

## EXERGoeonomic MODELING OF GEOTHERMAL DISTRICT HEATING SYSTEMS FOR BUILDING APPLICATIONS

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### ABSTRACT

Geothermal district heating systems (GDHSs) are modeled by examining the relations between thermodynamic losses and capital costs for the devices comprising the GDHSs, and some possible generalizations are proposed relating thermodynamic losses and capital costs. The model proposed is then applied to a GDHS installed in Turkey using actual data. Finally, the results are discussed in terms of the identification and evaluation of inefficiencies in the system and of possible improvements. The study provides insights into the relations between energetic and exergetic losses and capital costs for GDHSs, in particular, and for energy systems, in general. The results appear to be useful to those involved in the development of analysis and design methodologies that integrate thermodynamics and economics.

### INTRODUCTION

Many contend that costs are better distributed among outputs if cost accounting is based on the thermodynamic quantity exergy (Bejan et al., 2000; Sciubba, 2001; Tsatsaronis and Park, 2002; Rosen, 1990; Rosen and Dincer, 2003a,b). One rationale for this statement is that exergy, but not energy, is often a consistent measure of economic value. In recent years, numerous researchers have developed methods of performing economic analyses based on exergy, which are referred to by many names (e.g., thermoeconomics, second-law costing, cost accounting, exergoeconomics). In this regard, exergoeconomic analysis, which combines exergy and economics, has been applied by a number of investigators (e.g., Bejan et al., 2000; Sciubba, 2001; Chen, 2001; Tsatsaronis and Park, 2002; Rosen, 1990; Rosen and Dincer, 2003a,b; Ozgener and Hepbasli, 2005) to a wide range of thermal systems (e.g., power plants, cogeneration systems, heat exchangers, crude oil combined distillation units and

fuel cell systems). However, its application to geothermal district heating systems (GDHSs) has not appeared in the open literature.

As pointed out earlier (e.g., Rosen, 1990; Rosen and Dincer, 2003a,b; Dincer, 2003), cost accounting for energy conversion devices conventionally considers unit costs based on energy. Exergoeconomic analysis and related techniques encompass some common characteristics: (i) they combine exergy and economic disciplines to achieve the objectives listed above, and (ii) they recognize that exergy, not energy, is the commodity of value in a system, and they consequently assign costs and/or prices to exergy-related variables.

In the open literature, the studies conducted on energy and exergy analysis and thermodynamic optimization of geothermal energy systems can be classified into five groups as follows: (i) exergy analysis of geothermal power plants, (ii) evaluation of geothermal fields using exergy analysis, (iii) classification of geothermal resources by exergy, (iv) thermodynamic optimization of power plants, and (v) energy and exergy analyses of geothermal district heating systems, which have recently been investigated in terms of potential for improvements using energy and exergy analysis methods (Ozgener et al., 2004, 2005a,b,c). One of the first uses of exergy to analyze a geothermal power plant was performed by Badvarsson and Eggers (1972). They compared the performances of single and double flash cycles based on a reservoir water temperature of 250°C and a sink condition of 40°C and found exergy efficiencies to be 38.7% and 49%, respectively, (with an assumption of a mechanical efficiency of 65%). The most common type of geothermal reservoir is liquid-dominated. The liquid from the separator may be injected, used for its thermal energy via heat exchangers for a variety of direct heat applications, or flashed to a lower

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pressure by means of control valve or orifice plate, thereby generating additional steam for use in a low-pressure turbine. Plants in which only primary high-pressure steam is used are called single-flash plants, while plants using both high- and low-pressure flash steam are called double-flash plants (DiPippo, 1999).

Although many studies have been undertaken by many researchers on thermo-economic analysis of a wide range of thermal systems (e.g., power plants), to the best of the authors' knowledge no publications have appeared in the open literature except that of Ozgener et al. (2005c), in which a thermo-economic analysis was carried out of geothermal district heating systems for performance evaluation and improvement. This work provides the motivation for the present work, as we extend the previous work (Ozgener et al., 2004, 2005a,b,c), which include energy and exergy analyses of various geothermal district heating systems, to conduct a thermo-economic analysis of geothermal district heating systems and apply the results to the Balcova geothermal district heating system (BGDHS) in Izmir, Turkey, using actual system data (Ozgener et al., 2005c). Also, the relations between thermodynamic losses and capital costs for devices in the system are examined and possible generalizations in the relation between thermodynamic losses and capital costs are suggested.

## SYSTEM DESCRIPTION

Figure 1 provides a schematic diagram of the Balcova GDHS which includes hotels and official buildings heated by geothermal energy. The Balcova GDHS consists mainly of three cycles: (a) an energy production cycle through a geothermal well loop and geothermal heating center loop, (b) an energy distribution cycle through a district heating distribution network, and (c) an energy consumption cycle through building substations. In the present district heating facility, there are two systems: the Izmir-Balcova geothermal district heating system (IBGDHS) and the Izmir-Narlidere geothermal district heating system (INGDHS). The design heating capacity of IBGDHS is equivalent to 7500 residences. INGDHS was designed for 1500 residence equivalence but has a sufficient infrastructure to allow capacity growth to 5000 residence equivalence. Both IBGDHS and INGDHS are investigated here under Balcova geothermal district heating system (BGDHS) (for details, see Ozgener et al., 2004, 2005b,c). Here, BDs stand for deep wells and Bs stand for shallow wells. As of the end of 2001, there were 14 wells ranging in depth from 48 to 1100 m in the IBGF, while 10 wells were working at the date of the study. Of these, eight wells (designated as BD2, BD3, BD4, BD5, BD7, B1, B4, B5 and B10) and one well (BD8) are production and reinjection wells, respectively. The temperatures of the production wells vary from 95 to 140°C, while

the mass flow rates of the wells range from 8.3 to 41.7 kg/s, respectively.

## MODELLING

Analyses of GDHSs, as described in part in this paper and in more detail in companion studies by the authors (Ozgener et al., 2004, 2005a,b,c), have been applied to the design optimization of a GDHS, using realistic cost estimates. In this study we employ the methodology developed earlier by Rosen (1990) and used more recently by Rosen and Dincer (2003a,b) to conduct an exergoeconomic analysis of geothermal district heating systems. The exergetic equivalents of the capital and labor costs are evaluated based on global data available for Turkey.

Balances are written for mass, energy and exergy flows in the system and its components, which are considered to be steady-state steady-flow control volume systems. Appropriate energy and exergy expressions are developed for the overall system and its components, as given in this section. Heat losses from the distribution networks/pipelines are not specifically considered in the analysis. However, their indirect effects, which are temperature drops, are part of the calculations. Pressure drops in the distribution networks/pipelines are also considered negligible.

A mass flow rate balance for a quantity in a system may be written as

$$\dot{m}_i - \dot{m}_o = \dot{m}_a \quad (1)$$

where  $m$  denotes mass and the subscripts  $i$ ,  $o$  and  $a$  denote inlet, outlet and accumulation, respectively. Here, input and output refer respectively to quantities entering and exiting through system boundaries, and accumulation refers to build-up (either positive or negative) of the quantity within the system.

Energy, being subject to a conservation law like mass (neglecting nuclear reactions), can be neither generated nor consumed. Exergy is consumed during a process due to irreversibilities, and is therefore subject to a non-conservation law. Consequently, the respective energy and exergy rate balance equations can be written as

$$\dot{E}_i - \dot{E}_o = \dot{E}_a \quad (2)$$

$$\dot{E}x_i - \dot{E}x_o - \dot{L}_{ex} = \dot{E}x_a \quad (3)$$

where  $E$  denotes energy,  $Ex$  denotes exergy and  $L$  denotes loss.

Cost is an increasing, nonconserved quantity. The cost balance equation can be written as

$$K_i + K_g - K_o = K_a \quad (4)$$

where  $K$  denotes cost and the subscript  $g$  denotes generation. Cost input, output and accumulation represent respectively the cost associated with all inputs, outputs and accumulations for the system. Cost generation corresponds to the appropriate capital and other costs associated with the creation and maintenance of a system.

In order to map any geothermal field on the Mollier diagram as well as to determine the energy and exergy values of the geothermal brine, the average values for the enthalpy and entropy are then calculated from the following equations (Quijano, 2000)

$$h_{brine} = \frac{\sum_{i=1}^n \dot{m}_{wi} h_{wi}}{\sum_{i=1}^n \dot{m}_{wi}} \quad (5)$$

$$s_{brine} = \frac{\sum_{i=1}^n \dot{m}_{wi} s_{wi}}{\sum_{i=1}^n \dot{m}_{wi}} \quad (6)$$

The geothermal brine energy and exergy inputs from the production field of the geothermal district heating system investigated is calculated from the following equations (Ozgener et al, 2004, 2005a-c, Ozgener, 2005).

The balance equation for the mass flow rate of the overall BGDHS can be expressed as:

$$\sum_{i=1}^n \dot{m}_{w,i,Tot} - \dot{m}_r - \dot{m}_d = 0 \quad (7)$$

The total energy and exergy input to the BGDHS may be calculated from the following equations, respectively:

$$\dot{E}_{brine} = \dot{m}_w (h_{brine} - h_0) \quad (8)$$

The exergy rate is calculated from the following equation

$$\dot{E}x_{brine} = \dot{m}_w [(h_{brine} - h_0) - T_0 (s_{brine} - s_0)] \quad (9)$$

The exergy destructions in the heat exchanger and pump are calculated as follows, respectively:

$$\dot{L}_{ex,HE} = \dot{E}x_{dest,HE} = E x_i - \dot{E}x_o = \dot{E}x_{dest} \quad (10)$$

$$\dot{L}_{ex,pump} = \dot{E}x_{dest,pump} = \dot{W}_{pump} - (\dot{E}x_o - \dot{E}x_n) \quad (11)$$

and

$$\dot{L}_{ex,system} = \dot{E}x_{dest,system} = \sum \dot{E}x_{dest,HE} + \sum \dot{E}x_{dest,pump} \quad (12)$$

The exergy efficiency of a heat exchanger is determined by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream on a rate basis as follows:

$$\varepsilon_{HE} = \frac{\dot{m}_{cold} (\psi_{cold,out} - \psi_{cold,in})}{\dot{m}_{hot} (\psi_{hot,in} - \psi_{hot,out})} \quad (13)$$

In a similar way we define exergy efficiency as the ratio of total exergy output to total exergy input:

$$\varepsilon = \frac{\dot{E}x_{output}}{\dot{E}x_{input}} \quad (14)$$

where ‘‘output’’ refers to ‘‘net output’’ or ‘‘product’’ or ‘‘desired value’’, and ‘‘input’’ refers to ‘‘given’’ or ‘‘used’’.

The energy and exergy efficiencies of the BGDHS and are calculated from the following equations, respectively (Ozgener et al, 2004, 2005a-c, Ozgener, 2005).

$$\eta_{system} = \frac{\sum_{i=1}^n \dot{E}_{useful,HE,i}}{\dot{E}_{brine}} \quad (15)$$

$$\varepsilon_{system} = \frac{\dot{E}x_{useful,HE}}{\dot{E}x_{brine}} = 1 - \frac{\dot{E}x_{dest,system} + \dot{E}x_{natural\ discharged}}{\dot{E}x_{brine}} \quad (16)$$

The exergetic efficiencies and exergy destructions for the entire systems and their major system components are calculated using the above equations.

Energy losses can be identified directly from the energy rate balance in Eq. (2). For convenience, the energy loss rate for a system is denoted in the present analysis as  $\dot{L}_{en}$ . Exergy losses can be identified from the exergy rate balance in Eq. (3). There are two types of exergy losses: the ‘waste exergy output,’ which represents the loss associated with exergy that is emitted from the system, and the ‘exergy consumption,’ which represents the internal exergy loss due to process irreversibilities. These two exergy losses are sometimes referred to as external and internal losses, respectively. The two exergy losses sum to the total exergy loss, which is denoted here as  $\dot{L}_{ex}$ .

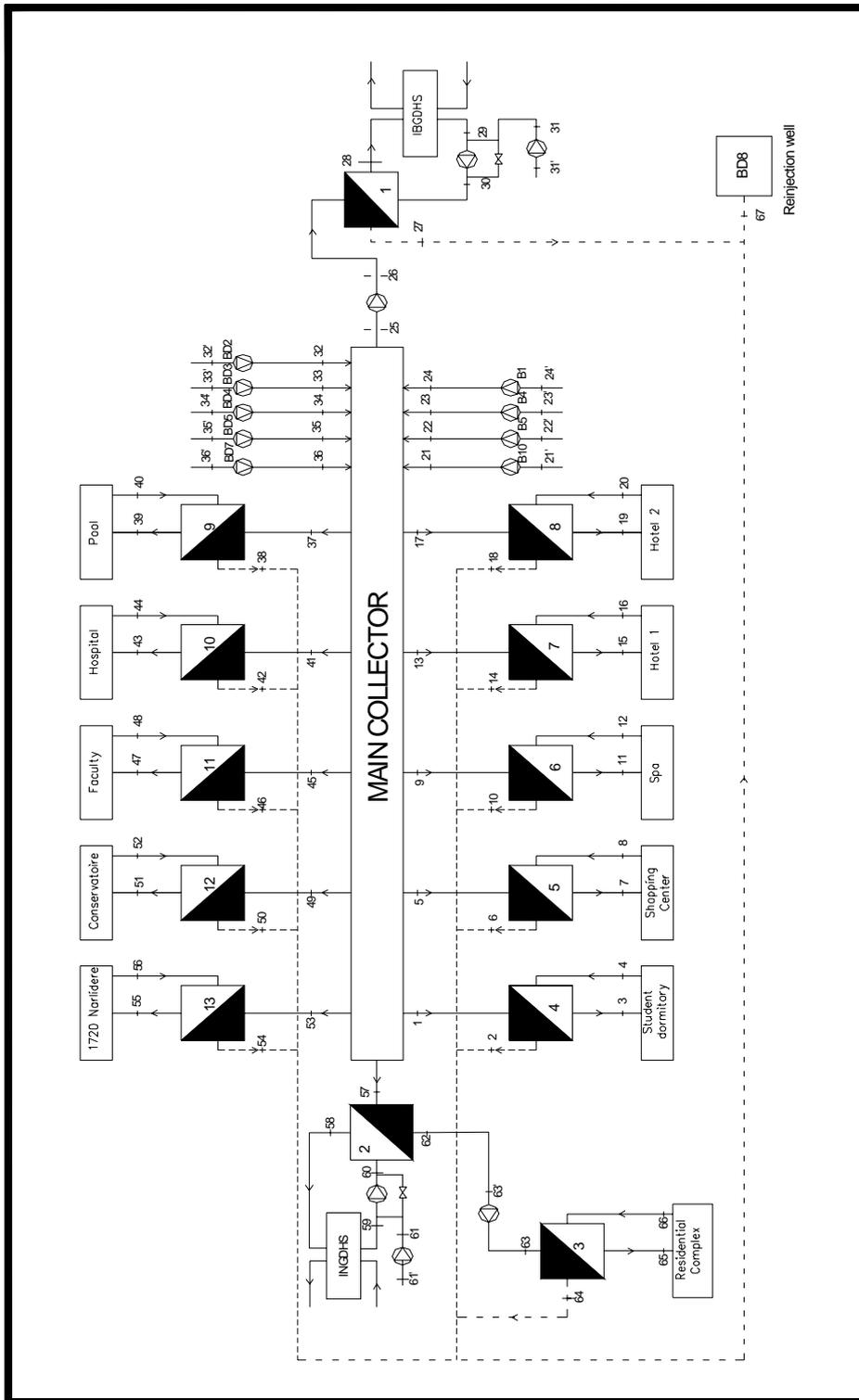


Figure 1. Schematic diagram of the BGDHS (Orgener et al., 2005b).

An instructive parameter is the ratio  $R$  of thermodynamic loss  $L$  to capital cost  $K_g$  (Rosen, 1990; Rosen and Dincer, 2003a,b). The capital cost is defined here using the cost balances in Eq. (4). The value of  $R$  generally depends on whether it is based on energy loss rate in which case it is denoted  $R_{en}$ , or exergy loss rate in which case it is denoted  $R_{ex}$ :

$$R_{en} = \dot{L}_{en} / K_g \quad (17)$$

and

$$R_{ex} = \dot{L}_{ex} / K_g \quad (18)$$

Here, the values of the parameter  $R$  based on energy loss rate, and on total, internal and external exergy loss rates are considered.

## RESULTS AND DISCUSSION

The results are now presented of a practical energy and exergy analysis of the system, using a realistic reference temperature set to the actual average local temperature rather than the standard environment temperature. In particular, we investigate the energy and exergy losses in the system at this practical reference temperature. The results are presented in Table 1 where are shown, for several devices comprising the geothermal district heating system and for the overall system, capital costs, thermodynamic losses based on energy and exergy, and loss-to-capital-cost ratios based on energy and exergy. The costs shown in Table 1 are in 2004

American dollars. The 2004 US–Turkish exchange rate was used to convert the Turkish costs to American dollars.

Here, 11.4°C was selected as reference environment temperature and represents the average ambient temperature data in Izmir on January 2 for the years 2000-2004 (Ozgener et al., 2005c). For analysis purposes, the actual data were taken from the BGDHS and the respective thermodynamic properties were obtained based on these data. Note that the number of wells in operation in the Balçova geothermal field may vary depending on the heating days and operating strategy (Ozgener et al., 2004a). The energy and exergy efficiencies of the BGDHS are determined to be 37.6% and 42.9%, respectively (Ozgener et al., 2004). The loss-to-capital-cost ratio based on exergy,  $R_{ex}$ , for the overall BGDHS is about 0.45.

The highest exergy loss of 24.1% is attributable to direct discharges from the system due to significant water leaks. This exergy loss also includes exergy destructions in the primary and secondary fluid networks, which were not separated out in this study. The second largest exergy destruction is associated with the thermal reinjection and makes up 22.7% of the total exergy input, which corresponds to about 2077 kW. This is followed by the total exergy destruction associated with the pumps and heat exchangers, which amount to some 943.3 kW and represent 10.5% of the total exergy input to the system.

Table 1

*Device parameter values for the BGDHS (using 2004 USD)*

Devices	$K$ ( $10^3$ US\$)	$\dot{L}_{en}$ (kW)	$R_{en}$ (kW/US\$)	$\dot{L}_{ex}$ (kW)	$R_{ex}$ (kW/US\$)
Balçova heat exchangers	1,456.5	50,364	34.58	618.54	0.42
Narlıdere heat exchangers	164.554	5,800	35.25	79.21	0.48
Well pumps (B10, B5, B4, BD2, BD3, BD4, BD5, BD7)	962.728	580	0.60	155.57	0.16
Balçova pumps (circulating pumps + booster pumps, etc.)	335.346	680	2.03	59.64	0.18
Narlıdere pumps (circulating pumps + Çağlayan booster pump)	33.780	52	1.54	20.27	0.60
Thermal line	8,150.377	14,483.81	1.78	4,129.21	0.51
Overall system (Balçova + Narlıdere heat centers)*	11,132.748	71,959.81	6.46	5,062.4	0.45

\*Including some miscellaneous equipment (e.g., valves, insulation)

The results in Table 1 show that the loss-to-capital-cost ratios based on energy for the devices comprising the geothermal district heating system and for the overall system, vary much more greatly than the loss-to-capital-cost ratios based on exergy. This observation is consistent results from earlier studies for power plants (Rosen, 1990; Rosen and Dincer, 2003a,b). The results suggest that a good design, in terms of balancing efficiency with cost, occurs when the loss-to-capital-cost ratios based on exergy for the devices comprising the geothermal district heating system approach the loss-to-capital-cost ratios based on exergy for the overall system. This is certainly not true for the the loss-to-capital-cost ratios based on energy.

More generally, it appears for any technology that the design may be made more successful if the overall system and its component parts are modified so that the value for each of  $R_{ex}$  approaches an “appropriate” value of  $R_{ex}$ . A balance is obtained between exergy loss and capital cost in real systems, and it is felt by the authors that these systems, through trial and error and other means, have achieved an appropriate combination of exergy loss and capital cost for the situation in which they exist. If successful technologies conform to an appropriate  $R_{ex}$ , then it follows that technologies which fail in the marketplace may do so because they deviate too far from the appropriate  $R_{ex}$ .

As can be seen in Table 1, the greatest potential for improvement and optimization is probably in the following BGDHS components: thermal line (pipes and other auxiliaries), heat exchangers and pumps.

In geothermal district heating systems, the temperature difference between the geothermal resource and the supply temperature of the district heating distribution network plays a key role in terms of exergy losses. The district heating supply temperature is determined bearing in mind the following criterion: “increasing the supply temperature will result in a reduction of investment cost for the distribution system and the electrical energy required for pumping stations while causing an increase of heat losses in the distribution network”. Further details are provided by Ozgener et al. (2005c). The work discussed in this paper can likely be extended to marginal costs. Here, the marginal cost would be the cost increase resulting from saving one unit of energy or exergy (i.e., from reducing the energy or exergy loss by one unit). The results would be expected to indicate for many devices that marginal costs based on exergy have similar values, while marginal costs based on energy vary widely.

## CONCLUSIONS

The primary exergy destructions in the GDHS system are attributable to the thermal line, the heat exchangers, and the pumps. It has been shown how the use of simple thermoeconomic optimization methods on GDHSs could contribute to determining the correct design of new equipment, especially by ensuring that value of  $R_{ex}$  for the equipment approaches an appropriate value of  $R_{ex}$ . A balance is obtained between exergy loss and capital cost in real systems. If successful technologies conform to an appropriate  $R_{ex}$ , then it follows that technologies which fail in the marketplace may do so because they deviate too far from the appropriate  $R_{ex}$ . This value is determined here to be found about 0.45 for the BGDHS. The appropriate  $R_{ex}$  value varies between 0.36-0.55 for the BGDHS as reference state temperatures varies from 0°C to 25°C. This exergoeconomic analysis of geothermal district heating systems indicates the main causes of exergy destruction in the systems occur in the thermal line, heat exchangers and pumps. The use of simple exergoeconomic optimization methodologies in geothermal district heating systems could contribute to determining the correct design of new equipment and to improving existing equipment and systems through retrofits.

## ACKNOWLEDGEMENTS

The authors acknowledge the support provided by Ege University, University of Ontario Institute of Technology, the Natural Sciences and Engineering Research Council of Canada, as well as the Turkish companies which provided some technical and operation data.

## NOMENCLATURE

$\dot{E}$	energy rate (kW)
$\dot{E}_x$	exergy rate (kW)
$h$	enthalpy (kJ/kg)
$K$	capital cost (US\$)
$\dot{L}$	thermodynamic loss rate (kW)
$\dot{m}$	mass flow rate (kg/s)
$R$	ratio of thermodynamic loss rate to capital cost (kW/US\$)
$s$	entropy (kJ/kgK)
$T$	temperature (°C)
BGDHS	Balcova geothermal district heating system

IBGDHS Izmir Balcova geothermal district heating system  
 INGDHS Izmir Narlidere geothermal district heating system

Subscripts

*a* accumulation  
*d* discharge  
*en* energy loss  
*ex* exergy loss  
*g* generation  
*HE* heat exchanger  
*i* input, successive number  
*o* output  
*r* re-injection  
*w* well  
*Tot* total

*Greek letters*

$\eta$  energy efficiency (-)  
 $\varepsilon$  exergy efficiency (-)

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