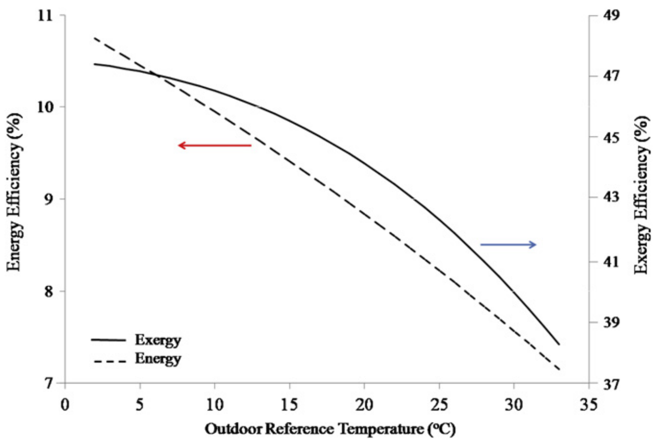

Fig. 2. Variation of the energy and exergy efficiency with outdoor reference temperature.

and the gross power potential, the total electricity production would be different in different regions as a result of the differences in the outdoor temperature distribution. In order to determine the outdoor temperature distribution as well as the system energy and exergy efficiency, the variation function is very important for forecasting monthly or annual electricity production. The monthly outdoor temperature distribution for Çanakkale was determined using the method proposed by Ref. [44]. The monthly total electricity production was calculated using the monthly outdoor temperature distribution and the energy efficiency function. The results are then presented in Fig. 3 for the whole system. As can be seen in Fig. 3, the monthly average electricity production was obtained in January in a range of 3822 and 5428 MWh/month. The annual total electricity production capacity was determined as 55,308 MWh/year, and the average electricity production capacity was calculated as 6.314 MW.

Exergy destruction/loss and heat loss of the plant components were calculated for two case study days and the details are listed in Figs. 4 and 5. The largest exergy destruction took place in the reinjection section. Then, the component annualized cost rate was calculated for the system components and are given in Fig. 6.

Based on the component annualized cost rate, the generator + turbine unit had the highest share in the annualized total cost. The second place was taken by the condenser unit. The total share of the generator + turbine unit and the condenser was 87.6% of the annualized total cost. Therefore the energy and the exergy efficiencies of the two components played a very important role in the system exergoeconomic analysis. The investigations on the exergetic improvement should focus on the generator + turbine unit and the condenser in geothermal power production systems.

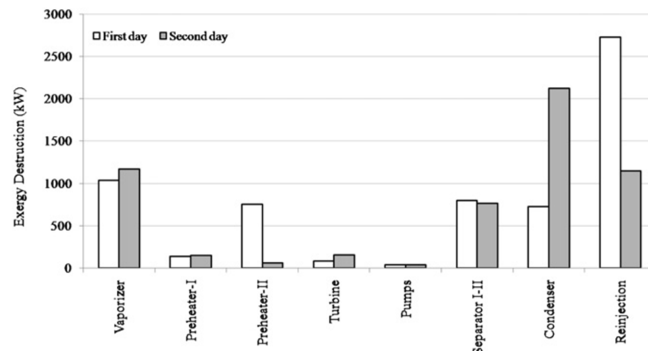

Fig. 4. Exergy destruction/lose for two sample days.

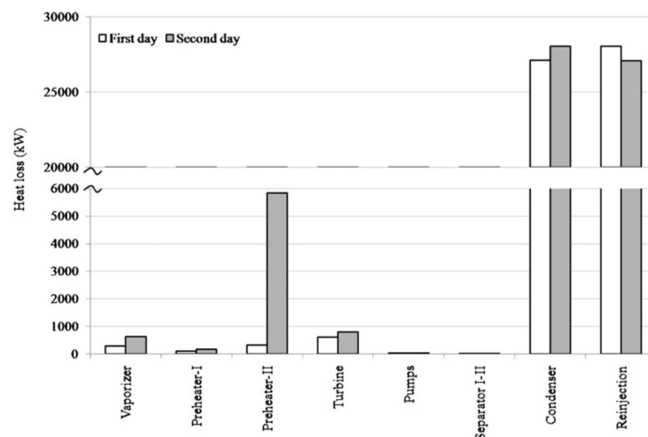

Fig. 5. Heat loss for two sample days.

The unavoidable exergy destruction/loss cost, avoidable exergy destruction/loss cost, unavoidable exergy production cost and the avoidable exergy production cost for each component and the overall system were determined using actual data. It was determined that the overall system avoidable exergy production cost and the avoidable exergy destruction/loss cost decreased as the outdoor reference temperature increased. On the contrary, the unavoidable exergy destruction/loss cost and the unavoidable exergy production cost decreased as the outdoor reference temperature decreased. The variation in $\dot{Z}^{UA}_{Tot.,DL}$ and $\dot{Z}^{UA}_{Tot.,P}$ is given in Fig. 7. As it may be seen in Fig. 7, $\dot{Z}^{UA}_{Tot.,P}$ varied between \$ 65/h and \$ 40/h. Also, $\dot{Z}^{UA}_{Tot.,DL}$ reached up to \$ 25/h. The variation in $\dot{Z}^{A}_{Tot.,P}$ and $\dot{Z}^{A}_{Tot.,DL}$ was very limited. $\dot{Z}^{A}_{Tot.,DL}$ varied between \$ 32/h and \$ 34/h.

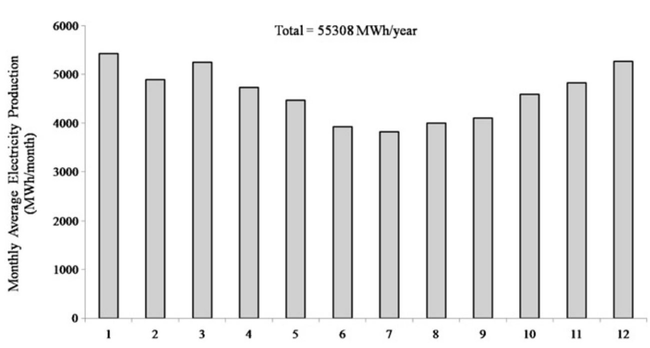

Fig. 3. Average monthly electricity production distribution.

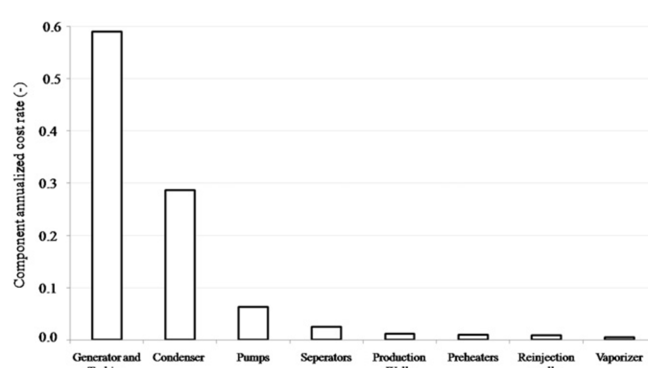

Fig. 6. Distribution of component annualized cost rate for investigated system.

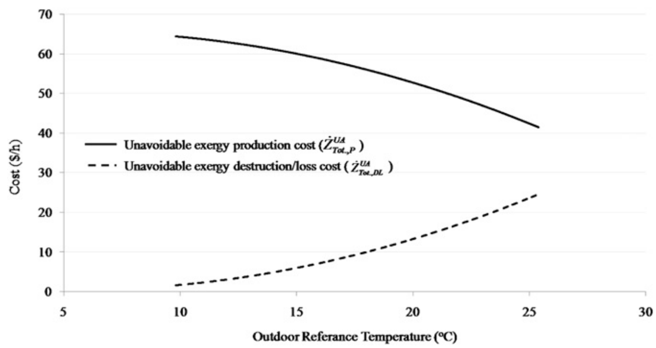

Fig. 7. Variation of unavoidable production and destruction/loss cost.

6. Conclusions

In this study, a modified exergoeconomic model is proposed for the analysis of geothermal power plants and applied to the Tuzla geothermal power plant. The present model contains six newly developed parameters, namely component annualized cost rate, exergy balance cost, overall system unavoidable exergy destruction/loss cost rate, overall system avoidable exergy destruction/loss cost rate, overall system unavoidable exergy production cost rate and the overall system avoidable exergy production cost rate. The main conclusions drawn from the present study are given as follows:

- The annual average $\dot{Z}^{UA}_{Tot.,P}$, $\dot{Z}^{UA}_{Tot.,DL}$, $\dot{Z}^{A}_{Tot.,P}$ and $\dot{Z}^{A}_{Tot.,DL}$ are found to be \$ 55.7/h, \$ 33.1/h, \$ 9.3/h and \$ 0.35/h, respectively, for the overall system.
- The system exergy efficiency varies between 37% and 48% in a temperature range from 0 °C to 35 °C. It decreases with increasing outdoor temperature.
- The annual average exergy efficiency is determined to be 45.2% using the outdoor temperature distribution.
- The exergy loss rates for the system devices range from 38 kW to 2730 kW. The largest exergy losses occur in the reinjection unit.

It is expected that the results of the present analysis will be beneficial to those, who deal with exergoeconomic assessment of geothermal power plant systems.

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Nomenclature

$\dot{C}_i$: annualized cost for any system unit ($/year)
$\dot{E}$: energy rate (kW)
$\dot{E}x$: exergy rate (kW)
$ExBC_{(i)}$: exergy balance cost ($/s or $/h)
GPPS: geothermal power plant system
h: specific enthalpy (kJ/kg)
hr: annual operating hours per year (h/y)
$\dot{m}$: mass flow rate (kg/s)
P: pressure (kPa)
R_{CAC}: component annualized cost rate (−)
R_{DL}^{UA}: overall unavoidable system exergy destruction/loss cost rate (−)
R_{DL}^{A}: overall avoidable system exergy destruction/loss cost rate (−)
R_{P}^{UA}: overall unavoidable system exergy production cost rate (−)
R_{P}^{A}: overall avoidable system exergy production cost rate (−)
s: specific entropy (kJ/kg °C)
T: temperature (°C or K)
$\dot{W}$: work input rate (kW)
$\dot{Z}_{(i)}$: annualized total cost of the component ($/s or $/h)
$\dot{Z}_{Tot}$: overall system total annualized cost ($/s or $/h)
$\dot{Z}_{(i),DL}$: exergy destruction/loss cost ($/s or $/h)
$\dot{Z}_{(i),P}$: exergy production cost ($/s or $/h)
$\dot{Z}_{(i),DL}^{UA}$: unavoidable exergy destruction/loss cost ($/s or $/h)
$\dot{Z}_{(i),DL}^{A}$: avoidable exergy destruction/loss cost ($/s or $/h)
$\dot{Z}_{(i),P}^{UA}$: unavoidable exergy production cost ($/s or $/h)
$\dot{Z}_{(i),P}^{A}$: avoidable exergy production cost ($/s or $/h)

Greek letters
η: energy efficiency (%)
ε: exergy efficiency (%)
ϕ_k: coefficient for mean total costs (−)

Subscripts
accum: accumulation
DL: destruction/loss
E: energy
Ex: exergy
HE: heat exchanger
i: successive number of elements
in: inlet
out: outlet
useful: useful
net: net
PL: parasitic load
Sys: overall system
Turb: turbine
Tot: total
0: reference (dead) stead