Journal of Cleaner Production 170 (2018) 978–990

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Exergoeconomic analysis and optimization of a solar based multigeneration system using multiobjective differential evolution algorithm

Halimeh Rashidi*, Jamshid Khorshidi

*Mechanical Engineering Department, University of Hormozgan, Bandar Abbas, Iran*

ARTICLE INFO

*Article history:*
Received 8 June 2017
Received in revised form
5 August 2017
Accepted 21 September 2017
Available online 22 September 2017

*Index terms:*
Multigeneration energy
Photovoltaic solar system
Exergy analysis
Multiobjective optimization
Differential evolution algorithm
Sensitivity analysis
Pareto frontier

ABSTRACT

This paper presents and analyzes a multigeneration energy system that consists of a reverse osmosis desalination unit, water heater, organic Rankine cycle, photovoltaic solar collectors, and a single effect absorption chiller. In doing so, energy and exergy analysis are first performed to evaluate the performance of the system and determine the irreversibility of each component. Next, considering minimizing total cost rate and maximizing exergy efficiency as two objective functions, a multiobjective optimization approach based on differential evolution algorithm is proposed to determine the best design parameters. A self-adaptive technique is utilized to deal with the search capability, population diversity, and convergence speed of the proposed optimization algorithm. An external archive list is used to save all nondominated optimal solutions during the optimization. Dynamic crowding distance approach is employed to decrease archiving size without losing its characteristics. Furthermore, a fuzzy clustering approach is used to select the desired solution among the Pareto-optimal solutions. Simulation results are compared with two other multiobjective optimization algorithms and effectiveness of the proposed optimization method is verified using various indices. Finally, a sensitivity analysis is employed to evaluate effects of design parameters on exergy efficiency and total cost rate of the system.



## 1. Introduction

Multigeneration energy systems can help in reducing thermal losses, greenhouse gasses, and grid failure (Ahmadi et al., 2014a). The main purpose of using multigeneration system is increasing sustainability and efficiency, thereby reducing the cost and environmental impacts. Global warming mitigation, hydrogen, heating, cooling, hot water and electricity production are other potential products of these systems (Joshi et al., 2009). Many research activities have been conducted to improve the efficiency of multigeneration systems. Some of them are based on energy analysis; while some others are based on exergy analysis. A critical review on energy, exergy and exergoeconomic analysis of a cogeneration system has been performed in Mehrpooya et al. (2017) where it has been concluded that exergy analysis can better address the system performance.

Several works have attempted to model and optimize multigeneration systems using different strategies and optimization methods. Authors in Patel et al. (2017) have considered the exergy efficiency and total system cost as two objective functions and presented an exergy based optimization method for identifying the best design parameters for a multigeneration energy system that generates electricity, heat, cooling and hot water. Authors in Ahmadi et al. (2014b) have examined the performance of a hybrid solar heating, cooling and power generation system. They concluded that compared to solar thermal power systems, exergy and energy efficiencies of hybrid systems might reach 2.7% and 47.8% respectively. An exergy modeling of solar based combined cooling, heat and power (CCHP) system with organic Rankine cycle (ORC) has been presented in Ezzat and Dincer (2016). Simulation results have shown that the CCHP system has higher exergy efficiency as compared to electrical and heating cogeneration systems. A techno-economic comparison between a ground-coupled heat pump (GCHP) system and an air-coupled heat pump (ACHP) system has been performed in Esen et al. (2007a). The test results have indicated that compared to ACHP systems, GCHP systems are economically more suitable for the purpose of space cooling.

Authors in Esen et al. (2007b) have investigated energetic and

* Corresponding author.
*E-mail address:* rashidi@hormozgan.ac.ir (H. Rashidi).

https://doi.org/10.1016/j.jclepro.2017.09.201
0959-6526/

exergetic efficiencies of ground-coupled heat pump system. They have concluded that the energetic and exergetic efficiencies of the system increase when heat source temperature increases in hot seasons.

Performance experiments and economic analysis of a horizontal ground source heat pump (GSHP) system have been performed in Esen et al. (2006). The GSHP system was compared to conventional heating methods using annualized life cycle cost method. Simulation results showed that the GSHP system offers economic advantages over the conventional heating methods; however, it is not an economic alternative system to natural gas.

The employed methods for optimization of multigeneration systems are generally categorized into classical methods and intelligent optimization algorithms. In some researches, the classical methods such as linear and non-linear programming models have been employed to conduct the optimization of energy systems. However, in some other researches, intelligent optimization algorithms have been used. Authors in Zhang et al. (2014) have applied a mixed integer nonlinear programming model to minimize the annual cost of a trigeneration system. In (Omu et al., 2013) the mixed integer linear programming approaches have been used for optimizing the total annual cost of a CCHP system in commercial sectors. Authors in Liu et al. (2013) have performed the sequential quadratic programming method to solve the optimization problem of a multigeneration system.

Analysis, design and optimization of multigeneration energy systems are defined as a complex optimization problem with large dimension including various types of objective functions and non-differentiable constraints. Linear-based programming algorithms are fast and reliable, however, their main disadvantage is requirement to piecewise linear estimation (Boyaghchi et al., 2016). The nonlinear-based algorithms also cannot guarantee the problem convergence when there are many design parameters. In addition, gradient based algorithms are sensitive to the initial condition values and may not converge to the optimal solutions (Khalid et al., 2015).

According to the results presented in the literature, in the complex and nonlinear optimization problems, the heuristic and meta-heuristics optimization algorithms are superior from classical methods in finding the optimal or near optimal solution in a reasonable time (Boyaghchi and Molaie, 2015).

Literature review shows that in majority of the recent published works, single-objective optimization has been considered for optimizing energy systems. Moreover, genetic algorithm (GA) and particle swarm optimization (PSO) have been employed as optimization algorithms. For example, authors in (Ziapour and Hashtroudi, 2017) have applied GA to optimize a trigeneration system. In their analysis, they considered energy, economy, and environmental aspects. In (Hajabdollahi et al., 2015) a modified genetic algorithm has been used to conduct the optimization of a CCHP based solar system. The objective function was selected from the view of economic aspect. Authors in Salcedo et al. (2012) have conducted a parametric optimization of a solar based CCHP system with ORC using of genetic algorithm. According to the results presented in the paper, the system could reach maximum exergy efficiency of 60.33% under optimum conditions.

Authors in Tichi et al. (2010) have used PSO algorithm for redundant building cooling, heating, and power system. Also, in Rabbani et al. (2018), PSO algorithm has been used to optimize a trigeneration system by considering the environmental aspect.

As there are many factors which have significant effects on the system performance from economic, thermodynamic and environmental aspects, single-objective optimization cannot comprehensively evaluate the performance of the system. For example, authors in Ebrahimi (2017) have performed optimal design of an energy system considering simultaneous economic, energetic and environmental aspects. They have demonstrated that there is not an optimal condition where all objective function can reach their optimum values. Therefore, multi-objective optimization appears to be an essential tool for determining the optimum conditions and gives better results when a complete thermodynamic cycle is considered. In (Arora et al., 2017) a two-stage optimal design method has been applied for a CCHP system. Nondominated sorting genetic algorithm (NSGA-II) has been utilized in multi-objective optimization on the first stage, and the mixed-integer linear programming algorithm on the second stage. Authors in Joshi et al. (2009) have applied the elitist NSGA-II to maximize the thermal efficiency and minimize the total cost rate of a multi-generation system simultaneously. The optimization results showed a 3.76% increase in efficiency and 3.84% decrease in total cost rate simultaneously. Authors in Shamoushaki et al. (2017) have performed the thermal modeling and optimal design of a trigeneration system. They have applied a multiobjective PSO, called MOPSO, to obtain the maximum actual annual benefit and exergy efficiency simultaneously. In (Soheyli et al., 2016) the MOPSO algorithm has been used to conduct the multi-objective optimization of a CCHP system. The objective functions have been selected from the view of thermodynamic, economic and environmental aspects. Although many works have been conducted on the analysis, design and optimization of multigeneration systems using single objective function, very few studies have been carried out using multi-objective optimization based on the state of art evolutionary algorithms.

This paper presents and analyzes a multigeneration energy system that consists of a reverse osmosis (RO) desalination unit, water heater, ORC evaporator, PV solar collectors, and a single effect absorption chiller. The thermodynamic modeling and energy and exergy analysis are performed for an integrated solar based multigeneration system to evaluate the performance of the system and to determine the irreversibility of each component. Minimizing total cost rate and maximizing exergy efficiency of the system are considered as objective functions. A multi objective differential evolution (MODE) with self-tuned parameter which employs binomial crossover and difference vector based mutation is employed to determine the best design parameters. A fuzzy based mechanism is employed to get the best compromised solution from the Pareto front to aid the decision maker. A closed form expression for the Pareto optimal solutions that can be used as an aid for designing optimal multigeneration system is also derived. Furthermore, the effects of different design parameters on the total cost rate and exergy efficiency are evaluated using sensitivity analysis. The main objectives of this paper are as follows:

- Modeling a multigeneration system that includes an organic Rankine cycle, single effect absorption chiller, photovoltaic solar collectors, reverse osmosis desalination unit and water heater.
- Conducting detailed exergy and economic analysis of the multigeneration system.
- Applying a new multiobjective optimization method based on differential evolution algorithm for the system under study.
- Analyzing the performance of the proposed multiobjective optimization algorithm and comparing it with other intelligent optimization methods.
- Facilitating optimal design of the multigeneration system by obtaining an equation for the Pareto optimal curve.