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Exergoeconomic optimization and environmental analysis of a novel solar-trigeneration system for heating, cooling and power production purpose

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ABSTRACT

In the present article attempt is made to develop an exergoeconomic optimization model to integrate solar energy into trigeneration system producing electricity, heating and cooling according to the exergetic, economic and environmental targets. The results show that by selecting final optimum solution for the trigeneration system, the unit cost of products reduced by 11.5% and exergy efficiency increased from 44.38% in the base case to 56.07% in the optimum case. The application of optimization process shows that exergoeconomic analysis improved significantly the total performance of the trigeneration system in a way that fuel cost, exergy destruction cost and environmental impacts (CO_2 emissions cost) are reduced by 24.17%, 38.87% and 24.17%. Finally, sensitivity analysis is carried out to examine the effect of changes in the trigeneration Pareto optimal solutions and the unit cost of products to the important economic parameters, such as interest rate, fuel cost, system operation period, and construction period.

1. Introduction

Providing different kinds of energy has become the mainstream application of distributed generation systems during the last decades. The proven advantages of cogeneration technology made it useful mainly in large-scale industrial plants and later on commercial or even resident buildings. Most recent advances, allow the investment on trigeneration systems that produce electricity, heat and cooling, utilizing the primary energy of a fuel even more efficiently, economically, reliably and with less harm to the environment than centralized dedicated production (Wu and Wang, 2006). Trigeneration, by means of the simultaneous production of electricity, heat and refrigeration from a primary source of energy, such as natural gas or bio-fuel, is a natural extension of cogeneration systems. From a strictly thermodynamic viewpoint, a trigeneration system is simply a traditional combined heat and power (CHP) system plus an absorption and/or a vapor compression chiller. However, the advantages of trigeneration, such as primary energy savings and greater overall efficiency attracted researchers and the construction community (Ziher and Poredos, 2006; Lin et al., 2007; Piacentino and Cardona, 2008; Lozano et al., 2009). In a trigeneration plant, the waste energy from the plant's prime mover, such as a gas turbine, is used to drive both the heating and cooling systems. Therefore, the use of a trigeneration system results in an improvement of the overall thermal efficiency and thus a reduction of the contamination to the environment.

The solar energy can be used directly to obtain electrical power through photovoltaic solar cells or to obtain thermal heat and then generate electrical power through a power cycle. There is a considerable increase in the number of power plants operated partially or completely by solar energy. Integrated Solar Combined Cycle System (ISCCS) using parabolic trough solar collectors (PTSC) is the one of the potential subsystems that can be used in trigeneration plants for the cooling, heating and electrical power productions. A general energy and exergy analysis on the ISCCS using the design plant data was conducted by Baghernejad and Yaghoubi (2010a). In their research, performance assessment of ISCCS is made through energy and exergy efficiencies, exergetic improvement potential, as well as some other thermodynamic parameters. A comprehensive review of trigeneration plants based on prime movers is given by Al-Sulaiman et al. (2011b). In their investigation, it is shown that a significant number of studies are conducted on trigeneration systems that are based on internal combustion engines as prime movers, but there are fewer studies on solar energy, gas turbines and microturbines as the prime movers. Baghernejad et al. (2015)

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Nomenclature

A_{ap}	aperture area (m^2)
A_r	area of receiver (m^2)
C	specific heat (kJ/kg K)
$\dot{C}$	cost rate ($/h)
c	cost per exergy unit ($/kW h)
CP	construction period (year)
D	diameter (m)
$\dot{E}x$	exergy rate (MW)
F_R	heat removal factor
f	annuity factor
H	operation period (h)
h	specific enthalpy (kJ/kg)
I	equipment investment ($)
I_b	solar radiation (W/m^2)
in	interest rate (%)
k	thermal conductivity (W/m), amortization factor (year)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar)
P_r	pressure ratio
Q	heat (kJ)
$r_{el/h}$	ratio of electricity to heating
$r_{el/c}$	ratio of electricity to cooling
S	absorbed radiation by the receiver (W/m^2)
T	temperature (K)
U_L	overall heat loss coefficient of the solar collector (kW/m^2 K)
w	collector width (m)
$\dot{W}$	electrical power (MW)
$\dot{Z}$	investment cost rate ($/h)

Greek symbols

η	isentropic efficiency
η_{ex}	exergetic efficiency
ρ	mirror reflectivity, density (kg/m^3)
α	HCE absorptivity
ε	HCE emittance
τ	HCE transmittance
φ	maintenance factor

Subscripts

1, 2, ..., 56	state points
D	destruction
f	fuel
i	inlet
k	Kth component
o	outlet, ambient
tot	total

Acronyms

ABS	absorber
AC	air compressor
BFP	boiler feed pump
CC	combustion chamber
CEP	condensate extraction pump
COND	condenser
DEA	dearator
ECO	economizer
EVAC	evaporator of cooling cycle
EVAH	high pressure evaporator
EVAL	low pressure evaporator
GEN	generator
GT	gas turbine
HCE	heat collection element
HTF	heat transfer fluid
HPU	heating process unit
HRSG	heat recovery steam generator
ISCCS	integrated solar combined cycle system
MOEA	multi-objective evolutionary algorithm
OILP	oil pump
ORC	organic rankine cycle
PTSC	parabolic trough solar collector
REV	refrigerant expansion valve
SAE	solar auxiliary evaporator
SEV	solution extraction valve
SHE	solution heat exchanger
SOFC	solid oxide fuel cell
SP	solution pump
ST	steam turbine
tri	trigeneration

introduced a new integrated SOFC-trigeneration system with the aim of producing electricity, heating and cooling. Modeling and exergoeconomic optimization of the system is carried out to determine the optimum decision parameters, accounting for exergetic, economic and environmental factors. Their study revealed that there was a significant saving in energy, increase in efficiency, as well as reduction in CO_2 emissions.

In the literature, a few researches carried out on trigeneration plants using solar energy as prime movers. An energy examination on system thermodynamic parameters such as coefficient of performance and prime mover thermal efficiency for a trigeneration pilot plant set up in an office building carried out by Marques et al. (2010). Their work is in no way comprehensive, but thermal engineers may find the method for sizing and choosing thermal equipment for buildings and other trigeneration systems. A biomass and solar integrated system for multigeneration, in which two renewable energy sources are combined to produce multiple outputs (e.g., power, cooling, hot water, heated air), is developed to assess the performance of the cycle, and the effects of various system parameters on energy and exergy efficiencies of the overall system and its subsystems in Khalid et al. (2015). Energy and exergy analyses of a new combined system, using solar and geothermal resources, for hydrogen production, along with power generation, cooling and heating is proposed and analyzed to assess the performance of the overall system by Bicer and Dincer (2016). Their results show that the overall energy and exergy efficiencies of the system can reach up to 10.8% and 46.3% respectively for a geothermal water temperature of 210 °C. Furthermore, the effects of varying geothermal water temperature and using different type of working fluids on the system performance are investigated. Al-Sulaiman et al. (2011a) conducted an exergy modeling to assess exergetic performance of a trigeneration system using PTSC and an Organic Rankine Cycle (ORC) considering three modes of operation including solar, solar and storage, and storage modes. Their result reveals that solar mode has the highest exergy efficiency as compared with the other two modes. Also, they showed that the main sources of exergy destruction rate in the system are the solar collectors and ORC evaporators. Calise (2011) investigated the integration of SOFC systems with solar thermal collector to design and make a dynamic simulation of a novel polygeneration system producing: electricity, space heating and cooling and domestic hot water. The system evaluated is extremely efficient and flexible from a thermodynamic point of view but future commercialization of these prototypes is found to be possible in case of dramatic reduction of SOFC capital cost and/or in the presence of an effective funding policy. It is showed that the selection of a