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Optimal design of residential cogeneration systems under uncertainty

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ABSTRACT

This paper presents a multi-objective optimization method for designing cogeneration systems in residential complexes and accounting for the involved uncertainty. The model accounts for satisfying the hot water and electric energy demands in a residential complex, while minimizing the total annual cost and the associated greenhouse gas emissions. The proposed model incorporates uncertain data for the ambient temperature, energy demands and prices of the local energy market, which are predicted through forecasting methods for determining the financial and environmental risks. Furthermore, the model accounts for determining the type and size of the central cogeneration unit, thermal storage unit, the needed auxiliary units, as well as the operating conditions. A housing complex in central Mexico is presented as case study. The results show significant economic and environmental benefits for the implementation of the proposed scheme as well as the importance of accounting for the involved uncertainty.

1. Introduction

The economic and environmental benefits yielded through the proper use of resources in the industrial sector have motivated the extension to residential complexes (Cucek et al., 2011; Terrazas-Moreno and Grossmann, 2011; Martin and Grossmann, 2012; Ahmetovic et al., 2014; Ibric et al., 2014; Abdelhady et al., 2015). This way, combined heat and power (CHP) systems have become an efficient alternative for supplying the needed power and heat in residential complexes. This is because CHP systems offer several advantages in terms of efficiency (Maghanki et al., 2013), environmental impact (Peacock and Newborough, 2005) and economic cost (De Paepe et al., 2006; Cravioto et al., 2014) compared with conventional systems. The design of cogeneration systems is determined by several factors, as the availability of natural resources that can feed the system (Tchanche et al., 2014), weather conditions (Lazos et al., 2014), energy demands (Alanne and Saari, 2004), available technologies (González et al., 2015) and the conditions and policies of the local energy market (Streimikiene and Baležentis, 2013). In this context, Collazos et al. (2009) proposed a method for management polygeneration systems. Zhou et al. (2013a) presented an economic assessment for distributing energy in a new residential area in China, and Zhou et al. (2013b) incorporated the impacts of the equipment size in designing cogeneration systems. Fazlollahi et al. (2014) presented a multi-objective optimization approach for designing district energy systems. Recently, Fuentes-Cortés et al. (2015a,b) reported an optimization formulation for designing CHP systems for the residential sector; however, this approach did not account for the involved uncertainty in the system. It should be noticed that there are several uncertain factors involved in the design of CHP systems (Jradi and Riffat, 2014; Li and Ierapetritou, 2008). But, usually designing CHP systems is based on overage values of the parameters that represent significant uncertainty (Gamarra and Guerrero, 2015). Nevertheless, this approach is not the best way to account for the involved uncertainty, since the ambient temperature, the energy market prices and the energy demands are factors that have involved significant uncertainty in designing residential CHP systems (Houwing et al., 2008). These variables have been addressed separately for analyzing CHP systems in the residential sector. In this context, Barbieri et al. (2012) proposed a model to adjust the design of CHP systems to variable energy demands in dwellings. Fubara et al. (2014) studied the seasonal changes in energy demands. Rezvan et al. (2013) used Monte Carlo-based models for determining uncertain energy demands, and Al-Mansour and Kozuh (2007) analyzed the uncertain energy prices in the market. Ren and Gao (2010) presented an analysis for the variations of electricity price through a year. Rysanek and Choudhary (2013) accounted for the installation costs and annual electricity demand. Arnold and Yildiz (2015) incorporated Monte Carlo models for the prediction of energy prices in distributed generation systems. Carvalho et al. (2011) proposed a model to take into account the influence

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Nomenclature

Index
t time period, h
s season: spring, summer, fall, winter
sc random scenario

Parameters
Cp heat capacity, kWh/kg °C
FC fixed cost, $
$G^{D}_{t,s_{sc}}$ hot water flow demanded by the housing complex, kg
$G^{UB\text{-}B}$ upper bound of water flow from boiler, kg
GHGF emissions factor ton, CO_2/kWh
H_D operating days (annual), day
k_F factor used to annualize the inversion, year^{-1}
PL^{MAX} maximum partial load, dimensionless
PL^{MIN} minimum partial load, dimensionless
$S^{UB\text{-}ST}$ upper bound for thermal storage capacity, kg
T temperature, °C
U convective factor, kWh/m^2 °C
UCCW unit cost for cold water, $/kg
UCF unit cost for fuel, $/kWh
UCOM unit cost for operating and maintenance, $/kW
UCP^{H} unit cost of heat from the boiler and the CHP system, $/kWh
UCP^{W} unit cost of power from the net of the electrical company, $/kWh
VC unit variable cost, $/kWh
VCS^{W} unit value of sale for electrical energy to the grid, $/kWh
$W^{D}_{t,s_{sc}}$ electricity demand for household, kWh
W^{UB} upper bound for the capacity of electrical production, kWh
β scale factor for the capital cost, dimensionless
η efficiency, dimensionless
$\rho^{W\text{-}ST}$ water density in the storage tank, kg/m^3

Continuous variables
A convective area for storage tank, m^2
CostCap annualized capital cost, $/year
CostOp operating cost, $/year
CostO&M operating and maintenance, cost $/year
$CostPowerPurch_{sc}$ cost of power purchase from the grid of the electrical company, $/year
F fuel consumed, kWh
G water flowrate, kg/h
G^{MAX-B} maximum water flowrate from boiler, kg/h
GHGE direct emissions annual CO_2, ton
$GHGE^{T}_{sc}$ total direct emissions from the proposed superstructure annual CO_2, ton
$Heat^{Sale-H}_{sc}$ heat sold by the boiler and the CHP system to the housing complex, $/year
PL partial load dimensionless
$Powersale^{CHP-H}$ annual electricity sold by the CHP system at the housing complex, $/year
Q thermal load produced, kWh
$Q^{loss}_{t,s_{sc}}$ heat loss by convection, kWh
SalePower annual sale of electrical energy to the grid of the electrical company, $/year
$S^{water}_{t,s_{sc}}$ stored hot water, kg
S^{MAX-ST} maximum capacity for thermal storage tank, kg
$T^{ST}_{t,s_{sc}}$ temperature of water in the thermal storage tank, °C
W electricity produced, kWh
$W^{sale}_{t,s_{sc}}$ electricity sold to the grid of the electrical company, kWh
W^{MAX} maximum electrical load produced, kWh
$W^{purchase}_{t,s_{sc}}$ electricity from the grid of the electric company, kWh
WGHGE worse GHG scenario, annual CO_2 ton
WTAC worse TAC scenario, $/year

Binary variables
y existence for units

Acronyms (superscript and subscript)
amb ambient condition
B boiler
CHP combined heat and power
CHP-Technology ICE, MT, FC, or SE
CW cold water
D demand
FC fuel cell
GHGE Greenhouse gas emissions
GRID grid of the electrical company
H sent to housing complex
HWS hot water for sanitary use
ICE internal combustion engine
MAX maximal value
MIN minimal value
MT microturbine
PL partial load purchase
SE Stirling engine
ST thermal storage tank
T total (sum of multiple factors as a final result)
TAC total annual cost

of climatic conditions on energy demands, and Kitapbayev et al. (2015) analyzed the losses in the thermal storage systems resulting from changes in ambient temperature. On the other hand, recently there have been reported proper optimization formulations to take into account the involved uncertainty in designing chemical processes. In this context, Steimel and Engel (2015) reported an optimization approach for designing chemical processes under uncertainty. Nemet et al. (2015) incorporated fluctuating utility prices for designing total site energy systems. Ricardez-Sandoval et al. (2011) accounted for parametric uncertainty in design and control of large-scale systems. Nápoles-Rivera et al. (2015) incorporated parametric uncertainty in designing macroscopic water networks. Guillén-Gosálbez and Grossmann (2010) presented a model for designing supply chains under uncertainty, whereas Longinidis and Georgiadis (2013) accounted for the trade-offs between financial performance and credit solvency in designing supply chains under uncertainty. Betancourt-Torcat et al. (2012) presented a study about the environmental and operational factors that affect the production of synthetic crude oil. The importance of financial analysis in the optimization of energy systems has been addressed by Pintaric and Kravanja (2015a). Similar models for the optimal design of processes under uncertainty have been presented by Wendt et al. (2002) for nonlinear modelling of distillation columns and reactors, Ricardez-Sandoval (2012) for the simultaneous design and control of a continuous stirred tank reactor, Gomes et al. (2014) and Bahakim et al. (2014) used uncertainty models for the operation of a reactor–heat exchanger system, Rooney and Biegler (2003) presented an approach for solving the multi-period problem in chemical processes, Sánchez-Sánchez and Ricardez-Sandoval (2013) presented a multi-scenario approach for determining the best operation of some chemical processes,