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Optimal design of modular cogeneration plants for hospital facilities and robustness evaluation of the results

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ABSTRACT

The widespread adoption of combined heat and power generation is widely recognized as a strategic goal to achieve significant primary energy savings and lower carbon dioxide emissions. In this context, the purpose of this research is to evaluate the potential of cogeneration based on reciprocating gas engines for some Italian hospital buildings. Comparative analyses have been conducted based on the load profiles of two specific hospital facilities and through the study of the cogeneration system-user interaction. To this end, a specific methodology has been set up by coupling a specifically developed calculation algorithm to a genetic optimization algorithm, and a multi-objective approach has been adopted. The results from the optimization problem highlight a clear trade-off between total primary energy savings (TPES) and simple payback period (SPB). Optimized plant configurations and management strategies show TPES exceeding 18% for the reference hospital facilities and multi–gas engine solutions along with a minimum SPB of approximately three years, thereby justifying the European regulation promoting cogeneration. However, designing a CHP plant for a specific energetic, legislative or market scenario does not guarantee good performance when these scenarios change. For this reason, the proposed methodology has been enhanced in order to focus on some innovative aspects. In particular, this study proposes an uncommon and effective approach to identify the most stable plant solutions through a multi-objective robust design optimization. In particular, the sensitivity of the expected results to possible difficulties in finding commercially available CHP gas engines with sizes reasonably close to the optimal numerical solutions has been estimated. The results indicate that the economic sensitivity is often higher than the energetic sensitivity for most of the optimal solutions, with standard deviation accounting up to 7% of its mean value for the SPB, whereas that percentage is always under 3% for the TPES. Furthermore, the research highlights how the expected results obtained through a deterministic definition of the input decision variables could be overestimated compared to the robust design approach. The proposed research also highlights how optimized CHP plants can be characterized by reasonable levels of energetic and economic sensitivity to changes in the following variable quantities: selling price of electricity, reference efficiency of the Italian thermoelectric generation and selling price of the energy efficiency certificates recognized by the Italian legislation. Indeed, Pareto optimal solutions indicate that the standard deviation for the SPB is always less than 3.5% of its mean value, while this percentage is always under 7% for the TPES.

1. Introduction

The objective of the proposed research is the study of the potential of optimized CHP plants in the hospital sector. In particular, comparative analyses have been conducted on the basis of the load profiles of two hospital facilities and through the study of the CHP system-user interaction. Moreover, to evaluate the sensitivity of the expected economic and energetic results to some possible changes in the reference scenarios, multi-objective robust design optimization techniques have been used by coupling a specific calculation algorithm developed by the authors to a genetic evolutionary algorithm.

The balance between energy supply and energy demand is a critical issue to address, especially in developed countries, as extensively discussed in [1]. In particular, more efficient use of energy and increasing use of renewable energy sources are mandatory to face the challenges imposed by this balance. The U.S. National Oceanic and Atmospheric Administration and NASA have recently stated that 2015 was the Earth's warmest since

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Nomenclature

CE_{uecog}	unit cost of cogenerated electricity (€/kW h)
C_{ueFi}	unit cost of electricity in time band F_i (€/kW h)
$CE_{uerif,Fi}$	reference cost of electricity in the time band of purchase F_i of a three-tier reference pricing system (€/kW h)
C_{um}	specific cost of the natural gas for the boiler (€/Nm^3)
C_{umcog}	specific cost of the natural gas for the cogeneration system (€/Nm^3)
E_e	yearly electrical energy supplied by the CHP plant (kW h)
$E_{e,exc}$	yearly electrical energy supplied by the CHP plant exceeding the user needs (kW h)
$E_{e,excFi}$ (h)	hourly electrical energy supplied by the CHP plant exceeding the user needs in the time band of purchase F_i (kW h)
$E_{e,selfFi}$ (h)	hourly cogenerated electricity self-consumed by the user in the time band of purchase F_i (kW h)
$E_{e,int}$	yearly electrical energy integrated by the electrical grid (kW h)
$E_{P,CHP}$	yearly primary energy supplied to the CHP plant (kW h)
E_t	yearly thermal energy supplied by the CHP plant (kW h)
$E_{t,int}$	yearly thermal energy integrated by auxiliary boilers (kW h)
H_i	fuel lower heating value (kW h/Nm^3)
I_{um}	natural gas taxation (€/Nm^3)
m_c	fuel mass flow rate (Nm^3/h)
M	CHP plant maintenance costs for an electric energy production of 1 kW h (€/kW h)
p_{grid}	factor representative of transmission and transformation losses on the electrical grid
P_t	hourly average thermal load at the generic hour "t" (kW)
P_{tcog}	cogenerated thermal power (kW)
P_{tnom}	nominal thermal power of a single CHP gas engine (kW)
P_{ueFi}	electricity selling price in time band F_i (€/kW h)
std dev	standard deviation of the considered quantity
T	natural gas tariff (€/Nm^3)

Abbreviations

CHP	combined heat and power
DII	Department of industrial engineering of the University of Naples Federico II
ICE	internal combustion engine (reciprocating)
h	hour of the year (h)
MOGA	multi-objective genetic algorithm
MOOP	multi-objective optimization process/problem
MPESM	maximum primary energy savings management logic
MPM	maximum profitability management logic
PEC	primary energy consumption
PES	primary energy savings (legislative)
SPB	simple payback period
TPES	total (or technical) primary energy savings
TI	thermal index, where $TI = Pt/Pt_{nom}$.
TI_{thr}	threshold thermal index

Greek

ΔCE_{ue}	profitability of cogenerated electricity (€/kW h)
η_b	average boiler efficiency
η_e	nominal electrical efficiency of the CHP gas engine
$\eta_{e,ref}$	reference efficiency for thermo-electric power generation
η_{eREF}	average efficiency of the Italian thermoelectric power generation
η_t	actual thermal efficiency of the cogeneration plant $(= P_{tcog}/(m_c * H_i))$
η_{tnom}	nominal thermal efficiency of the cogeneration plant
$\eta_{t,ref}$	reference efficiency for thermal energy production

record-keeping began in 1880 [2]. For this reason, achieving lower carbon dioxide emissions has become even more important to address the global warming effects. In this scenario, the widespread application of the cogeneration technique could promote a significant reduction of the global energy demand and carbon dioxide emissions [3,4] (in [4] the authors also proposed a model to analyze micro-CHP plants from the techno-economic point of view). Distributed generation could even play a strategic role in power reliability, as demonstrated in [5].

The strategic role of combined heat and power (CHP) generation [6] has led many research centers to study and develop micro-CHP systems based on internal combustion reciprocating engines [7,8]. However, in addition to the energetic performance optimization of the specific cogeneration system, equally important is the study of an effective utilization of the recovered heat. This is fundamental to identify a set of CHP solutions that maximize the relevant energetic and economic objectives (e.g., primary energy saving and simple payback period) through a suitable use of the recovered thermal power and generated electricity.

To face this challenging task, several simulations and optimization tools, characterized by different features and levels of complexity, have been adopted in recent years [9–16]. In [9], for example, the authors propose empirical equations to improve the linear scalability costs, but they do not consider possible revenue from selling surplus electricity to the greed. Other studies considered fixed power demands [17]. As reported in [18], the current most comprehensive approaches consider fluctuating energy prices, variable energy demands, part-load efficiency integration, a carbon price and the possibility of selling electricity exported to the grid. However, designing a CHP plant for a specific energetic, economic, regulatory or market scenario does not guarantee good performance when these scenarios change. In [19], for example, the authors stated that many studies ignore uncertainties that could alter the outcome of the optimizations. For example, most of the researches considered fixed energy prices, electricity tariffs, grid carbon intensity, etc., while these and others quantities can vary through the plant life. Moreover, as also stated in [18], most of the proposed models do not provide real-life solutions because CHP unit sizes obtained from the numerical solution of the optimization problem could not be available in the market.

Therefore, a specific calculation algorithm has also been developed by the authors [1] to address these and other topics that have not yet been addressed in scientific works already published, thus constituting the main novelty of this research. In particular, the proposed methodology, based on the multi-objective robust design approach, has been used to analyze two key issues:

(a) the sensitivity of the expected results to an eventual mismatch between the CHP gas engine size currently available in the market and that suggested by the numerical solution;
(b) the sensitivity of the results to certain possible changes in the reference energetic scenario and electricity market.

Moreover, the developed calculation algorithm, together with the overall methodology obtained by coupling this algorithm to specific genetic evolutionary algorithms, consider all the elements