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An original multi-objective criterion for the design of small-scale polygeneration systems based on realistic operating conditions

A. Piacentino *, F. Cardona

DREAM – Department of Energetic and Environmental Research, Engineering Faculty, Università di Palermo, Viale delle Scienze, Building 9, 90128 Palermo, Italy

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Abstract

The optimal design and operation of cogeneration and trigeneration systems for buildings applications is a complex issue, which has been investigated by several different approaches. Both the two basic management strategies, namely heat-tracking and electricity-tracking, have advantages and drawbacks in terms of operating results and may lead the plant designer either to undersize or oversize the CHP unit with respect to the optimal lay-out. Experimental works have demonstrated how the actual on-site performance of small-scale polygeneration systems significantly differs from their expected operation, due to the need for a regular plant operation and the effects of outages for scheduled or unscheduled maintenance activities. After pointing out that heuristic approaches based on demand duration curve are weak instruments for plant design optimization, a more refined method is proposed, based on realistic operating conditions. The method integrates results of previous researches, like the proven convenience in using a duration curve of the "aggregate thermal demand" and in adopting flexible and techno-economically feasible management strategies; it is also based on original indicators to be used for the real time optimization of plant operation. The proposed hybrid management criterion represents a good compromise between *profit-oriented* and *energo-environment-oriented* solutions, ensuring the combined production system to be eligible for support mechanisms. Finally, the method is applied for demonstrative purposes to a large hotel situated in Italy; implementing the innovative phases of the method by successive steps allowed to recognize what margins for profitability and energy saving each phase provides.

Keywords: Cogeneration; Trigeneration; Management strategy; Energy saving; Optimization; Plant design

1. Introduction

Despite the recognized potential for combined heat and power (CHP) and combined heat, cooling and power (CHCP) applications in buildings, such systems actually cover a negligible share of the installed capacity, even in large buildings of the tertiary sector where a major profitability could be achieved. Difficulties in making small-scale polygeneration viable have a various nature: tariff volatility, legislation dynamics at the initial stages of the free energy market and non-deterministic behaviour of internal energy demand. Also, the profitability of polygeneration systems heavily depends on plant lay-out, size of components, management strategy, control system effectiveness and energy prices, that is why the optimization of small-scale cogeneration and trigeneration systems is not a trivial issue, which has been widely investigated adopting different approaches. Optimization procedures can be found based on thermodynamic analysis and energy consumption calculations [1,2] and linear programming models which adopt economic objective functions, eventually including different scenarios for the stochastic variables involved [3,4]. Also, heuristic approaches have been adopted, based on the cumulative curve of energy demand [5] or on enhanced immune algorithms coupled with appropriate rules [6]; such approaches are usually oriented to determine

* Corresponding author. Tel.: +39 091 236302; fax: +39 091 484425.
E-mail address: piacentino@dream.unipa.it (A. Piacentino).

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Nomenclature

ATD aggregate thermal demand (kW)
ATD^* modified aggr. thermal demand (kW)
C cooling
CHCP combined heat, cooling and power
CHP combined heat and power
CHP_{prof} CHP profitability (€/h)
$CHP_{prof,unit}$ specific CHP profitability (€/kW h_t)
COP coefficient of performance
E electricity (kW)
ESFL energy supply at full load
ET electricity-tracking
F chemical energy associated to fuel flow (kW)
H heat
HLV heat low value (kJ/S m^3)
HT heat-tracking
LL load level of the CHP unit, dimensionless
MP market price
P_x capacity of the *x*th component
PES primary energy saving
PHR_{CHP} power to heat ratio of the CHP unit, dimensionless
SS spark-spread
TSS total supply spread

Greek letters
η efficiency, dimensionless
Γ surplus heat production factor

Subscripts
abs absorption chiller
CHP-min minimum acceptable CHP size
e, t, c electrical, thermal and cooling
fuel fuel consumed by the CHP unit
hp reversible heat pump for cooling
i referring to the *i*th hour
indirect for indirect uses, i.e., for feeding the absorption chiller
min, max minimum and maximum value
prod produced
ref reference value for separate production
tot total

Symbol
$\dot{X}$ rated output of the X type of energy (kW)

"physically meaningful" solutions which do no result from a pure mathematical optimization.

The choice of an appropriate objective function is complex too: a main difficulty consists of finding a good compromise between a profit-oriented plant design, which may be determined basing on the internal rate of return (IRR), the net present value (NPV) or the payback time (PT), and a design oriented to maximise the *social-benefits*, i.e., the primary energy saving or the reduction in pollutant-emissions. Furthermore, being assessed as "high efficiency CHP" (no specific legislation for CHCP plants exist) becomes more and more important under the growing regulatory framework and support mechanisms concerning cogeneration [7]; in fact, energy/pollutant-emissions saving oriented and profit-oriented optimizations actually interact, because depending on the magnitude of the incentives to be fixed on harmonized bases in European Union (EU) countries, the internalization of "social cost" is expected to influence increasingly the profit-oriented optimizations. Hence, the need for a multi-objective decision function or a constrained optimization (constraints expressed by minimum energy savings to be assessed as environment-friendly system) is evident. In this paper an original approach to the optimization of polygeneration systems is proposed, which takes origins from the analysis of few basic concepts.

1. Design of grid-connected CHP or CHCP systems covering a variable energy demand cannot be effectively optimized with no regard to the optimization of management philosophy; these two aspects are strongly interrelated [8] and algorithms for the integrated optimization of design and operation are needed.
2. The internal demand variability plays a primary role in polygeneration applications for buildings, as evident in [9] where a rigorous approach to model the fluctuations from the average load and compute the effects on system's performance is presented.
3. Being electricity price highly variable on hourly basis, in order to maximise the profit a flexible management strategy should be pursued, to be optimized hour by hour. Thus, the adoption of a heat-tracking or an electricity-tracking operation should not represent a binding constraint. In this paper, appropriate indicators will be proposed to deal with hourly optimization of management strategy.
4. A technically-feasible operation should be ensured and kept into account since the optimization of design and operation. In this sense, the conventional approach to heuristic methods like the maximization of the energy supplied at full load operation on the duration curve of heat demand [10] will be conveniently adjusted.
5. The bi-directional power exchange with the grid, the dispatching priority for CHP electricity and the expected growth of Distributed Generation in energy supply of developed countries suggest more and more to focus on polygeneration systems as power producer and not only as "system dedicated to a single costumer". This approach, usually adopted for large industrial