Energy and Buildings 60 (2013) 330–344

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Application of the multi-objective optimization and risk analysis for the sizing of a residential small-scale CCHP system

Gholamhossein Abdollahi, Hoseyn Sayyaadi*

Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis Str., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form
29 December 2012
Accepted 20 January 2013

Keywords:
CCHP system
Multi-objective optimization
Thermoeconomics
Exergetic analysis
Environmental impact
Availability and risk analysis
Decision-making

ABSTRACT

Multi-objective optimization for sizing of a small-scale combined cooling, heating, and power generation (CCHP) system is performed. In multi-objective optimizing the s CCHP system, the three objective functions including the exergetic efficiency, total levelized cost rate of the system product and the cost rate of environmental are optimized, simultaneously. The environmental impact and thermoeconomic objective are minimized while the exegetic objective is maximized. A comprehensive emission assessment framework suitable for addressing of distributed cogeneration systems is formulated according to an electrical output-based emission factor approach and the environmental impact objective function are defined and expressed in cost terms. The economic analysis is conducted in accordance with the total revenue requirement (*TRR*) method. The genetic algorithm is applied to find the set of Pareto optimal solutions with respect to the aforementioned objective functions. In the present work, reliability and availability are introduced in the developed models of the system, so that redundancy is embedded in the optimal solution. In this regard, risk analysis is used as a decision-making tool for the selection of the final optimal solution from the obtained Pareto optimal frontier. The sensitivity of the optimal solution respect to variations of input parameters is analyzed.

1. Introduction

The adoption of cogeneration or combined CCHP systems for small-scale applications (below 1 MWe) is one of the key drivers to the diffusion of thermal prime movers for distributed generation [1]. CCHP systems are effective in reducing the primary energy consumption with respect to conventional separate producing heat (produced in boilers), electricity (produced in power plants) and cooling (produced in absorption chillers) [2]. The evolution of the energy generation scenario envisages a deeper penetrating CCHP system in urban areas, where local emissions of hazardous air pollutants such as NO_x, CO, may pose serious concerns [3,4]. The complexity of issues involved in environmental assessments of distributed energy systems in urban fabrics calls for adequate approaches and methodologies. The optimization of small-scale combined cooling, heating, and power generation (CCHP) systems is one of the most important subjects in the energy engineering field. Because of the high prices of energy and decreasing of fossil fuel resources, the optimum application of energy and the energy consumption management methods are very critical.

Analysis and optimization of energy systems including CCHPs can be performed with several aspects such as exergetic, economic, environmental and so on. Exergy analysis that is developed based on the first and second laws of the thermodynamics is a significant tool to analyze the energy systems. On the other hand, the second law of thermodynamics deals with the quality of energy and determines the maximum amount of work obtainable from an energy resource. In this regard, exergetic optimization reveals minimizing thermodynamic inefficiency through energy systems. This may cause additional capital cost since a higher efficiency systems are usually more expensive than similar systems with a lower efficiency. Exergetic optimization improves thermodynamic feature of an energy system with no concern on economic features of the proposed system. In contrast, thermodynamics have been developed in order to acquire a more generalized tool for thermodynamic and economic analysis of energy systems. It combines the exergy analysis with economic principles and incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system [5]. These costs can conduct designers to find out the cost formation process in an energy system and it can be utilized in the optimization of thermodynamic systems, in which the task is usually focused on minimizing the unit cost of the system product. In analyzing and optimizing of energy systems we usually encounter several criteria beside thermodynamic and thermoeconomic criteria. One of the most important criteria that we are

---

* Corresponding author. Tel.: +98 21 8406 3212; fax: +98 21 8867 4748.
E-mail addresses: sayyaadi@kntu.ac.ir, hoseynsayyaadi@gmail.com
(H. Sayyaadi).

0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.01.026

Nomenclature

ADJ	adjustment to book depreciation ($)
AFUDC	allowance for the fund used during construction ($)
BBY	balance at the beginning of the year ($)
BD	book depreciation ($)
BL	book life (years)
CC	carrying charge ($)
CRF	capital recovery factor
DC	direct cost ($)
DITX	differed income tax ($)
$\dot{E}$	the rate of exergy (kW)
FC	unit cost of the fuel ($\$\,(\mathrm{kWh})^{-1}$)
$\dot{I}$	the rate of exergy destruction (kW)
e	specific exergy ($\mathrm{kJ\,kg^{-1}}$)
h	specific enthalpy ($\mathrm{kJ\,kg^{-1}}$)
IC	indirect cost ($)
ITX	income taxes ($)
i_{eff}	average annual discount rate (the cost of money) (%)
i_{FC}	escalation rate for the fuel cost
j	jth year of the system operation
LHV	lower heat value of the fuel (kJ)
$\dot{m}$	fow rate ($\mathrm{kg\,s^{-1}}$)
OMC	operating and maintenance cost ($)
OTXI	other taxes and insurance ($)
P	pressure (kPa)
PEC	purchase equipment cost ($)
PFI	plant facilities investment ($)
$\dot{Q}$	heat transfer rate (kW)
ROI	return on investment ($)
r_e	average value of escalation (inflation) rate for all expenditures except the fuel (%)
r_{FC}	annual escalation rate for the fuel cost
r_{OMC}	annual escalation rate for the operation and maintenance cost (%)
T	temperature (°C or K)
s	specific entropy ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$)
TRR	total revenue requirement ($)
$\dot{W}$	power (kW)
$\dot{Z}_k$	the total cost rate of kth component including the capital investment and operating-maintenance cost ($\$\,\mathrm{s^{-1}}$)
$\dot{Z}_k^{CI}$	the rate of the capital investment of the kth component ($\$\,\mathrm{s^{-1}}$)
$\dot{Z}_k^{OMC}$	the rate of the operating and maintenance cost of the kth component ($\$\,\mathrm{s^{-1}}$)
η	efficiency

Subscripts

AbC	absorption chiller
air	air
AuB	auxiliary boiler
C	cooling
EC	electrical chiller
elec	electricity
exhaust	exhaust gas
Fuel	fuel
gas	natural gas (as a fuel)
H	heating
HRSG	heat recovery steam generator
k	kth component
MT	micro turbine
NG	network grid
s	isentropic

usually faced with is environmental issues. Assessing the environmental impact from conventional (centralized) and decentralized generation paradigms is particularly relevant in today's changing energy scenario.

In general, objectives involved in the design optimization process are: thermodynamic (e.g., maximum efficiency, minimum fuel consumption, minimum irreversibility and so on), economic (e.g., minimum cost per unit of time, maximum profit per unit of production) and environmental (e.g., limited emissions, minimum environmental impact) [6,7]. A generalized optimization approaches deals with several and even conflicting objectives simultaneously.

In this work, the sizing of a small scale CCHP system is performed based on the multi-objective optimization with exergetic, thermoeconomic and environmental objectives. Exergetic objective is obtained by thermodynamic modeling of the CCHP system while thermoeconomic objective is developed based on the combination of the exergetic analysis and economic model. Economic modeling of the system is performed based on the total revenue requirement (*TRR*) method [5]. For obtaining of the environmental cost impact objective as a third objective, a systematic framework for evaluating the emission impact of small-scale CCHP systems under general full-load conditions is presented. The distributed nature of distributed generation systems with respect to centralized power plants is addressed through a conceptual distinction between local and global emissions. Specific models based on an emission factor approach are formulated for assessing global emissions, and for approximately representing the contribution to the environmental impact caused by local emissions from sources close to the receptors. The relevant quantities characterizing the energy efficiency and local and global emissions (formulated in terms of equivalent reference emission factors) refer to the electrical output of the CCHP system.

In the multi-objective optimization rather than having a unique optimal solution a series of optimal solutions namely as the Pareto frontier is obtained. In this case a process of decision-making for selection of a final solution from the Pareto frontier is required. There are several decision-making methods including LINMAP [8,9], TOPSIS [8,9], Bellman–Zadeh fuzzy [10]. However in this work a novel decision-making method based on the availability of solutions is developed. In this regard, the risk analysis is performed for each solution located on the Pareto frontier and a solution with a higher availability is selected as a desired final optimal solution. In this way additional criterion (maximum availability) is added to the exergetic, thermoeconomic and environmental aspects and a high availability among the solutions of the Pareto frontier is guaranteed for the final solution.

2. Case study

A CCHP system is designed for simultaneous providing of the heating, cooling and electrical demands for a proposed building in Tehran, Iran. The weather condition for Tehran is indicated in Table 1.

The proposed building has 40 flats in 10 floors where the area of each apartment is 200 m^2. The estimated electrical, heating and cooling loads are calculated. This building has 30 m height and 20 m × 60 m ground area, external wall with 0.22 m thickness composed of 0.005 m face stone, 0.01 cm cement mortar, 0.20 m brick and 0.005 gypsum board from outside to the inside of the wall. Internal walls (partitions) have 0.12 m thickness with 0.005 m gypsum boards inside and outside of the wall and 0.10 m common brick. Further ceilings and roof are composed of 0.01 m flooring mosaic, 0.001 m water proofing material, 0.10 m cement block, 0.20 m hollow brick and 0.005 m gypsum plaster. Further at the