Energy Policy 38 (2010) 945–954

Contents lists available at ScienceDirect

Energy Policy

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

Multi-objective optimization of a trigeneration plant

K.C. Kavvadias *, Z.B. Maroulis

School of Chemical Engineering, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece

ARTICLE INFO

Article history:
Received 29 June 2009
Accepted 21 October 2009
Available online 18 November 2009

Keywords:
Pareto
Genetic algorithm
Operation strategies

ABSTRACT

A multi-objective optimization method was developed for the design of trigeneration plants. The optimization is carried out on technical, economical, energetic and environmental performance indicators in a multi-objective optimization framework. Both construction (equipment sizes) and discrete operational (pricing tariff schemes and operational strategy) variables were optimized based on realistic conditions. The problem is solved using a multi-objective evolutionary algorithm. An example of a trigeneration system in a 300 bed hospital was studied in detail in order to demonstrate the design procedure, the economic and energetic performance of the plant, as well as the effectiveness of the proposed approach even under fluctuating energy prices.

1. Introduction

Combined generation of different kinds of energy has become a mainstream application of distributed generation during the last decades. The proven advantages of cogeneration technology made it useful firstly in large-scale industrial plants and later on commercial or even resident buildings. Most recent advances, allow the investment of 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 system design aims at the determination of the sizing and operational variables involved by optimizing a suitable criterion. Of course, the proposed designed solution must be subject to the restrictions fixed by the legislation, while it is very sensitive on the country's energy policy and on wider geopolitical facts (i.e. abrupt oil price change). Optimization based on economical criteria from the investor's point of view, has been studied thoroughly for both cogeneration and trigeneration plants (Chicco and Mancarella, 2005; Arcuri et al., 2007; Badami et al., 2008; Sanaye et al., 2008). Energy savings and environmental benefits of trigeneration system have also been discussed and proven to be important (Cardona and Piacentino, 2003; Chicco and Mancarella, 2007a, b).

However, the increasing need for more efficient systems that are both economically attractive and friendlier to the environment request the development of new criteria and determine new design rules. Economic performance, energy savings and emission reduction can be formulated by using indices that compare the benefits of trigeneration with energy production by conventional means. It is obvious that the design of such a system is associated with the above conflicting objectives. The use of a single-objective function, which is usually a weighted combination of several objectives, does not facilitate the judgement of the decision maker as it is often difficult to interrelate several objectives of different natures properly. Moreover, it is often wrong to claim that there is only one optimal solution because the trade-offs between conflicting objectives are important. Assuming so, certain optimal solution may be lost since they may never be 'explored' (Deb, 2001). On the contrary, with the use of multi-objective techniques a set of several non-dominated optimal solutions is obtained, also known as Pareto optimal set. As a result, the solution is not a single mathematically figure but a set of efficient solutions that can be examined using a judgment of the trade-offs involved, giving the decision-maker more flexibility.

On the basis of the above, trigeneration system design is a complex multi-objective optimization problem involving an economic (net present value), an energetic (primary energy savings) and an environmental (emission reduction) objective function, as well as physical and capacity constraints derived from the mathematical model and the requirements of the decision-maker.

The scope of this work is to present a method of optimizing a trigeneration plant based on economical, energetic and environmental criteria. The full set of efficient optimal solutions is evaluated and the effect of optimal design variables on the characteristics of the system is studied for a typical hospital building.

2. System description

The trigeneration system consists of the following units:

- A prime mover, usually gas turbine, steam turbine or in smaller scales internal combustion engine, which is driven by natural gas. It produces electrical energy and cogenerated heat and represents the core of the plant.

---

* Corresponding author. Tel: +30 2107723149; fax: +30 2107723155.
E-mail address: kavadias@mail.ntua.gr (K.C. Kavvadias).

0301-4215/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2009.10.046

Nomenclature

A	absorption chiller nominal electrical power, kW
AOC	annual operating cost, €
AOP	annual operating profit, €
B	boiler nominal power, kW
C	cost, €
CF	capacity factor, %
Co	cooling energy, kW
CO	continuous operation strategy
COP	coefficient of performance
E	electrical chiller nominal power, kW
EeF	electrical-equivalent load following strategy
El	electricity, kW
ERR	emission reduction ratio
F	fuel, kW
HeF	heat equivalent demand following strategy
HPR	heat power ratio
HRF	heat recovery factor
mC_p	thermal capacity, kW/K
NPV	net present value, €
P	prime mover nominal electrical power, kW
PESR	primary energy savings ratio
PS	peak shaving strategy
Ss	discrete decision variable for summer operation strategy selection
Sw	discrete decision variable for winter operation strategy selection
T	temperature, °C
Ta	discrete decision variable for tariff selection
Th	thermal energy, kW
η	efficiency, %
Superscripts	
AC	produced or consumed by absorption chiller
Boiler	produced by boiler
Buffer	buffer vessel
CHP	produced by combined heat, power
EC	produced or consumed by electric chiller
EndUse	consumed in end uses
GridIn	imported from grid
GridOut	exported to grid
n	scale index
OM	operation and maintenance
SP	produced by separate production means
Waste	wasted
Subscripts	
el	electrical (efficiency)
k	months
t	hours
th	thermal (efficiency)

- An absorption chiller which utilizes excess low temperature heat from the prime mover, and produces cooling energy, increasing the electric to thermal load coincidence in the summer months. These chillers have a relatively low coefficient of performance, usually under unity, and as a result they are considered 'bad' energy converters. Hence, in trigeneration systems, the absorption chiller only work when waste heat is available; no extra heat is generated in order to be converted to cooling.
- An auxiliary boiler is used as a backup when the thermal output from the prime mover, is not sufficient to cover the heat demand.
- A conventional electric chiller which utilizes electric energy in order to produce cooling. This chiller is preferred to operate when waste heat is not available and absorption chiller operation is uneconomical.

The main factors that affect the design and operation of such a system are discussed below.

2.1. Energy load profiles

Energy loads can be described precisely by taking into consideration the following parameters: seasonal variation which depend on ambient temperature, daily profiles as a function of the working schedule and day type, i.e. working or non-working day. Usually non-working day profiles are smoother, closer to base load and with less hourly variations. Historical energy data for at least a year are necessary for designing of a trigeneration plant.

2.2. Energy tariffs

Energy tariffs affect heavily a trigeneration investment. The most common energy pricing schemes that are used worldwide are the following:

- Charge volumetric and maximum demand fees for a month. Maximum demand fees are charged depending on the maximum power demand during the month, regardless of how often the max level occurs. Due to the structure of this tariff, hourly spark-spread based optimization routines and operation strategies cannot be applied.
- Charge only volumetric fees and divide the day in peak load, high load and low load hours, this is also known as time of use (TOU) tariffs.
- Any combination of the above including fixed fees.

The optimal design must be adjusted and estimated according to the pricing policy applied, taking into consideration all pricing schemes available. A quick index that helps in the tariff selection process is grid utilization factor (UF). It shows by the percentage of the energy bought in each month in relation with the energy that could be bought on maximum load. An equivalent expression is the average power demand divided by the peak power on the same timeframe.

2.3. Operation strategies

Operation strategies that are used in distributed generation plants are part of the process control system, which is dependent on the following factors: demand for each kind of energy, prime mover nominal power, coefficients of performance and conversion factors for all energy conversions devices involved. In literature the most common kinds of cogeneration systems are designed by either covering a constant part of energy or by following the evolution the electrical (or heat) load (Chicco and Mancarella, 2006). However, conventional load following strategies cannot be applied successfully in a trigeneration system as they do not exploit all the benefits of the system. More specifically, in strictly heat demand following, the prime mover will always produce the heat needed, so there will not be any waste heat available to feed the absorption chiller.