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Energetic and economic assessment of cogeneration plants: A comparative design and experimental condition study

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ABSTRACT

In the present paper, the nominal design data and the experimental data of eleven industrial cogeneration power plants, based on different prime mover technologies and actually in operation in Italy, have been compared. The aim of the study is to compare the expected energetic and economic results with the real performance and economic profitability of the plants in operation: the analyses have highlighted that, in the design phase, the simple payback time is usually underestimated. An assessment of the European incentives policy on cogeneration has also been undertaken, focusing on Italian legislation, which foresees a tax reduction for fuel and Tradable White Certificate support mechanisms: these incentives allow an average SPB (Simple PayBack) reduction of about 15–20%. A sensitivity analysis on the SPB has also been performed, changing the fuel and maintenance costs, and the thermal and electrical energy prices, and the particular features of the different CHP (Combined Heat and Power) technologies have been pointed out.

1. Introduction

CHP production (Combined Heat and Power), commonly called cogeneration, allows the efficiency of a power plant to be increased as the exploitation of the primary energy is improved, and environmental impacts, compared to separate heat and power production, are therefore reduced. In 2004, the European Commission issued Directive 2004/8/EC [1], which determines the requirements of a CHP plant to be classified as a "HEC plant" (High Efficiency Cogeneration) and assigns the decision on how to increase cogeneration to each individual European country. As a consequence of the 2004/8/EC Directive, many countries in the EU have launched new support mechanisms to make this technology economically more attractive [2,3].

The installation of a cogeneration plant, in fact, requires important initial capital investments, and the possibility of taking advantage of any form of subsidy can therefore influence the final decision on whether to proceed with the investment to a great extent. The evaluation of the economic profitability of cogeneration plants is a topic that has already been dealt in detail in the literature. For example, a simple model for the profitability analysis of a CHP system at different power levels has been presented in Ref. [4], while in Ref. [5] the authors have developed a reliable tool for the economic evaluation of cogeneration systems in order to improve the decision making process. A cash-flow analysis was performed in Ref. [6], to determine the SPB period (Simple PayBack), the IRR (Internal Rate of Return) and the NPV (Net Present Value) of a cogeneration system with thermal energy storage, together with a sensitivity analysis on the interest rate, fuel price and the electricity price. An economic assessment of the application of cogeneration systems in different climate zones in Iran has been performed in Ref. [7], in which a sensitivity analysis on the Cost Saving Ratio, an index defined by the authors, which shows how the profitability of CHP systems is influenced by both the energy prices and the heating period, has also been carried out. A techno-economic assessment and sensitivity analysis have also been performed in Ref. [8] in order to investigate the feasibility of a large sized (300 MW_{el}) biofuel CHP power plant in Sweden (natural gas combined cycle system) for different biofuel fractions. In Ref. [9], the potential for cogeneration systems in the sugar industry in Vietnam has been evaluated, together with a sensitivity analysis on the IRR, and a higher dependence of this index on the electricity buyback rates than on the investment cost variation has been shown. An economic profitability analysis, in which the performances of three different CHP technology solutions, for an industrial user with a large steam demand, were compared and a sensitivity analysis on the NPV index was implemented to identify which solution can offer the highest profits, has also been

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Nomenclature

P_{el}	net electrical power delivered by the CHP plant
P_{fuel}	input fuel power to the CHP plant
P_{th}	thermal power recovered from the CHP plant
C_{el}	electricity price
C_{th}	thermal energy price
C_{fuel}	natural gas price
E_{fuel}	primary energy of fuel into the CHP plant
E_{el}	total electricity produced by the CHP plant
E_{th}	total thermal energy produced by the CHP plant
C_{eff}	correction factor for the $E_{el,CHP}$ calculation
$E_{el,CHP}$	electricity quota which has to be accounted to calculate a tax reduction
$E_{el,NO\ CHP}$	electricity quota not considered for tax reduction
$E_{fuel,CHP}$	fuel energy quota which has to be accounted to calculate a tax reduction
η_{el}	electrical efficiency of the CHP plant
η_{th}	thermal efficiency of the CHP plant
$\eta_{el,s}$	electrical efficiency of the reference separate production
$\eta_{th,s}$	thermal efficiency of the reference separate production
I	investment cost
LHV_{fuel}	lower heating value of natural gas
$C_{O\&M}$	operation and maintenance costs
$FUEL_{no\_tax}$	quantity of fuel that can obtain a tax reduction
K	coefficient for the calculation of Tradable White Certificates
$C_{I,sp}$	specific power plant investment cost

Acronyms

AEEG	Italian electricity and gas authorities
BOP	balance of plant
CC	combined cycle power plant
CHCP	combined heat, cooling and power
CHP	Combined Heat and Power
EBITDA	earnings before interest, taxes, depreciation and amortization
EU	European Union
EUF	energy utilization factor
GT	gas turbine power plant
HEC	High Efficiency Cogeneration
HRSG	heat recovery steam generator
HTW	high temperature hot water
ICE	internal combustion engine power plant
IEA	International Energy Agency
IRR	internal rate of return
LTW	low temperature hot water
O&M	operation and maintenance
PES	primary energy saving
PES_R	recognized PES
PES_{min}	minimum value of PES to be reached by a CHP plant to be classified as an HEC plant
SHW	super-heated water
SHS	super-heated steam
SPB	Simple PayBack
SS	saturated steam
TWCs	Tradable White Certificates

presented in Ref. [10]. The NPV index was also employed in Ref. [11], to assess the profitability of a CHP installation for a factory plant, and in Ref. [12], where the profitability of a university campus CHP investment was investigated.

As far as subsidies and cogeneration support schemes are concerned, an analysis of the support schemes has been presented in Ref. [2], in which the theoretical aspects of the governing laws promoting cogeneration in some European countries and in the US have been compared. Another study has been conducted in Ref. [13], where CHP promotion schemes in EU countries, including the Italian subsidy mechanism based on TWCs (Tradable White Certificates), have been described, while an analysis of the current Spanish legislation, regarding the promotion of cogeneration, has been performed in Ref. [14]. The same topic has also been studied in Ref. [15], where the authors have modeled a 28 kW_{el} natural gas internal combustion engine in order to investigate the effect of subsidies on the SPB and NPV indexes. Obviously, in order to carry out these analyses, it is necessary to have operational data of the plants under investigation available as input. These data can be taken, for example, from detailed energy audits, such as in Ref. [16], where the authors presented an economic analysis of a cogeneration power plant installed in Turkey, considering experimental data measured during a specified operational period. In other cases, data have been derived from statistical surveys found in literature [13,17], with consequent uncertainties on the assumed values.

The aim of the present work was to conduct a techno-economic evaluation of eleven CHP plants operating in Italy with different kinds of prime movers, such as ICE (internal combustion engine), CC (combined cycle) and GT (gas turbine) technologies. The novelty of this work is that a double set of data has been available for each power plant: design data, foreseen by the engineers during the plant design phase, and real data, obtained experimentally over a full working year. The availability of experimental data obviously leads to a more reliable and realistic evaluation of the energetic performances. The discrepancies between the predicted and the actual figures have been studied, and a comparative energetic analysis has been performed, considering the actual legislation in force, that is, Directive 2004/08/EC [1,18]. A detailed analysis of the subsidy mechanisms foreseen by Italian legislation has also been conducted, together with a sensitivity analysis on the payback periods, and the results obtained when design data have been considered, rather than real operational data, have been highlighted. The results are presented and discussed in detail in the following sections.

2. Description of the plants

The eleven cogeneration power plants analyzed in this work operate in different industrial sectors, ranging from the automotive to the food sector. The thermal production of the CHP plants almost entirely meets the users' requirements, while the electrical production is mainly self-consumed by the users, and any eventual surplus is sold to the National grid. Five plants have internal combustion engines as prime movers, six plants have gas turbines and three are combined cycle power plants. The nominal technical data of the ICE, CC and GT power plants are reported in Tables 1 and 2.

Both design and real experimental data have been taken into account in the energetic performance assessment. The design data were based on the estimated electricity and heat consumption of the users, while the real data were instead related to one year of effective plant operation. Results are shown in Figs. 1 and 2, for the design data and the real operational ones, respectively. The post-