Applied Energy 86 (2009) 2096–2106

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Global and local emission impact assessment of distributed cogeneration systems with partial-load models

Pierluigi Mancarella [a,b], Gianfranco Chicco [b,*]

[a] Imperial College London, Department of Electrical and Electronic Engineering, Exhibition Road, SW7 2AZ London, UK
[b] Politecnico di Torino, Dipartimento di Ingegneria Elettrica, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 29 February 2008
Received in revised form 17 December 2008
Accepted 20 December 2008
Available online 3 February 2009

Keywords:
Cogeneration
Distributed generation
Emission factor
Emission reduction
Environmental impact
Greenhouse gases
Local emissions
Microturbine
Natural gas

ABSTRACT

Small-scale distributed cogeneration technologies represent a key resource to increase generation efficiency and reduce greenhouse gas emissions with respect to conventional separate production means. However, the diffusion of distributed cogeneration within urban areas, where air quality standards are quite stringent, brings about environmental concerns on a local level. In addition, *partial-load* emission worsening is often overlooked, which could lead to biased evaluations of the energy system environmental performance.

In this paper, a comprehensive emission assessment framework suitable for addressing distributed cogeneration systems is formulated. *Local* and *global* emission impact models are presented to identify upper and lower boundary values of the environmental pressure from pollutants that would be emitted from reference technologies, to be compared to the actual emissions from distributed cogeneration. This provides synthetic information on the relative environmental impact from small-scale CHP sources, useful for general indicative and non-site-specific studies. The emission models are formulated according to an *electrical output-based emission factor* approach, through which off-design operation and relevant performance are easily accounted for. In particular, in order to address the issues that could arise under off-design operation, an *equivalent load model* is incorporated within the proposed framework, by exploiting the duration curve of the cogenerator loading and the emissions associated to each loading level. In this way, it is possible to quantify the contribution to the emissions from cogeneration systems that might operate at partial loads for a significant portion of their operation time, as for instance in load-tracking applications.

Suitability of the proposed methodology is discussed with respect to hazardous air pollutants such as NO_x and CO, as well as to greenhouse gases such as CO_2. Two case study applications based on the emission data of real microturbines are illustrated in order to highlight the effectiveness of the proposed assessment techniques. The numerical results exemplify the emission impact of distributed cogeneration systems operating under general and realistic loading conditions with respect to average and state-of-the-art conventional technologies.

1. Introduction

Assessing the environmental impact from conventional (centralized) and decentralized generation paradigms is particularly relevant in today's changing energy scenario that is witnessing a radical shift from the *status quo* towards more distributed energy systems. The adoption of cogeneration or Combined Heat and Power (CHP) systems for *small-scale* applications (below 1 MW_e) is one of the key drivers to the diffusion of thermal prime movers for Distributed Generation (DG) [1]. CHP systems are effective in reducing the primary energy consumption with respect to the conventional Separate Production (SP) of heat (produced in boilers) and electricity (produced in power plants) [2]. The most adopted DG CHP technologies are fuelled on Natural Gas (NG) and include Internal Combustion Engines (ICEs) and, more recently, Microturbines (MTs) [3,4]. The reduction in the fuel consumption from such CHP systems could bring a corresponding reduction of *global* emissions of CO_2 seen as a Greenhouse Gas (GHG) [5–7].

The evolution of the energy generation scenario envisages a deeper penetration of CHP systems inside *urban areas*, where *local* emissions of hazardous air pollutants such as NO_x, CO, SO_x, Particulate Matter (PM), Unburned Hydrocarbons (UHC), and so on, may pose serious concerns [8–12]. Indeed, in urban contexts dispersion in the atmosphere of pollutants from small-scale generators sited among buildings may be more difficult than,

* Corresponding author. Tel.: +39 011 090 7141; fax: +39 011 090 7199.
E-mail addresses: p.mancarella@imperial.ac.uk (P. Mancarella), gianfranco.chicco@polito.it (G. Chicco).

0306-2619/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2008.12.026

Nomenclature

Acronyms

BAT	best available technologies
CHP	combined heat and power
CO2ER	CO_2 emission reduction
DG	distributed generation
FESR	fuel energy savings ratio
GHG	greenhouse gases
GSP	global separate production
ICE	internal combustion engine
LHV	lower heating value
LSP	local separate production
NG	natural gas
MT	microturbine
PM	particulate matter
SP	separate production
UHC	unburned hydrocarbons

Symbols

F	fuel energy content (*LHV*-based) [kWh_t]
M	number of hourly time intervals in the period of observation
N	number of loading levels
Q	heat [kWh_t]
W	electricity [kWh_e]
X	generic energy output [kWh]
d	duration weight
m	mass of pollutant [g]
n	number of hourly time intervals associated to a loading level
η	efficiency
μ	emission factor [g/kWh]

Subscripts

e	electrical
i	dummy index
p	pollutant
t	thermal
y	cogeneration
$x\%$	percentage loading level

Superscripts

F	fuel
GSP	global separate production
LSP	local separate production
Q	heat
SP	separate production
W	electricity
X	generic energy vector
y	cogeneration

for instance, for big power plants with high stacks [13]. In addition, also due to the high population density, there is a number of relative weak *receptors* (elderly and sick people, children, etc.), with other potential impacts of pollutant emissions referred to ecosystems, monuments, and so forth [14]. A further critical point is represented by the already high background emission level mostly due to road traffic pollution. As a consequence, air quality standards and emission level limits can be quite stringent in urban areas, and environmental assessments tend to be conservative. Nevertheless, often little attention is paid at a regulation and planning stage to the emission worsening that could be brought about by consistent operation of DG systems at partial loads. This could lead to biased environmental assessment of thermal DG that were to be evaluated only on the basis of the full-load performance, whereas load-tracking operation can frequently occur for both thermal and electrical applications. In the latter case, in particular, future power system portions operated as microgrids [15,16] could more and more include the adoption of small-scale CHP or micro-CHP systems.

The complexity of the issues involved in environmental assessments of distributed energy systems in urban fabrics calls for adequate approaches and methodologies. In this outlook, a systematic framework for evaluating the emission impact of small-scale CHP systems under general partial-load conditions is presented in this paper. The *distributed* nature of DG systems with respect to centralized power plants is addressed through a conceptual distinction between *local* and *global* emissions. Specific models based on an emission factor approach are formulated for assessing global emissions, and for approximately representing the contribution to the environmental impact due to local emissions from sources close to the receptors. The outcomes obtained from the two models can be seen as representative of boundary conditions, providing useful information to assist the operators to better understand the results under the large uncertainties characterizing the data used in the study. In the framework introduced, the relevant quantities characterising energy efficiency and local and global emissions (formulated in terms of *equivalent reference emission factors*) are referred to the electrical output of the CHP system. This allows the development of analyses depending on generic operational and loading conditions of the CHP system. In particular, an *equivalent load approach* is introduced to take into account the wide range of loading levels (with the corresponding off-design emissions) at which a CHP system might be operated. Thereby, an integrated emission assessment for DG CHP systems is addressed by incorporating the equivalent load model into the local/global emission assessment methodology.

The above issues are illustrated in the rest of the paper as follows. Section 2 introduces the representation of the energy efficiency and emission characteristics of cogeneration systems, with special focus on partial-load modelling. Section 3 describes and discusses the global and local emission assessment models, and introduces the relevant equivalent reference emission factors. Section 4 illustrates general issues related to off-design emission characterization for small-scale CHP equipment and presents the equivalent load approach. Section 5 reports the results from the methodology introduced here for two specific case study applications with commercially available MTs. The last section contains the conclusive notes.

2. Cogeneration energy efficiency performance and emission characterization

2.1. Cogeneration energy efficiency performance

The energy efficiency performance of a CHP system is characterized by representing the partial-load operation conditions in function of the electrical output W_y (the subscript y points out *cogeneration* entries). Considering the fuel thermal input F_y (based on the *Lower Heating Value – LHV*) and the thermal output Q_y, it is possible to define the *electrical*, *thermal*, and *overall cogeneration efficiencies* respectively as