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Optimum sizing and operational strategy of CHP plant for district heating based on the use of composite indicators

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ABSTRACT

The aim of the paper is to discuss the possible use of Combined Heat and Power (CHP) plants and to highlight some abnormal effects, generated by the available support mechanisms, both in sizing and management and to propose guidelines for defining optimal operational strategies of CHP power plants. Some composite indicators are proposed to give a more comprehensive assessment of the performances of a plant, for the design and optimization phase and for a possible approach to support mechanisms. A new composite indicator is introduced in order to assess the benefits of different scenarios. The method is tested with reference to a case study: a medium size district heating system, powered by a CHP plant supported by conventional auxiliary boilers. Data coming from a real plant equipped with a remote monitoring system are analyzed. Operating data of a typical month are used in order to test the approach for the reference system. The paper shows how the use of the defined composite indicators can modify in a meaningful way the operating strategy of the CHP, increasing a lot the share of thermal energy produced with the CHP unit with respect to the conventional boilers.

1. Introduction

The economic impact and the environmental benefits generated by the application of cogeneration in the industrial sector led to the spread of this technology to civil and residential complexes. For this reason, Combined Heat and Power (CHP) systems have become an attractive alternative for heating, hot tap water and electricity production with sizes ranging from a few kW_{th}, for individual or multi-family dwellings, to some MW_{th} with special attention to commercial and public buildings like hospitals, schools and offices.

In order to encourage people to use CHP systems to generate simultaneously heat and electricity, after 1990 the governments of many countries have proposed many incentive policies and national programmes to promote the CHP systems. Especially UK, Netherlands and Denmark had adopted this policy, taking CO2 reductions into consideration. Other countries as Spain, Italy, Portugal and France have diffusely considered the use of gas-fired CHP, while countries as Sweden and Finland developed biomass based CHP. The advantages of small plants (differentiated into micro-CHP and small-CHP according to maximum electrical power required [1]), compared to conventional systems, in terms of energy efficiency [2], the environmental impact [3] and economic costs [4] are still object of study and great interest in the scientific literature. The market offers several types of mini-cogeneration-plants. CHP with conventional combustion engine, micro-turbines and fuel cells are the most common ones [5]. In contrast, larger plant sizes, if well designed, provide great economic and energetic advantages because they allow the application of well-established technologies such as internal combustion engines, steam turbines and gas turbines.

The project of the CHP plant is determined by several factors such as the availability of fuels that can feed the system [6], weather conditions [7], available technologies [8], the financial support context and obviously by the characteristics of the load that must be satisfied. Cogeneration is also preferred to heat and electricity separated production for the opportunity to benefit the electrical network balancing, especially in the presence of intermittent renewable sources with net production drops during the winter season. However, the existence of financial support mechanisms is often the more relevant element of promotion of CHP plants, instead of the attention to a real efficiency increase of the national energy system. In this framework, a critical point is the ability to plan an optimal control strategy to regulate the interactions between the

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Nomenclature

E	energy [kWh]
f	energy factor
h	hours [h]
I	exergy losses [kWh]
K	cost
P	power [kW]
Q	thermal energy [kWh]
Q^*	thermal energy coming from renewables [kWh]
t	time
U	utility function
w	weight factor for defining the utility function
W	electric energy [kWh]
Z	capital cost
ε	quantification factor for thermal energy value
γ	quantification factor for input energy value
γ^*	quantification factor for input energy from renewable energy value
η	efficiency
Ψ	composite utility function considering exergy losses
Ψ'	composite utility function considering exergy losses and renewable energy input
Ψ''	composite utility function considering different energy output

Subscripts

aux	required for the operation of auxiliary systems
dn	to the heat distribution network
e	relative to the environment
el	electric
fuel	of the fuel
GN	natural gas
in	input
k	referred to the k-th component of the system
n	net
out	output
P	primary energy
r	referred to the r-th main part of the system
th	thermal energy
u	distributed to the end-users

Abbreviations

CHP	Combined Heat and Power
DH	District Heating
DHN	District Heating Network
PEE	Primary Energy Efficiency
PEF	Primary Energy Factor; PES Primary Energy Saving

various components operating in the energy systems, like CHP systems and fluctuating renewable energy sources. The topic is covered in several papers available in the literature, like [9–11], taking into account the different perspectives of the problem.

The technical aspects that limit the spread of CHP plants in the residential sector are related to the characteristics of the demand for heat and electricity, i.e. very low intensity, limited duration, high temporal variability, low contemporary factor between daily electric and thermal load demands and highly unbalanced heat/electricity ratios.

Except in the case of district heating systems, residential users require small plants which have not yet achieved the scale economies that make them competitive in current market conditions: the specific investment costs grow highly with decreasing size and the return on investment is delayed by the reduced number of operation hours (typically smaller than 2000 annual equivalent hours) [12]. By contrast, the sector of public facilities is more suitable to be powered by CHP systems, especially hospitals, sport centres with swimming pools and hotels with spa because of high and constant loads during the year.

Even if the use of CHP for district heating networks has been largely supported, analysing the main applications of CHP units, a frequent observed situation is that systems do not operate at their full potential but mainly to cover the electrical self-consumption or the minimum values of the thermal load. Considering the very high variation of the thermal energy requirement, the most of the thermal demand is met by integration systems (in general a conventional boiler). Such management strategy does not follow the real purposes of the CHP connected to district heating networks because it does not take full advantage of the technology to reduce primary energy consumption and pollutant emissions. Another issue that complicates the system management also lies in the sizing of power generation systems: boilers are significantly oversized and are often forced to work at very low partial loads because of the large fluctuations in the heat demand. From an energy point of view, in a lot of specific application the marginal role of the CHP unit is clearly evident.

The topic of increasing the share of CHP generation in district heating systems is highly relevant. Considering the above exposed problems but knowing the real beneficial effect of the promotion of CHP plants for energy saving policies, the aim of the present paper is to propose some different point of view in order to appreciate the benefit of CHP technology both for industrial and civil sector. The definition of optimal strategies both for the design of the system and for the operation is proposed. A test case is used in order to analyse the differences between current results and optimized results. Finally, some proposal for the definition of tools for optimum design of CHP, considering operational objectives, and for the definition of future economic support policies of CHP-DHN plants, based on the use of some composed indicators, is discussed and analysed.

The paper is structured as follows: after an analysis of the state of the art of the support mechanisms for promotion of CHP plants and the recent evolution of the installation, in Section 3 the authors discuss about a methodological instrument for a correct analysis of CHP plants and propose the use of some different energy-based synthetic indicators that can support both the design of the plant and the definition of a correct operational strategy.

In Sections 4 and 5, the use of the various available indicators is discussed and tested with reference to a specific case and a final discussion about the possible impact of the methodology both on design and definition of operational strategy of CHP plants is provided.

2. Effects of support mechanisms for CHP plants and recent developments

Since the European Directive 2004/8/EC concerning the promotion of cogeneration, the principles on which the EU member states can encourage combined heat and power generation (CHP),