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An analytical study of critical factors in residential cogeneration optimization

John Gelegenis [a,*], George Mavrotas [b]

[a] Technological Educational Institute of Athens, Ag. Spyridonos Street, 12210 Athens, Greece
[b] National Technical University of Athens, Iroon Polytexneiou 9, Zografou, 15780 Athens, Greece

HIGHLIGHTS

- Reasonable assumptions allow analytical approximation of optimum CHP capacity (error 3.3%).
- Optimum capacity depends primarily on base temperature and load duration curve.
- Full load operation (with thermal storage) lead to higher (>+10%) optimum capacities.
- Optimum capacity is dependent on the scale exponent (0.43) of CHP units cost.
- Energy prices proved to have a minor effect on the optimum capacity of cogeneration.

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ABSTRACT

An analytical study is elaborated to determine the principal factors that affect the optimum size of combined heat and power (CHP) units in residential applications. The optimum thermal capacity of CHP was found to correspond to 30–50% of the maximum heating load, but proved to be stronger correlated to the annual heating degree-days instead of the minimum temperature of the area. The optimum capacity was found dependent on the balance temperature of the dwelling; the shape of the ambient temperature duration curve; the economy of scale exponent of CHP units cost; the variation of CHP part load efficiencies. On the contrary, prevailing energy prices proved to have a minor effect on the optimum CHP capacity.

1. Introduction

Combined heat and power production (CHP) may lead to significant primary energy savings and a reduction of equivalent CO_2 emissions [1]. Despite the attractive concept behind CHP, in practice there are a lot of barriers that restrict its application, with the most important one probably being its high cost and the often limited utilization of the recoverable heat, especially when used in space heating applications. Indeed, CHP units are not always optimally dimensioned, thus affecting their performance and economy, as noticed by Hunt [2] "...*CHP is an important technology but, if used inappropriately, it will not offer the benefits that it has the potential to provide*...". For this reason the size of the plant should be carefully selected; this task is quite complicated however, being dependent on the diurnal and seasonal variation of the thermal and electrical loads, any scale economies, the achievable utilization factor, the technology of CHP, the strategy of operation, the energy prices, any financing possibilities and the prevailing legislative framework. The uncertainty in some of these factors (e.g. energy prices) seems to introduce additional difficulties in the design stage [3]. In spite of the complication of this issue, some rough guidelines are proposed by the manufacturers, like the specification of the thermal capacity of the unit at about 30–50% of the maximum thermal load to cover 50–70% of annual thermal needs and to achieve a minimum of 4000 h operation annually [4], which are quite generalized however.

Due to the technical and economic limitations, and the several parameters that affect the operation and economy of the system, the capacity of a CHP unit is actually based on a case by case optimization, rather than the adoption of any rule of thumb. Various optimization criteria have been suggested to this aim, like the mean annual profit [5], the determination of the hourly trend of the daily thermal load [6], the total life cycle emissions [7], or a compromise of some of them in a multi-objective approach [8]

* Corresponding author. Tel.: +30 210 538 5308; fax: +30 210 538 5306.
E-mail address: jgelegenis@teiath.gr (J. Gelegenis).

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Nomenclature

A,a	regression coefficients
B,b	regression coefficients
C	specific cost (€/kW h)
DD_H	heating degree-days (K-days)
E	energy (kW h)
I	investment (€)
n	efficiency
N	life time (years)
NB	net benefits (€)
P	capacity of the CHP unit (kW)
q	scale economy exponent
r	discount rate
t	time (days)
T_a	ambient temperature (°C)
T_b	base temperature of the dwelling (°C)
TLC	total heat loss coefficient of the dwelling (kW/K)
ΔT	heat demand intensity (K)

Greek letters

ε	part load (dimensionless)

Indexes

B	boiler
EL	electric
H	heating
$MAIN$	maintenance
NOM	nominal conditions
TH	thermal

Acronyms

BCR	benefit to cost ratio
CHP	combined heat and power
DHW	domestic hot water
DPBT	discounted pay-back time
IRR	internal rate of return
NPV	net present value
PWF	present worth factor
SPBT	simple pay-back time

(e.g. considering simultaneously the primary energy savings and the payback time). Although general purpose energy analysis software tools have been used in CHP evaluation (e.g. RETScreen [9]), dedicated simulation is necessary to accurately estimate the annual performance of the unit [10], which can be elementary elaborated by the use of a spreadsheet [11]. For accurate calculations in more complicated systems however (including more energy sources, thermal storage, simultaneous supply of electricity, high and low temperature heating or cooling) and under various conditions and constraints (variable tariffs, part load operation and efficiencies, consideration of start-up costs, load ramps etc.) detailed simulation is needed; in addition, the application of a powerful and efficient optimizing tool like the mixed integer linear programming MILP [12] is indispensable to concluding to the most appropriate strategy of operation.

The availability of models and tools to optimize the design (and operation) of a CHP system, becomes apparent from the literature review; the necessary steps have been elsewhere comprehensively presented [1]. Nevertheless, numerical solutions of the models are case specific; as a consequence, relevant results and experiences cannot be assumed as a rule in all cases, and detailed simulation and optimization remains necessary for each new project. Referring specifically to residential cogeneration systems, these are of small size (mainly up to 5–10 kW_e [13]) and of lower budget and probably with no provision for detailed optimization expenses. This situation may lead to improperly dimensioned units, affecting in this way both their economy, but most importantly the reputation of this technology; some indications of this unpleasant situation have already become apparent [2]. In this context, the development of an analytical approach to optimize the capacity of a CHP unit, and reveal the principal factors that mostly affect this optimum capacity, may prove to be a valuable tool for the engineers who are involved in this kind of projects. In the present work, a simplified model is firstly developed for the technical and economic prefeasibility evaluation of CHP for residential applications. To this aim, an Internal Combustion Engine (ICE) based CHP is assumed. Typical electrical loads of dwellings and the use of recoverable heat for space heating and production of domestic hot water (DHW) are taken into consideration. The analytical solution of the above optimization problem is developed, validated and finally used to determine the factors that primarily affect the optimum capacity of residential CHP units.

2. The model

A residential cogeneration system is assumed, including a commercial packaged CHP unit interconnected with the external electrical network and the heat distribution network of the dwelling. An auxiliary boiler covers the loads above the thermal capacity of the CHP unit; the CHP is switched on by priority when heating is necessary, and continues operating after the auxiliary boiler has been switched on. A boiler is suggested preferably, instead e.g., of a heat pump, as the application of the latter under low utilization factor (CHP will anyway cover the base load) would significantly increase the respective capital expenses. The heating system is modulating the load firstly with the use of the auxiliary boiler, whenever operating, and then with the CHP unit. The effect of thermal storage is separately investigated, as well; the considered system finally consists of the CHP unit, the auxiliary boiler, the thermal storage tank and the necessary control and electrical and thermal interconnections, as also considered in other similar works [13,14].

A variety of CHP operation modes are applicable, falling into the main categories of heat match or electrical match. In general the heat match mode leads to the highest primary energy savings [15], and is more cost-effective in buildings. Interconnection to the external electrical network allows supply of electricity and simultaneously injection of any surplus production by the CHP unit to the network. The same price is assumed for both buying and selling electricity to the network, which is approximately valid in net-metering application, thus ignoring in the potential benefits from feed-in-tariffs. Furthermore, a constant price of electrical energy is assumed, neglecting also any profit yielding or costly hours for the operation of the CHP. Actually, these chances (application of feed-in-tariffs, profitable hours) are generally variable in the long term, and in this sense the avoidance to base on these volatile factors the optimization, dimensioning and specification (design optimization) of a long-life and expensive equipment, like CHP is, sounds quite reasonable. Obviously, these factors will be