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Trigeneration primary energy saving evaluation for energy planning and policy development

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Abstract

Trigeneration or combined heat, cooling and power (CHCP) is becoming an increasingly important energy option, particularly on a small-scale basis (below 1 MW_e), with several alternatives nowadays available for the cooling power production and the coupling to cogeneration systems. This paper deals with the introduction of a suitable framework for assessing the energy saving performance of trigeneration alternatives, orientated towards energy planning studies and the development of regulatory policies. In particular, a new generalized performance indicator—the trigeneration primary energy saving (TPES)—is introduced and discussed, with the aim of effectively evaluating the primary energy savings from different CHCP alternatives. The potential of the TPES indicator is illustrated through specific analyses run over different combinations of trigeneration equipment, providing numerical examples based on time-domain simulations to illustrate the dependence of the energy saving characteristics on the CHCP system configurations and equipment, as well as on the loading levels. In addition, the key aspect of adequately establishing the reference efficiencies for the conventional separate production of electrical, thermal and cooling power is addressed in detail. This aspect affects both equipment selection and potential profitability of the considered solutions under the outlook of receiving financial incentives.

Keywords: Trigeneration; Energy efficiency; Primary energy savings

1. Introduction

In recent years, the operators of the energy sector have put an increasingly high focus on issues concerning energy saving and implementation of high-efficiency energy systems, both from the technical and from the regulatory point of view (Cardona and Piacentino, 2005). In particular, the latest concerns in the energy sector are mainly related to the worldwide increase of energy consumption, the attempts to reduce the energy dependence from some regions of the world holding a relevant share of fossil primary sources and the emergence of binding environmental constraints aimed at limiting the production of greenhouse gases (GHGs). In addition, the development of liberalized energy markets in many countries has created new interests for analyzing the possibility of exploiting the equipment available for electricity production in a more profitable way.

Cogeneration (Horlock, 1997) is being extensively used as an efficient technique to produce heat and electricity, leading to a substantial energy saving with respect to the "conventional" separate production (SP) of the same energy vectors, respectively, in heat generators and in the power system. In particular, in the past, mostly because of economy-of-scale reasons, cogeneration was limited to large-sized (industrial and district heating) plants. Yet, the recent development of "thermal" distributed generation (DG) technologies, such as microturbines (MTs) and internal combustion engines (ICEs) (Willis and Scott, 2000; Borbely and Kreider, 2001) has enabled the deployment of various small-scale (below 1 MW_e) applications. In addition, DG technologies are being encouraged in several countries owing to their high potential for emission reduction of CO_2 and other hazardous pollutants, as, for instance, discussed by Strachan and Dowlatabadi (2002) and Strachan and Farrell (2006). As a further point, fuel

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Nomenclature

Acronyms

CERG	compression electric refrigerator group
CHCP	combined heat, cooling and power
CHG	combustion heat generator
CHP	combined heat and power
COP	coefficient of performance
DG	distributed generation
EDC	engine-driven chiller
EHP	electric heat pump
FC	fuel cell
FESR	fuel energy saving ratio
GARG	gas absorption refrigerator group
GHG	greenhouse gases
ICE	internal combustion engine
LHV	lower heating value
MT	microturbine
SP	separate production
TPES	trigeneration primary energy saving
WARG	water absorption refrigerator group

Symbols

Subscripts represent energy sources or end use (y = cogeneration, z = trigeneration, e = electricity, t = thermal, c = cooling, F = fuel, d = demand) and specify the measuring units. For the energy vectors, the same symbols are used for energy (kWh) or average power (kW): W for electricity, Q for heat, R for cooling (refrigeration), F for fuel thermal content. The Greek letters η and ε denote efficiency.

cells (FCs) (Willis and Scott, 2000; Borbely and Kreider, 2001) could play an important role in the future, within alternative high-efficiency energy scenarios based on a potential hydrogen economy (Clark and Rifkin, 2006; McDowall and Eames, 2006).

Several small-scale cogeneration applications, besides heat and electricity, require cooling power (e.g., for air conditioning purposes). In order to supply this threefold energy need, it is possible to set up the so-called *trigeneration* or combined heat, cooling and power (CHCP) plants (EcoGeneration Solutions LLC Companies, 1999; Resource Dynamics Corporation, 2003).

Trigeneration can be seen as the simultaneous production of electricity, heat and cooling power from the same source of energy (typically gas). From this point of view, a trigeneration plant can be considered as the extension of a cogeneration or combined heat and power (CHP) plant. The literature typically refers to trigeneration as the combination of a traditional CHP prime mover (i.e., a thermal machine such as an ICE, a MT or a FC that cogenerates electricity and heat) with an absorption group, fed by hot water or steam produced by the cogeneration group (Colonna and Gabrielli, 2003; Bassols et al., 2002; Maidment and Prosser, 2000; Hwang, 2004). The rationale of this approach is based on the potential efficiency of using the thermal power cogenerated also in the summertime to fire the absorption machine for cooling production, enabling better and longer exploitation of the prime mover, as shown, for instance, by Havelsky (1999), Heteu and Bolle (2002), and Cardona and Piacentino (2003). This kind of application may be referred to as "seasonal" trigeneration. However, an array of other applications (for instance, hospitals, department stores, hotels and so forth) require an actual trigeneration production throughout the whole year, so that the optimal setup of the plant, also accounting for the economic issues, could be different from the cases of seasonal trigeneration. Thus, in previous works (Chicco and Mancarella, 2005, 2006; Mancarella, 2006), the authors have considered a generalized concept of trigeneration, considering a set of different optional technologies and sizes for the cooling side coupled to the CHP side.

As a consequence of the increasing diffusion of various types of plants, the evaluation of a trigeneration system is becoming a crucial issue and requires the adoption of adequate performance indicators. From this perspective, the energy savings attributable to adopting one plant configuration compared with another could be a suitable indicator for evaluating and comparing the effectiveness of each alternative. However, the definition of "energy saving" in a trigeneration system also needs to be discussed and clarified. In fact, as pointed out by Chicco and Mancarella (2006), classical tools for evaluating CHP plants, such as the fuel energy saving ratio (FESR) indicator (Horlock, 1997), are not always adequate for CHCP plant assessment. Thus, other approaches may be necessary, such as the ones taken up by Havelsky (1999) and Heteu and Bolle (2002), that assess trigeneration systems by explicitly accounting for the SP of cooling power, besides heat and electricity. In addition, it is not always clear *how* to evaluate specific energy savings and *what* reference situation to apply (Boonekamp, 2006). As a further fundamental point, to date and to the authors' knowledge, there is no official regulatory framework dealing with the issue of evaluating the performance of CHCP systems. Differently, CHP plants, whose energy saving are officially recognized and expressed through suitable indicators, receive financial incentives in many countries. The details are discussed by Cardona and Piacentino (2005), with practical applications provided, for instance, in Italy by Deliberation no. 42/02 of the Italian AEEG (2002), and in the European Directive