Energy Conversion and Management 157 (2018) 307–316

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Optimal integrated sizing and operation of a CHP system with Monte Carlo risk analysis for long-term uncertainty in energy demands

Luca Urbanucci, Daniele Testi*

Department of Energy, Systems, Territory, and Constructions Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino 1, 56122 Pisa, Italy

ARTICLE INFO

Keywords:
Combined heat and power
Optimization
Uncertainty
Monte Carlo method
Multi-objective
Decision-making

ABSTRACT

In this study a probabilistic approach for optimal sizing of cogeneration systems under long-term uncertainty in energy demand is proposed. A dynamic simulation framework for detailed modeling of the energy system is defined, consisting in both traditional and optimal operational strategies evaluation. A two-stage stochastic optimization algorithm is developed, adopting Monte Carlo method for the definition of a multi-objective optimization problem. An Italian hospital facility has been used as a case study and a gas internal combustion engine is considered for the cogeneration unit. The results reveal that the influence of uncertainties on both optimal size and annual total cost is significant. Optimal size obtained with the traditional deterministic approach are found to be sub-optimal (up to 30% larger) and the predicted annual cost saving is always lower when accounting for uncertainties. Pareto frontiers of different CHP configurations are presented and show the effectiveness of the proposed method as a useful tool for risk management and focused decision-making, as tradeoffs between system efficiency and system robustness.

1. Introduction

Cogeneration is the simultaneous production of electric energy and useful heat. Combined Heat and Power (CHP) plants haven been shown to be a reliable, competitive and less polluting alternative to separate generation. The European Union has promoted the use of high-efficiency cogeneration as a measure to save primary energy, avoid electric network losses, reduce emissions, namely greenhouse gases, and improve the security of energy supply [1]. CHP technology is considered an essential means of achieving the European 20% energy efficiency target by 2020 [2].

The energy, environmental and economic performances of CHP systems are strongly influenced by prime mover selection, equipment capacity and operational strategy. Undersizing and oversizing of CHP plants are frequent and do not allow the full exploitation of the energy saving of such systems [3]. For this reason, in recent years, many studies have focused on appropriate CHP system design methods [4]. Multi-objective optimization approaches for designing cogeneration systems have been developed both for residential [5] and for large-scale building energy systems [6]. The importance of integrated sizing and operational strategy methods for optimal selection of cogeneration systems has been explicitly addressed [7,8].

Different optimization techniques have been used over the years to identify the optimal design of polygeneration systems [9]. Arcuri et al. [10] presented a Mixed Integer Linear Programming (MILP) model for the determination of the design and the running conditions of a trigeneration plant for a hospital complex. Guo et al. [11] carried out a two-stage optimal planning and design method for Combined Cooling Heat and Power (CCHP) microgrid system, using both genetic algorithm and MILP algorithm techniques. Elsido et al. [12] and Arcuri et al. [13] proposed Mixed-Integer Non-Linear Programming (MINLP) models for determining the most profitable synthesis, design, and annual scheduling of CHP systems.

Other works have focused on the optimal exploitation of the CHP potential in existing plants. Franco and Versace [14] defined the optimal operational strategy of a cogeneration plant connected to a District Heating System. Li et al. [15] analyzed the effect of optimized operational strategy on a CCHP system for office and residential buildings. Bischi et al. [16], Ortiga et al. [17] and Ünal et al. [18] investigated the optimal operating schedule of CCHP systems, with a given design.

Many of these studies [6,11] have clearly indicated the importance of considering, in future research, the effect of uncertainties in CHP optimal design. Such a task is very challenging, but it is worthwhile for gaining accurate and robust results. In fact, it is well-known how intrinsic uncertainties affecting Distributed Energy Systems (DES), such as energy demands, fuel price fluctuations, regulation, and so on, might undermine the potential profit of such systems [19]. In this regard,

* Corresponding author.
E-mail address: daniele.testi@unipi.it (D. Testi).

https://doi.org/10.1016/j.enconman.2017.12.008
Received 23 July 2017; Received in revised form 12 November 2017; Accepted 4 December 2017
0196-8904/

Nomenclature

Parameters

c	unit cost, €/kWh
C	cost, €
DLT	design lifetime, years
t	timestep, 1 h
η	efficiency, dimensionless

Continuous variables

AC	annual cost, €/year
$ACSP$	annual cost saving percentage,%
E	electric energy, kWh
F	energy content of the consumed fuel, kWh
HPR	heat-to-power ratio, dimensionless
L	load factor, dimensionless
P	electric power, kW
Q	heat, kWh

Binary variables

δ	on-off state for cogeneration units

Subscripts

$2.5th\%ile$	2.5-th percentile
boi	boiler
CGU	cogeneration unit
CHP	combined heat and power production scenario
d	demand
E	Electric
EV	expected value
F	fuel
I	annualized investment
M	annual maintenance
min	minimum
nom	nominal (L = 1)
p	purchased
PEG	electricity purchased by the grid
Q	thermal
s	sold
SEG	electricity sold to the grid
SP	separate-production scenario
TI	total investment

several approaches of optimization under uncertainty have been employed, such as general sensitivity analysis [20,21], sensitivity analysis in mathematical programming [22], fuzzy programming [23,24], dynamic programming [25], robust optimization [19], and stochastic programming [26]. Each of these studies focused on specific types of uncertainties and energy systems. Yokoama and Ito [27] proposed a robust optimal design method, through a case study on a cogeneration system, considering uncertain energy demand of a single representative day. Akbari et al. [28] focused on designing a multi-technology distributed energy system in a neighborhood, under demand uncertainty concerning data insufficiency. Momen et al. [29] provided a Monte Carlo method applied to a gas-turbine-based cogeneration system, considering uncertainties in economic parameters. Mavrotas et al. [30] dealt with risk management for uncertainty in fuel costs and discount rate, by means of the combined use of Monte Carlo simulation and MILP algorithm. Li et al. [31] optimized a building CCHP system, considering fluctuations in the hourly energy demands.

In the mentioned studies, long-term uncertainties in energy demand are ignored and typical load year data are considered for the whole lifetime of CHP systems. However, fluctuations in energy demand over the years may be significant and their effect on overall performance and optimal sizing must be specifically evaluated.

The main purpose and novelty of this study is therefore to accurately investigate the effect of long-term uncertainties in energy demand on CHP systems. For this purpose, an original optimal integrated sizing and operational strategy methodology is defined, which takes analytically into account uncertainties in energy demand. More specifically, this study provides a probabilistic methodology for risk analysis, based on the simulation of the entire life-cycle of the cogeneration project. Such an approach allows to highlight shortcomings and inaccuracies of usual deterministic methods. Moreover, the adopted methodological framework provides results in the form of probability distributions, thus providing fruitful and complete information to decision-makers.

The remainder of the paper is organized as follows. In Section 2 the methodological framework is presented in detail. An essential description of the case study follows in Section 3. Section 4 contains a detailed analysis of the results, while the last section contains concluding remarks.

2. Methodology

In pursuit of the above-mentioned goals, a specific methodological framework has been developed. Three main tools have been employed: the dynamic simulation based on a full mathematical model of the system, the so-called Monte Carlo sampling Method, and an optimization algorithm.

2.1. System simulation

It is commonly accepted that an extensive and accurate analysis of a CHP unit requires a detailed simulation of the energy system [32]. In fact, preliminary sizing methods, such as the load duration curve, are useful only for assessing orders of magnitude of the project and cannot fully embrace the complexity of a CHP system. Multiple time-varying loads, part-load performances, simultaneous energy balances and various economical features make any rule-of-thumb approach inaccurate. Furthermore, the importance of considering electrical and thermal load fluctuations instead of mean values is recognized [33].

For these reasons, a CHP simulation, based on hourly averaged values for load representation, should be adopted [34]. This approach allows several key factors to be considered, such as part-load efficiency, load factor lower bound, hourly time-dependent prices for purchasing and selling electricity, actual operational hours, different operational strategies. In such a way, comprehensive system performances and a detailed CHP operational scheduling can be obtained.

In fact, CHP systems can be run by several possible operational strategies. The two most common forms of operational strategies are: *Following the electric load* (FEL) and *Following the thermal load* (FTL). Nevertheless, these traditional strategies might not guarantee the best performance of the systems and optimal operating strategies have therefore been investigated in the last few years. [35,36]. Obviously, the adopted operational strategy can significantly influence the optimal sizing of the CHP system [7] and, consequently, it is essential to opt for an integrated methodology, which simulates all the possible operational strategies.