Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

MODELLING AND ASSESSMENT OF GROUND-SOURCE HEAT PUMP SYSTEMS USING EXERGOECONOMIC ANALYSIS FOR BUILDING APPLICATIONS

Onder Ozgener[1], Arif Hepbasli[2,**], Ibrahim Dincer[3,*], and Marc A. Rosen[3]

[1] Solar Energy Institute, Ege University, 35100 Bornova, Izmir, Turkey
[2] Department of Mechanical Engineering, Faculty of Engineering, Ege University, 35100 Bornova, Izmir, Turkey
[3] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

ABSTRACT

Ground source heat pumps (GSHPs) are modelled, analyzed based on exergy, cost, energy and mass, and evaluated exergoeconomically. In this regard, the system considered here is a GSHP heating system with a 50 m vertical U-bend ground heat exchanger having a 32 mm nominal diameter. This system was designed and installed at the Solar Energy Institute, Ege University, Izmir, Turkey. The results show that the major losses take place in the motor–compressor subassembly due to poor isentropic efficiency, in the condenser of the GSHP unit due to temperature drop, and-in the capillary tube due to pressure drop. The evaporator is responsible for the lowest irreversibility of the units comprising the heat pump cycle.

INTRODUCTION

Enhanced plant-growth conditions can be achieved using greenhouses. A greenhouse protects plants by creating a favorable environment, allowing effective use of soil, and helping control sanitary conditions for plants. From an economic point of view, the main objective of horticultural greenhouses is to extend the normal season production or to attain production off-season, when crop prices are typically higher. Many variables must be controlled in order to provide good environmental conditions. The most important parameters to be controlled inside a greenhouse are temperature, humidity and light (Albright, 1991). The night temperature is an especially important variable. Although different species are cultivated in greenhouses, a common requirement is usually the avoidance of low temperatures at night. The conventional solution for this problem is the burning of fossil fuel inside the greenhouse at night, particularly during the dangerous condition when temperatures are below freezing. Where fuel prices are high, this option is very expensive, but it is necessary when the alternative is the complete loss of plants. The energy consumed for greenhouse heating depends on season and daily climatic conditions. Solar energy gain normally permits greenhouses not to be heated during days, unless they are sufficiently cold.

The climatic conditions of the region are the prime factors that affect plant development and the economics of greenhouse production. It normally is necessary to heat greenhouses when the temperature goes below 12°C in order to obtain high quality and high yield crops, which are especially important for export purposes (Zabeltitz, 1992).

Greenhouses provide an important economic contribution in Turkey. To establish optimum growth conditions in greenhouses, heating is necessary at times and it is desirable for many reasons to utilize renewable energy sources as much as possible. Solar energy gain is sufficient during many days, but greenhouses usually need supplemental heating during nights and cold days. Despite Turkey's geothermal energy potential, the use in that country of geothermal energy in heating greenhouses is very low. At present, it is estimated that only 35.7 ha of greenhouses are heated by geothermal energy in Turkey, although the country has a total greenhouse area of 22,000 ha. The majority of the geothermal greenhouse applications are in the western part of Turkey and heating capacity ranges from 3.0 million kJ/h to 103 million kJ/h. Effective use of heat pumps will likely play a lead role in heating modern greenhouses in Turkey in the future (Ozgener and Kocer, 2004).

Ground-source heat pumps (GSHPs), often refered to as geothermal heat pumps (GHPs), provide space heating and cooling and water heating with relatively high efficiency. The efficiency of these systems may be evaluated using energy and exergy analyses.

In recent years, various exergy-based economic analysis methodologies (e.g., exergoeconomics,

* Corresponding author: Ibrahim.Dincer@uoit.ca (I. Dincer).
** Currently a visiting professor in the Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada.

thermoeconomics, second-law costing,) have been applied by many investigators (e.g., Rosen and Dincer, 2003a,b). Exergoeconomic analysis has been used to optimize thermal systems (e.g., Rosen and Dincer, 2003a,b). Among these, EXCEM (exergy, cost, energy and mass) analysis, proposed by Rosen and Scott (1987) and utlized recently by Rosen and Dincer (2003a,b), can be useful to investigators in engineering and other disciplines. The methodology provides a comprehensive assessment by accounting for the quantities exergy, cost, energy and mass.

As pointed out earlier (e.g., Rosen and Dincer, 2003a,b; Dincer, 2003), cost accounting for energy conversion devices conventionally considers unit costs based on energy. Researchers have developed methods of performing economic analyses based on exergy. These analysis techniques have some common characteristics: (i) they combine exergy and economic disciplines to improve or optimize economic performance, 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.

Although many studies have been undertaken by many researchers for thermoecomomic analysis of a wide range of thermal systems (e.g., power plants), to the best of the authors' knowledge the only report in the open literature of a thermoeconomic analysis for performance evaluation and improvement of a GSHP for greenhouse heating is that of Ozgener and Hepbasli (2005c). That work provided the motivation for the present work, in which the authors apply a type of exergoeconomic analysis (Rosen and Scott, 1987; Rosen and Dincer, 2003a,b) to a GSHP. The relations between thermodynamic losses and capital costs for devices are investigated.

SYSTEM DESCRIPTION

The experimental solar-assisted ground source heat pump (SAGSHP) for greenhouse heating considered in the present study is illustrated in Fig. 1. The system consists of three separate circuits: (i) the ground coupling circuit with a solar collector (i.e., the brine or water-antifreeze solution circuit), (ii) the refrigerant circuit, which includes a vapour-compression system that can operate in forward or reversed modes, and (iii) the fan-coil circuit for greenhouse heating (i.e., the water circuit). The main characteristics of the solar-assisted ground source heat pump system are given in more detail elsewhere (Ozgener and Hepbasli, 2005a-d). Conversion from the heating cycle to the cooling cycle is obtained by means of a four-way valve. To avoid water freezing during the winter and other cold periods, a 10% ethyl glycol mixture by weight is used. The refrigerant circuit is a closed loop and utilizes copper tubing. The working fluid is R-22. The SAGSHP system studied was installed at Solar Energy Institute of Ege University (latitude 38^o 24' N, longitude 27^o 50' E), Izmir, Turkey. The solar greenhouse faces south. The greenhouse is environmentally conditioned during the summer and winter seasons according to the type of agricultural products being grown.

MODELLING AND ASSESSMENT

Here, we apply the model and assessment methodology outlined earlier by Rosen and Dincer (2003a,b) to a GSHP greenhouse heating system (Ozgener and Hepbasli, 2005d). Actual local cost data are used. The exergetic equivalents of the capital and labour costs have been evaluated based on data available for Turkey.

Balances are written for mass, energy and exergy flows in the system and its components. The overall system and components are considered to be control volumes in which steady-state steady-flow processes occur. Appropriate energy and exergy expressions are developed for the overall system and its components. The analysis of the SAGSHP system is partly described in this paper. A more detailed description of the system, and how corresponding energy and exergy calculations are performed, can be found elsewhere (e.g., Ozgener, 2005a-d).

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

$$\dot{m}_i - \dot{m}_o = \dot{m}_a \tag{1}$$

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.

Like mass, energy is subject to a conservation law (neglecting nuclear reactions) and can be neither generated nor consumed. Exergy is subject to a non-conservation law and can be consumed during a process due to irreversibilities. Consequently, rate balances for energy and exergy, respectively, can be written as

$$\dot{E}_i - \dot{E}_o = \dot{E}_a \tag{2}$$

$$\dot{E}x_i - \dot{E}x_o - \dot{L}_{ex} = \dot{E}x_a \tag{3}$$

where *E* denotes energy, *Ex* exergy and *L* loss. The balance equation for cost, a non-conserved quantity, can be written as

$$K_i + K_g - K_o = K_a \tag{4}$$

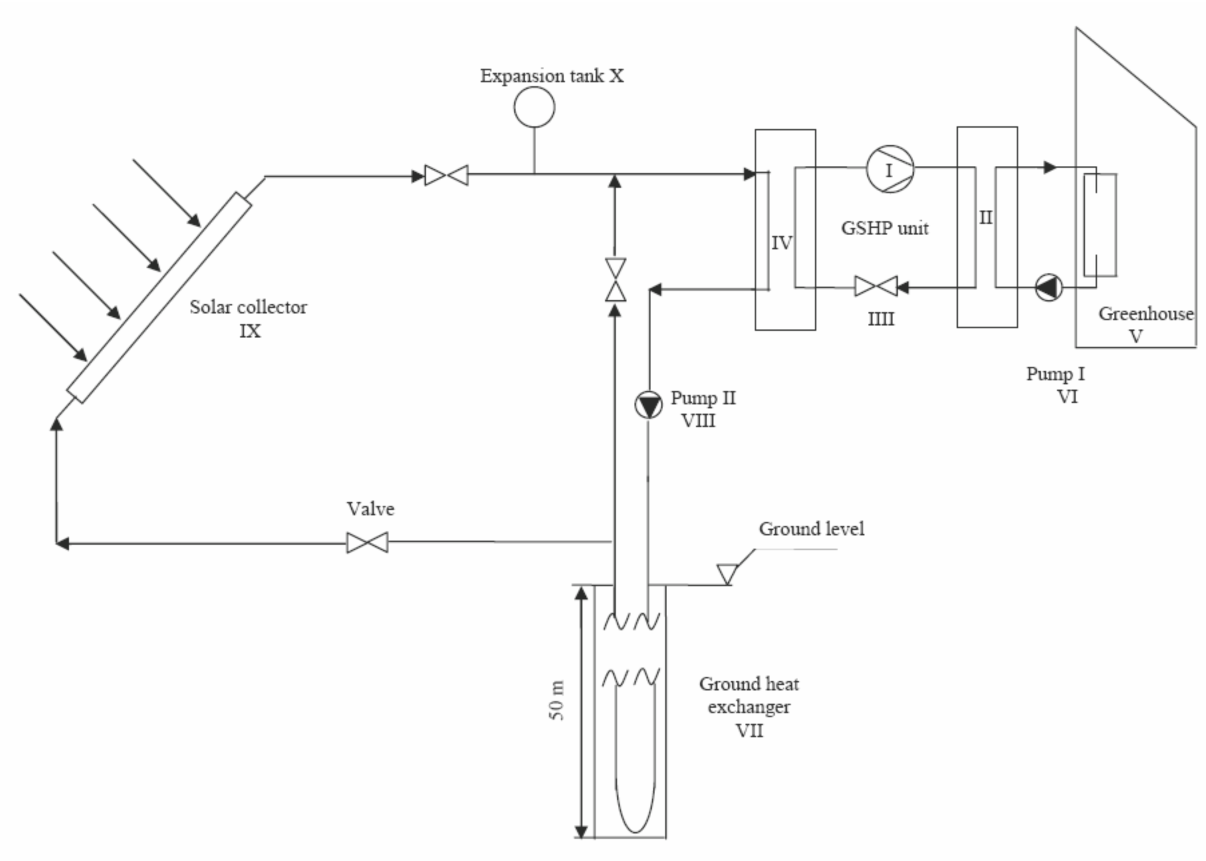

Figure 1 Schematic diagram of the experimental solar-assisted ground source heat pump for greenhouse heating (Ozgener and Hepbasli, 2005b).

where K denotes cost and the subscript g denotes generation.

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 balance in Eq. (3), and are of two types: external (i.e., the loss associated with exergy that is emitted from the system, or waste exergy output) and internal (i.e., the exergy losses within the system due to process irreversibilities, or exergy consumption). These two exergy losses sum to the total exergy loss. The loss rate based on exergy is denoted $\dot{L}_{ex}$.

The exergy rate is calculated with the following expression

$$\dot{E}x = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \quad (5)$$

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

$$\dot{L}_{ex,HE} = \dot{E}x_{dest,\,HE} = Ex_i - \dot{E}x_o = \dot{E}x_{dest} \quad (6)$$

$$\dot{L}_{ex,\,pump} = \dot{E}x_{dest,\,pump} = \dot{W}_{pump} - \left(\dot{E}x_o - \dot{E}x_n\right) \quad (7)$$

The energy (or first law) efficiency of the heat pump unit is termed a coefficient of performance (COP_{HP}). This coefficient of performance, as well as that for the overall heat pump system (COP_{sys}), can be defined respectively as follows:

$$COP_{HP} = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \quad (8a)$$

$$COP_{sys} = \frac{\dot{Q}_{cond}}{\dot{W}_{comp} + \dot{W}_{pumps} + \dot{W}_{fc}} \quad (8b)$$

Expressions for exergy efficiency (second law efficiency) can be formulated in different ways and with different meanings. Some examples of alternative exergy-based efficiencies are effectiveness and rational efficiency). Such efficiencies are described in the literature in detail. The exergy efficiency for a general system can be written as follows:

$$\varepsilon_{sys} = \frac{\dot{E}x_o}{\dot{E}x_i} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_i} \qquad (9)$$

The exergy efficiency of a GSHP unit can be evalulated as

$$\varepsilon_{HP} = \frac{\dot{E}x_{heat}}{\dot{W}_{act,i}} = \frac{\dot{E}x_{i,cond} - \dot{E}x_{o,cond}}{W_{act,i}} \qquad (10)$$

The exergy efficiency of the heat exchangers (condenser and evaporator) 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:

$$\varepsilon_{HE} = \frac{\dot{m}_{cold}\left(\psi_{cold,o} - \psi_{cold,i}\right)}{\dot{m}_{hot}\left(\psi_{hot,i} - \psi_{hot,o}\right)} \qquad (11)$$

The exergy efficiency of the circulating pumps can be determined as

$$\varepsilon_{pump} = \frac{\dot{E}x_o - \dot{E}x_i}{\dot{W}_{pump}} \qquad (12)$$

The ratio R of thermodynamic loss L to capital cost K_g is a significant parameter (Rosen and Scott, 1987; Rosen and Dincer, 2003a,b). The capital cost is defined here using the cost balance in Eq. (4) and is denoted by K_g. The value of R generally depends on whether it is based on energy loss rate (R_{en}) or exergy loss rate (R_{ex}):

$$R_{en} = \frac{\dot{L}_{en}}{K_g} \qquad (13)$$

and

$$R_{ex} = \frac{\dot{L}_{ex}}{K_g} \qquad (14)$$

Here, the values of R based on energy and exergy loss rates are considered.

RESULTS AND DISCUSSION

The results are presented in Table 1 where are shown, for several devices comprising the solar-assisted ground source heat pump 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 in Table 1 are in 2004 U.S. dollars and were obtained based on the 2004 Turkish-$US exchange rate. Here, the reference state for the SAGSHP is considered to be 10.93°C, and the atmospheric pressure is taken to be 101.32 kPa. These values were selected so that the system assessment would be based on a realistic energy and exergy analysis approach; these values have been measured at the time when the SAGSHP system data were obtained during the experimental period.

In the analysis, thermodynamic quantities were obtained using actual data from the experimental set up. The coefficient of performance (COP) and exergy efficiency of the overall system were determined to be 2.38 and 67.7%, respectively. The loss-to-capital-cost ratio based on exergy, R_{ex}, for the overall SAGSHP is about 0.30.

The sources of exergy destruction in the system include the compressor, greenhouse, heat exchanger (ground heat exchanger, condenser and evaporator), circulating pumps and solar collector. The highest irreversibility is seen in Table 1 to occur in the compressor (device I) and greenhouse (device V). More specifically, the losses in the motor-compressor subassembly are due to the electrical, mechanical and isentropic inefficiencies and emphasize the need for paying close attention to the selection of this type of equipment, since components of inferior performance can considerably reduce the overall performance of the system. The second largest irreversibility in the GSHP unit is in the condenser. This is partly due to the large degree of superheat achieved at the end of the compression process, leading to large temperature differences associated with the initial phase of heat transfer. The third highest irreversibility is in the capillary tube due to the pressure drop of the refrigerant passing through it. The evaporator has the lowest irreversibility of the heat pump components. Table 1 suggests that the greatest potential for efficiency improvement is likely in the compressor and its components.The values of the ratio of thermodynamic loss rate to capital cost are seen in Table 1 to range from 0.05 to 1.49. The greatest potential for improvement, by balancing thermodynamic losses and capital costs, probably lies in the compressor, pump II and condenser, followed by pump I and the greenhouse. The exergy loss rates for the system devices range from 0.010 kW to 0.480 kW. As expected, the largest energy and exergy losses occur in the greenhouse and compressor.The results in Table 1 show that the loss-to-capital-cost ratios based on energy for the devices comprising the solar-assisted ground source heat pump 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 (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 loss-to-capital-cost ratios based on energy. More generally, it appears for any technology that the design of a device may be made more successful if the overall system and its component parts are modified so that the value of R_{ex} approaches an appropriate value of R_{ex}. A balance is obtained between exergy loss and capital cost in real systems. The authors believe that these systems have over time achieved a balance of exergy loss and capital cost that is appropriate to the circumstances. 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}.

Table 1

Device parameter values for the SAGSHP greenhouse heating system (based on US dollars).

Device no.	Device	K (USD)	L_{en} (kW)	R_{en} (kW/USD)	L_{ex} (kW)	R_{ex} (kW/USD)
I	Compressor	302	0	0	0.450	1.49
II	Condenser	553	0	0	0.220	0.39
IV	Evaporator	553	0	0	0.140	0.25
V	Greenhouse	2000	3.977	1.988	0.480	0.24
VII	Heat exchanger pipe	859	0	0	0.040	0.05
VI, VIII	Pumps (I-II)	244	0	0	0.078	0.32
IX	Solar collector	183	0	0	0.010	0.05
	Overall system	*4694*	*3.977*	*0.85*	*1.418*	*0.30*

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 that marginal costs based on exergy for many devices have similar values, while marginal costs based on energy vary widely.

Actual thermal data from the system are utilized to carry out a system performance evaluation including determinations of energy and exergy efficiencies. Moreover, the exergy destructions (representing the losses) in the overall system are quantified and illustrated. This system has been satisfactorily operated without any serious difficulties during the 2003/2004 heating season. The energy and exergy analysis results also show that the independent central heating operation cannot overcome the overall heat loss of greenhouse and the increasing destroyed exergy if the ambient temperature is very low (Ozgener and Hepbasli 2005a-d). An integrated dual operation can be suggested as a best solution in the Mediterranean and Aegean regions of Turkey, if peak load heating can be easily controlled.

CONCLUSIONS

In the paper, an exergoeconomic analysis has been used to determine the optimal design of the compressor and condenser to be used in a conventional vapour-compression heat pump. Particular attention must be given to improving energy savings of SAGSHP system due to the increasing influence such systems are having in global energy consumption.

An exergoeconomic analysis has been applied to a ground source heat pump and shows how the use of exergoeconomic methodologies could contribute to determining the \correct design of equipment in a solar-assisted ground source heat pump system. It is expected that the results may (i) provide useful insights into the relations between thermodynamics and economics, both in general and for SAGSHP systems for building applications, and (ii) help demonstrate the merits of exergy analysis.

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, and the Turkish

companies which provided some technical and operation data.

NOMENCLATURE

COP	heating coefficient of performance of heat pump (-)
$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
h	specific 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	specific entropy (kJ/kg K)
T	temperature (ºC)
GSHP	ground source heat pump
SAGSHP	solar-assisted ground source heat pump
Greek letters	
ε	exergy (or second law) efficiency (%)
ψ	specific exergy rate (kW/kg)
Subscripts	
a	accumulation
act	actual
cond	condenser
comp	compressor
dest	destroyed
en	energy
ex	exergy
fc	fan coil
g	generation
HP	heat pump
HE	heat exchanger
i	input
o	output
sys	system
0	restricted state

REFERENCES

Albright, L.D. 1991. Production Solar Greenhouses. In: *Solar Energy in Agriculture*, Ed. B.F. Parker, *Elsevier*, pp. 213-229.

Dincer, I. 2003. On Energy Conservation Policies and Implementation Practices. International Journal of Energy Research Vol. 27(7), pp. 687-702.

Ozgener, O., Kocer, G. 2004. Geothermal Heating Applications. Energy Sources Vol. 26(4), pp. 353-360.

Ozgener, O., Hepbasli, A. 2005a. Experimental Performance Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System. Energy and Buildings Vol. 37(1), pp. 101-110.

Ozgener, O., Hepbasli, A., 2005b. Experimental Investigation of the Performance of a Solar Assisted Ground-Source Heat Pump System for Greenhouse Heating. International Journal Energy Research Vol. 29, pp. 217-231.

Ozgener, O., Hepbasli, A., 2005c. Performance Analysis of a Solar Assisted Ground-Source Heat Pump System for Greenhouse Heating: An Experimental Study. Building and Environment Vol. 40, pp. 1040-1050.

Ozgener, O., Hepbasli A., 2005d. Exergoeconomic Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System. Applied Thermal Engineering Vol. 25, pp. 1459-1471.

Rosen, M.A., Dincer, I. 2003a. Exergoeconomic Analysis of Power Plants Operating on Various Fuels. Applied Thermal Engineering, Vol. 23, pp. 643–658.

Rosen, M.A., Dincer, I. 2003b. Thermoeconomic Analysis of Power Plants: An Application to a Coal-Fired Electrical Generating Station. Energy Conversion and Management Vol. 44, pp. 1633–1651.

Rosen, M.A., Scott, D.S. 1987. A Methodology based on Exergy, Cost, Energy and Mass for the Analysis of Systems and Processes. *Proc. Meeting of Int. Soc. for General Systems Research*, 20-22 May, Toronto, pp. 8.3.1-8.3.13.

Zabeltitz, C. 1992. Energy Efficient Greenhouse Designs for Mediterranean Countries. Plasticulture, No: 96.