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Emission characterization and evaluation of natural gas-fueled cogeneration microturbines and internal combustion engines

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ABSTRACT

The increasing diffusion of small-scale energy systems within the distributed generation (DG) paradigm is raising the need for studying the environmental impact due to the different DG solutions in order to assess their sustainability. Addressing the environmental impact calls for building specific models for studying both local and global emissions. In this framework, the adoption of natural gas-fueled DG cogeneration technologies may provide, as a consequence of cogeneration enhanced overall energy efficiency and of natural gas relatively low carbon content, a significant reduction of global impact in terms of CO_2 emissions with respect to the separate production of electricity and heat. However, a comprehensive evaluation of the DG alternatives should take into account as well the impact due to the presence of plants spread over the territory that could increase the local pollution, in particular due to CO and NO_x, and thus could worsen the local air quality.

This paper provides an overview on the characterization of the emissions from small-scale natural gas-fueled cogeneration systems, with specific reference to the DG technologies nowadays most available in the market, namely, microturbines and internal combustion engines. The corresponding local and global environmental impacts are evaluated by using the emission balance approach. A numerical case study with two representative machines highlights their different emission characteristics, also considering the partial-load emission performance.

1. Introduction

In recent years, the energy systems have evolved towards increasing adoption of local generation sources connected to various points of the electricity distribution systems, commonly defined as distributed generation (DG) [1–4]. However, the impact of the DG paradigm with respect to the centralized electric power system goes well beyond the electricity-only generation outlook. Indeed, various small-scale (below 1 MW_e) *thermal* prime mover technologies, such as internal combustion engines (ICEs) and microturbines (MTs), allow for exploiting the thermodynamic exceeding heat for on-site production of cogenerated thermal energy. Cogeneration plants, also known as combined heat and power (CHP) plants, are widely acknowledged for their excellent overall efficiency in terms of fuel consumption with respect to the separate production (SP) of the same cogenerated energy vectors (namely, heat and electricity) [5,6]. However, for decades cogeneration has been basically limited to industrial and district heating applications, mostly due to economy-of-scale reasons [5,7]. On the contrary, the latest years, owing to the progressive market diffusion and performance improvement of MTs and ICEs for DG, are witnessing an increasing deployment of the CHP potentiality also towards small-scale applications; for instance, among the most suitable sites it is possible to mention office buildings, hospitals, hotels, residential blocks, swimming pools, universities, shopping malls, and so forth [2,7–9].

The diffusion of DG technologies has been accompanied, at the same time, by a number of research programmes around the world, aimed at improving the performance of small-scale energy systems (see for instance [10]), as well as reducing the emissions from electricity generation. This is due to a host of reasons, above all need for preserving the fossil sources, cutting down of the production of CO_2 as a greenhouse gas (GHG), in particular claimed by the Countries signing the Kyoto's Protocol, and arising of a more mature awareness on several environmental and sustainable development aspects, also from a regulatory point of view [11].

The promotion of DG suits well this scenario, having among its objectives to resort to the use of renewable sources, able to provide energy with a lower impact on the environment.

CHP plants, as well known, are often assimilated in several Countries to energy systems fed by renewable sources, and as such they

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Nomenclature

Acronym list

CHG	combustion heat generator
CHP	combined heat and power
DG	distributed generation
DLN	dry low NO_x
GHG	greenhouse gases
ICE	internal combustion engine
LCA	life cycle assessment
LHV	lower heating value
MT	microturbine
NMOC	non-methane organic compounds
NSCR	non-selective catalytic reduction
PM	particulate matter
SCR	selective catalytic reduction
SP	separate production
SVOC	semi-volatile organic compounds
UHC	unburned hydrocarbons
THC	total hydrocarbons
VOC	volatile organic compounds

Subscripts

e	electricity
p	pollutant
t	thermal energy
y	cogeneration

Letters

F	fuel thermal content [kWh_t]
Q	heat [kWh_t]
W	electrical energy [kWh_e]
X	generic energy vector [kWh]
m	mass [g]
Δ	difference operator
λ	air ratio
μ	emission factor [mg/kWh]
η	efficiency

may enjoy regulation incentives [11,12] (Deliberation 42/02 [13] for Italy); this is due to their high overall efficiency that allows for enhanced exploitation of the primary energy contained in the fuel.

However, whilst basically all CHP plants provide primary energy saving with respect to the heat-and-electricity separate production, and thus potential CO_2 emission reduction at a *global* level [4,14], the impact of a CHP DG system over the environment is an issue to analyze with care, since several components come into play while evaluating the changes induced by the generation system in the surrounding areas, in the climate and in the ecosystems [15,16]. In particular, the diffusion of small-scale DG plants over urban areas might worsen the *local* air quality [8,17,18], also depending on the characteristics of the stack and of the site; often this aspect is not sufficiently addressed when evaluating the environmental impact of DG. Furthermore, despite the importance of the debated issue, official regulations are yet scarcely available in this field, which increases the uncertainty from the investors and thus risks to shrink the DG market potentiality. As an additional hurdle, there is also the lack of comprehensive data on the equipment emission characteristics (for instance at partial loads) [19], as well as the intrinsic difficulty of drawing general and effective models even for similar equipment [20].

In this work, following the lines drawn in [21], the main performance and emission characteristics of the most widespread small-scale CHP equipment, MTs and ICEs, both natural gas-fed [2,3,22], are presented and discussed. In particular, among the *criteria air pollutants* limited by law in many Countries (see for instance [23]), the substances considered most hazardous to the human health, namely NO_x and CO, are analyzed in detail. The analysis is extended to entail also CO_2 because of its GHG characteristics. The environmental impact from natural gas DG CHP systems on both *local* and *global* levels is addressed according to the *emission balance* model [8]. In addition, further considerations regarding possible extension to entail other types of machines as well as fuels by means of a life cycle assessment (LCA) approach [15,24,25] are provided. The concepts of global and local emission balance are highlighted with a numerical case study that illustrates the different local and global environmental impact characteristics, with respect to the separate generation of heat and electricity, of commercially available natural gas MTs and ICEs. A specific focus is set on the different out-of-design emission behavior from the two technologies, which might change the emissive scenario of the relevant pollutants with respect to the full-load operation.

2. Components and models of distributed cogeneration plants

2.1. General structure and components of a small-scale CHP plant

A general cogeneration plant scheme is basically composed of a CHP prime mover and an auxiliary combustion heat generator (CHG) plant, as shown in Fig. 1 [26]. The final use of the produced energy vectors (heat Q and electricity W) is to supply the user's needs or to inject the exceeding electricity into the electrical grid, as well as to use the exceeding heat for local purposes or to send it to a district heating network. The prevalent fuel adopted for small-scale applications is natural gas, above all in urban areas, also owing to the broad availability of distribution networks, as well as to the relatively lower environmental impact with respect to other fuels, as pointed out in the sequel. Thus, F indicates the thermal energy contained in the natural gas, based on the fuel LHV. The subscript y, in particular, refers to cogeneration entries.

The CHP prime mover is the core of the plant. The technologies nowadays most adopted on a small-scale basis are the MT and the ICE, while fuel cells might play a more important role in the future. If the prime mover is a MT, usually the heat is recovered by means of either hot water or steam, for whose production conventional heat exchangers or recovery boilers can be used [2,8,9,22,27]. If the prime mover is an ICE, hot or superheated water can be produced, as well as steam, by recovering heat from exhaust gases, jacket cooling water, lubricant circuit and intercooler air [2,8,22,27].

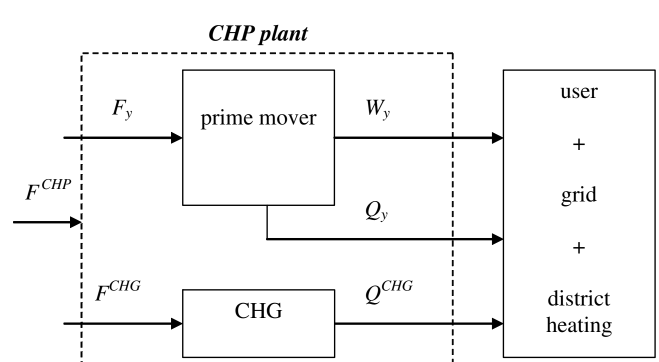

Fig. 1. General CHP plant scheme.