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Optimization of trigeneration systems by Mathematical Programming: Influence of plant scheme and boundary conditions

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ABSTRACT

The large potential for energy saving by cogeneration and trigeneration in the building sector is scarcely exploited due to a number of obstacles in making the investments attractive. The analyst often encounters difficulties in identifying optimal design and operation strategies, since a number of factors, either endogenous (i.e. related with the energy load profiles) and exogenous (i.e. related with external conditions like energy prices and support mechanisms), influence the economic viability.

In this paper a decision tool is adopted, which represents an upgrade of a software analyzed in previous papers; the tool simultaneously optimizes the plant lay-out, the sizes of the main components and their operation strategy. For a specific building in the hotel sector, a preliminary analysis is performed to identify the most promising plant configuration, in terms of type of cogeneration unit (either microturbine or diesel oil/natural gas-fueled reciprocate engine) and absorption chiller. Then, sensitivity analyses are carried out to investigate the effects induced by: (a) tax exemption for the fuel consumed in "efficient cogeneration" mode, (b) dynamic behavior of the prime mover and consequent capability to rapidly adjust its load level to follow the energy loads.

1. Introduction

A large potential for energy saving and greenhouse gases (GHGs) emissions reduction is recognized to Combined Heat and Power (CHP) and Combined Heat, Cooling and Power (CHCP) applications in buildings [1]. Main barriers to a wide spread of polygeneration systems are represented by the relatively high cost of CHCP components and the difficulties in achieving an economic viability, especially in buildings characterized by discontinuous (either on daily or seasonal terms) activities and irregular energy load profiles [2].

The efforts of researchers have been consequently focused on developing principles, heuristic rules and algorithms to identify optimal design and operation strategies for CHCP application in buildings. The term "optimal" should be here considered in a wide perspective, since the expected benefits from CHP/CHCP plant operation may regarded both from a "private investor" perspective, thus perceiving the cost reduction as a priority, or from a "social or collective" perspective, thus being related with the energy saving and environmental benefits achievable [3]. Several approaches have been proposed, based on accurate analyses, in energetic and monetary terms [4], of the interactions between the trigeneration plant, the served building and the grid [5]. The critical role of the operational strategy has been addressed in many contributions: in [6] the benefits deriving from a hybrid thermal-electric load following strategy have been quantified, while in [7] an in-depth analysis based on marginal costs in simple trigeneration systems has been proposed.

Among the optimization techniques, Mathematical Programming algorithms have represented a mostly diffuse approach. Some researchers, in particular, have privileged the accuracy of their physical models, thus adopting Nonlinear formulations: in [8] a detailed model accounting also for reactive power exchanges has been presented, while in [9] a multi-objective optimization has been proposed for a CHP plant in a commercial building. In [10] a Nonlinear Modeling approach has been applied to model the variation of plant unitary cost with the size of the CHP unit and the decrease of its nominal efficiency at part load. However, due to the high unavoidable uncertainties related with future energy load and price profiles along the plant life time span, many other researchers conversely preferred to adopt simpler and more computationally efficient Mixed Integer Linear Programming

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Nomenclature

C	hourly operation costs
$C_{abs,nom}$	nominal capacity of the absorption chiller (kW_c)
CHCP	Combined Heat, Cooling and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
D	hourly energy load from the user (kW)
DO	Diesel Oil
$E_{CHP,nom}$	nominal capacity of the cogeneration unit (kW_e)
En.Sav.	energy saving (MW h)
GT	gas turbine
ΔH_i	hourly percent heat loss rate from the heat storage
H	heat rate available from the CHP unit (kW)
$i°$	interest rate
ICE	Internal Combustion Engine
LL	load level (real values in the range [0,1])
mhlv	maximum hourly load variation
MILP	Mixed Integer Linear Programming
MP	market price
n_{life}	expected plant life cycle
NG	natural gas
NPC	Net Present Cost
$PES_{\%}$	primary energy saving index
PUN	Unique National Price of electricity
Q_{TES}	charging/discharging rate of the thermal energy storage (kW)
Size	design variable expressing the capacity of a component (kW)
$STOR_{TES}$	thermal energy stored in the tank (kW h)
V_{TES}	volume of the heat storage tank (m^3)
Z	investment cost for a component (EUR)

Greek letters

β	correction factor
δ	binary 0–1 synthesis variable
η	efficiency
π	maintenance cost of the CHP unit (EUR/kW h_e)

Superscripts

buy	related to energy purchase from the grid
max	maximum annual value of energy load
sell	related to energy sell to the grid
reference	reference value for separate production

Subscripts

abs	absorption chiller
boil	boiler
c	cooling
CHP	referring to the virtual unit operating in CHP mode
e	electricity
h	heat
lt	low temperature
ht	high temperature
unit	referred to the total energy flows to/from the CHP unit
TES	thermal energy storage
waste	energy wasted/dissipated to the surrounding environment

(MILP) techniques [11], renouncing to model accurately the plant components.

The present paper is structured as follows:

– In Section 2 an optimization method is presented, which is implemented into a MILP solver consisting of several Lindo API routines. The tool represents a methodological evolution of routines developed in previous projects [12]. The analytical model is here described in brief, while the focus is posed on the three basic superstructures used to represent different CHCP plant lay-outs;
– In Section 3 a case-study is defined, that is represented by a large hotel building. As the paper is aimed at identifying the influence of plant scheme and boundary conditions on the energetic and economic viability of CHP and CHCP plants, referring to a case study is not only used to test the optimization method, but is rather necessary to develop the computer-assisted sensitivity analyses;
– In the remaining sections, sensitivity analyses are proposed to attempt answering the following questions: (i) is the optimal solution, in terms of plant lay-out, size of components and operation strategy, robust or highly sensitive to the temporal basis adopted to define the energy loads and price profiles? (ii) how are the energetic and economic results influenced by the adopted technologies (types of prime mover and absorption chiller, temperature level of heat storage, etc.)? (iii) is the optimal plant design sensitive to the tax exemption for CHP fuel? (iv) how strongly does the viability of trigeneration system depend on the dynamic performance of the CHP unit (i.e. on its capability to rapidly adjust the load level following the energy loads or the daily tariff profiles)? Even if results are calculated for a specific case-study, the resulting trends may be considered qualitatively valid for different CHCP applications in buildings; also, providing an answer to the above questions has an evident methodological relevance, since they represent open themes in the scientific community and have evident interest for private investors in the energy sector and policy makers aiming at defining efficient support mechanisms for combined production systems.

2. Analysis of the optimization method

The original optimization algorithm adopted in this paper assumes that energy load profiles are available for electricity, cooling and heat requests, with values discretized on hourly basis.

Let $D_{e,i}$, $D_{c,i}$ and $D_{h,i}$ (where the subscripts e, c and h stand for "electricity", "cooling" and "heat") indicate the hourly load, in a generic i-th hour, by. Also, as concerns the energy tariffs, hourly prices for energy purchase-from/sell-to the grid must be known on hourly basis, and are respectively indicated as $MP^{buy}_{e,i}$ and $MP^{sell}_{e,i}$. The tool simultaneously allows to optimize decision variables at:

– Synthesis level: in order to identify the optimal lay-out, a redundant superstructure is adopted, where all the possible plant components are included. Then, each component is associated with a binary 0–1 synthesis variable δ_{comp}; the optimal value of any δ_{comp} will suggest whether the associated component should be included (if $\delta_{comp} = 1$) or not (if $\delta_{comp} = 0$) in the final plant lay-out;
– Design level: the optimal sizes $E_{CHP,nom}$ (rated electric capacity of the CHP unit, in kW_e), $C_{abs,nom}$ (rated cooling capacity of the absorption chiller, in kW_c) and V_{TES} (volume of the sensible heat storage, in m^3) are determined. The size of the auxiliary components, like the back-up boiler and electric chiller/air conditioner, are assumed equal to the heat and cooling load peaks to guarantee safety of supply;