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Methods for optimized design and management of CHP systems for district heating networks (DHN)

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ABSTRACT

The paper analyzes some of the problems connected with the design, construction and management of cogeneration plants for district heating networks (CHP-DHN). Although the advantages of cogeneration systems compared with conventional ones for separate energy production, one of the unresolved problems is that of the variability of operating conditions, can often render the application of these solutions ineffective. In particular, the aim of this study is to propose a multi-objective optimization methodology that tries to take into account both energy and economic aspects.

After an analysis of the current scenario, the application and use of CHP plants in the international context and the main technological features, followed by the identification of incentive systems that have allowed or limited the spread, attempts are made to define a design methodology based on a multi-level optimum design based approach for increasing the operation share of CHP. The methodology starts from a general system vision, up to detailed aspects such as the management of a CHP-DHN system, taking into account the multiplicity of variables and constraints involved. This methodology has been applied to two case studies representative of the different applications, to verify its robustness and analyze the possible results obtainable.

In particular, a general case was taken into consideration, in which a first level design was performed by analyzing various possible system configurations and evaluating their goodness through the tools provided by the aforementioned multi-objective methodology. Then the methodology has been applied to an intermediate level, taking into consideration an existing CHP-DHN plant and going to evaluate the performance considering possible modification of the operation.

The results obtained confirm that a combined energetic and economic approach to design allows to obtain an economically feasible system, but at the same time avoids incurring over-sizing, under-sizing or functioning phenomena far from the concept of energy efficiency, difference of what happens for many plants today in operation. Furthermore, through a simple variation of the modularity of the plant, significant benefits can be obtained.

1. Introduction

The combined production of electricity and heat (Combined Heat and Power, CHP) allows, in principle, to improve the overall energy efficiency of complex energy systems compared to the case of separate electricity production in thermoelectric plants and heat in conventional systems [1].

A district heating network (DHN) is a heat supply system based on centralized production or localized in a few production units and on distribution to the end user through an energy vector consisting of a fluid in temperature. with further savings prerogatives [2]. The idea of combining cogeneration systems with district heating (CHP-DHN) arises from combining the advantages of the two technologies, which can be reconciled in a natural way, to obtain a more efficient energy system, with a total cost reduction and an improvement in terms of environmental impact.

Anyway the problem is that thermal civil/residential loads are often difficult to be predicted because they are characterized by a strong seasonal and daily variability, also due to the different use of buildings; moreover, the thermal demand sometimes presents high ratios between maximum and minimum values (peaks of 3–10 times the base load). This does not allow the plants to be used in conditions close to those of the project, imposing the mandatory use of thermal integration systems, like auxiliary boilers, with the specific function of covering the peaks of the thermal load [3].

To date the design of CHP plants for district heating (CHP-DHN) is

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Nomenclature

c	specific cost [€/kWh]
C	total cost value [€]
f	gain function [€]
F	dimensionless function
G	gain from the sale of energy [€]
I	exergy losses [W]
p	price [€/kWh]
P	power [W]
Q	thermal energy required for the operation [kWh]
$\dot{Q}$	thermal power [W]
r_p	relationship between prices of electricity and thermal energy
t_{eq}	equivalent time [h]
w	weight factor
$\dot{W}$	electrical power [W]

Greek symbols

α_{CHP}	cogeneration share
λ	cogeneration ratio
η	efficiency

Pedices, acronyms and abbreviations

biom	obtained using biomass as input fuel
boiler	of the boiler
CHP	Combined Heat and Power or of the cogeneration system
cn	cumulative normalized
DHN	District Heating Network
el	of the electricity
h	instantaneous value
grid	from the grid
GT	Gas Turbine
i	relative to the single user
I	relative to the irreversibilities (exergy losses)
ins	relative to the installation
load	of the whole thermal load
O&M	relative to operation and management
ref	reference value
ST	steam turbine
th	of the thermal energy
tot	total value

performed according to various methods, linked to technological needs, to economic incentive systems taking into account the characteristics of the loads to be satisfied. The choice of the management logic of these systems is one of the aspects that often constrain the sizing, producing, for similar applications, different engineering solutions [4].

In recent years, the diffusion of CHP plants has been strongly encouraged by the various national governments, especially in Europe [5]. The incentive system has often been linked to generic technical concepts such as "high performance" and "primary energy savings", by qualifying the plants through the use of synthetic indicators, the evaluation of which is often carried out in a particular condition. The use of these indicators, being connected to the design conditions does not evaluate the real operation of the plant. The economic advantage that derives from incentives tends therefore to overshadow some negative aspects related to the real operation of the systems [6]. In particular, observing the various CHP applications, there is a tendency to phenomena such as over-sizing or under-sizing, which cause distortions in the energy saving potential of those systems [7].

After carefully analyzing the problems related to the design and operation of the plants, the paper tries to develop an optimized multilevel design methodology, starting from a general analysis up to dealing with aspects of detail, and multi-objective, as it proposes a combined energy and economic analysis [8] assigning a penalty cost to the energy degradation: the aim is to maximize the share of cogeneration production by minimizing the contribution of additional thermal units (auxiliary boilers) thus reducing the irreversibility of the system. Then the methodology is applied to two case studies, one considering the design of a new plant starting from a typical load conditions, while the second is an optimization of the operation management of an existing plant considering the possible introduction of a storage system.

2. Cogeneration plants and district heating: technology, state of the art and open problems

The first element to be considered in the analysis of a CHP plants is the reference technology. Although often this is considered almost as a predetermined variable, this being mainly linked to the size, there are some peculiarities that make the various solutions quite different. A very important element is the parameter known as a cogeneration ratio λ, defined as the ratio between thermal and electrical power produced by the plant in nominal conditions:

$$\lambda = \frac{\dot{Q}}{\dot{W}} \quad (1)$$

the main CHP technologies currently available are shown in Table 1. A primary distribution system and a secondary one are required, deriving from the main line of distribution a network of pipes with reduced diameters and operating pressures. The network hosts secondary heat exchange substations and pumping substations. The exchange substations allow transferring heat for the final uses.

Fig. 1 shows a typical scheme of a district heating network with the various components (CHP units, auxiliary boilers, heat exchangers, storage systems and piping network); the typical values of the main operating parameters are shown in Table 2.

Table 1
Cogeneration technologies and main features.

	Technology	λ	Positive characteristics	Negative characteristics
Medium to high size	Steam turbine (ST)	0.5–10	Modulability, quite low costs	Quite low electrical efficiency, not good for intermittent operations
	Gas turbine (GT)	0.5–2.5	High temperature recovery, high flexibility	Low operational flexibility, medim to low efficiency values
	Combined cycle (CC)	0.5–3	High electric efficiency, possibility of modulation	Reduced starts-and-stops, high specific costs
Medium to low size	Internal combustion engines (ICE)	1–5	Flexibility, quite good efficiency at partial load	Direct link between electricity and thermal energy
	ORC plants (ORC)	0.5–10	Adaptability at Renewable Energy Sources	Use of a different operating fluid
	Fuel cells (FC)	0.5–2	Very low power	Technology not commercially developed
	Microturbines (μTG)	0.5–2.5	High quality technology	Reduced flexibility, quite low efficiency values, high costs