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Multi-objective optimization for the maximization of the operating share of cogeneration system in District Heating Network

Alessandro Franco *, Michele Versace

Department of Energy, Systems, Territory and Construction Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino 1, 56122 Pisa, PI, Italy

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ABSTRACT

The aim of the paper is to define optimal operational strategies for Combined Heat and Power plants connected to civil/residential District Heating Networks. The role of a reduced number of design variables, including a Thermal Energy Storage system and a hybrid operational strategy dependent on the storage level, is considered.

The basic principle is to reach maximum efficiency of the system operation through the utilization of an optimal-sized Thermal Energy Storage. Objective functions of both energetic and combined energetic and economic can be considered. In particular, First and Second Law Efficiency, thermal losses of the storage, number of starts and stops of the combined heat and power unit are considered. Constraints are imposed to nullify the waste of heat and to operate the unit at its maximum efficiency for the highest possible number of consecutive operating hours, until the thermal tank cannot store more energy.

The methodology is applied to a detailed case study: a medium size district heating system, in an urban context in the northern Italy, powered by a combined heat and power plant supported by conventional auxiliary boilers. The issues involving this type of thermal loads are also widely investigated in the paper. An increase of Second Law Efficiency of the system of 26% (from 0.35 to 0.44) can be evidenced, while the First Law Efficiency shifts from about 0.74 to 0.84. The optimization strategy permits of combining the economic benefit of cogeneration with the idea of reducing the energy waste and exergy losses.

1. Introduction

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.

CHP plants are particularly profitable in industrial sector but they are also suitable for applications in the civil/residential sector, where a combined and simultaneous use of electricity and thermal energy can be observed in a quite long period during the year and, in particular, in combination with residential District Heating Networks (DHN).

The diffused development of CHP plants is considered a strategic element to attain remarkable energetic, economic and environmental benefits. Several studies in the scientific literature have focused on the possible exploitation potential of CHP for the residential sector [1]. However, even though the combined generation of heat and power is in principle an highly efficient solution, compared with the separate production of electricity and thermal energy, it is necessary to consider in an accurate way the electrical and thermal load of the users, in particular an adequate level of heat demand close to the plant site: heat should be used in the proximity of the generation plant in contrast to electricity which can be fed into the grid.

In order to encourage people and communities to use CHP systems, after 1990 the governments of many countries have proposed many incentive policies and national programmes to support the CHP systems diffusion. Especially Netherlands and Denmark have adopted this policy, taking CO2 reductions into consideration too [2]. Other countries as Spain, Italy, Portugal, France, Sweden and Finland have diffusely considered CHP plants both in the version of gas-fired or in the alternative version of biomass based CHP. In many cases the CHP has been supported by a conventional system (auxiliary boilers) for thermal energy production, in order to integrate the production in special cases (for example in cases of increased heat load requirements) [3].

The effects produced by the support mechanisms in the European countries have been widely studied in the scientific literature,

* Corresponding author at: Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, Largo Lucio Lazzarino, 2, 56126 Pisa, Italy.

E-mail address: alessandro.franco@ing.unipi.it (A. Franco).

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Nomenclature

C	cost of the storage tank [€]
C_{cm}	specific cost of the storage tank [€]
C_r	reference cost [€]
E	energy [kW h]
f_i^{max}	maximum value for the *i*th performance parameter
f_i^{min}	minimum value for the *i*th performance parameter
F_i	constant factor of the composite indicator for the *i*th performance parameter
h	hours [h]
I	composite indicator
N	number of operation hours
T	temperature [°C]
U	heat transfer coefficient [W/m^2 K]
V	volume of the storage tank [m^3]
V_r	reference volume for the investment cost equation of the storage tank [m^3]
w	weighting factor of the composite indicator
α	exponent for investment cost of storage tank
η	efficiency

Subscripts

el	electric
th	thermal

Abbreviations

CHP	Combined Heat and Power
DD	Degree Days
DH	District Heating
DHN	District Heating Network
ELT	Electrical Load Tracking
FPO	Fixed Point Operation
HO	Hybrid Operation
ICE	Internal Combustion Engine
TES	Thermal Energy Storage
TLT	Thermal Load Tracking

both as regards the impact they had on the cogeneration evolution [4], both as regards the effectiveness in applying new technologies such as fuel cells [5] or the diversification of investments between the different states of Europe [6]. Some effects were positive as the system spread, optimization and cost reduction. Other effects were "distorted" because of the dominant role of economic elements. The main issues related to the development of CHP power plants have been oversizing, downsizing with a consequent increase of size of the conventional thermal system, or very low share of production of CHP systems in comparison with the conventional boilers, used to integrate the thermal energy production.

The commercial and residential sectors play an important role for further efficiency improvements. In the EU, the energy consumption for space heating and water heating is about 20% of the total energy consumption. In this context, an increase in CHP plants connected to district heating is one of the ways of improving efficiency in the EU, and, in a recent study, Connolly et al. have identified the potential of DH in the EU and have proposed a new "district heating plus heat savings" scenario to reach an 80% reduction in annual greenhouse gas emissions by 2050 [7].

In the last years, mainly in Europe, CHP plants are well considered not only for the typical advantage obtained with respect to separated production of heat and electricity, but also for the opportunity to benefit the electrical grid balancing, especially in presence of intermittent renewable sources [8].

Many technical elements, related to the characteristics of heat and electricity demand, limit the diffusion of CHP plants in the residential sector. CHP plants would require, for optimal operational strategy, a fixed proportion between electricity and heat production. On the contrary load in residential sector is characterized by the following peculiar elements: very low intensity, limited duration, high temporal variability, low contemporary factor between daily electric and thermal load demands and highly unbalanced heat/electricity ratios.

The project of the CHP plant is also determined by several factors such as the type of user [9], weather conditions [10], available technologies [11], the financial support and obviously the characteristics of the load. Additional constraints are imposed by the possibility to recover thermal energy from industrial activities (electricity generation from cogeneration, incineration of waste, etc.) or to exploit the resources that the territory makes economically and geographically accessible (biomass, geothermal resource, etc.). The use of renewable sources is still growing, despite the enormous potential, as it involves the need for accurate energy and economic analysis [12].

Several papers, like [13], propose analysis and methodological instruments for policy makers through which they can better orientate themselves among the different available technologies and the different scenarios determined by the specific climatic condition and the specific economic supply programme. Other contributions, like [14,15] analyze the problem of the correct management of CHP plants in the field of District Heating Networks.

In the various analysis available in the literature it is clear that the typical variations in the thermal load cannot be satisfied only by a CHP plant but an integration system is quite always necessary in order to support the operation of the CHP system: the size of CHP should be as large as possible, while the conventional boiler must be of reduced size. The use of Thermal Energy Storage (TES) system, discussed in the literature by some authors, can contribute to optimize the operational strategy, as [16,17].

Analysing the main applications of CHP units, it can be usually observed 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 major part of the thermal load is satisfied by means of the integration systems (in general a conventional boiler), while the CHP unit operates at partial load and for reduced times. Such management strategy does not follow the real purposes of the CHP plants because it does not take full advantage of the technology to reduce primary energy consumption, energy degradation (exergy losses) and pollutant emissions.

It is well known that the installation of a Thermal Energy Storage (TES) system and the use of a correct management strategy could aid in a meaningful way to reduce the exergy losses and to maximize the operating time of CHP. From an energy point of view, in a lot of specific applications, the marginal role of the CHP unit appears to be clearly evident.

The large potential for energy saving by cogeneration in the building sector is scarcely exploited due to a number of obstacles in making the investments attractive. The analyst often encounters difficulties in identifying optimal design and operation strategies, since a number of factors, either endogenous (i.e. related with the energy load profiles) or exogenous (i.e. related with external