Energy Conversion and Management 79 (2014) 749–770

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part II: Environmental and economic analyses

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A R T I C L E I N F O

Article history:
Available online 25 October 2013

Keywords:
Cogeneration
Thermoeconomic analysis
Transient operation
Energy saving
Carbon dioxide
Operating cost

A B S T R A C T

This work examines the performance of a residential building-integrated micro-cogeneration system during the winter by means of a whole building simulation software. The cogeneration unit was coupled with a multi-family house composed of three floors, compliant with the transmittance values of both walls and windows suggested by the Italian Law; a stratified combined tank for both heating purposes and domestic hot water production was also used for storing heat. Simulations were performed considering the transient nature of the building and occupant driven loads as well as the part-load characteristics of the cogeneration unit.

This system was described in detail and analyzed from an energy point of view in the companion paper. In this paper the simulation results were evaluated in terms of both carbon dioxide equivalent emissions and operating costs; detailed analyses were performed in order to estimate the influence of the most significant boundary conditions on both environmental and economic performance of the proposed system: in particular, three volumes of the hot water storage, four climatic zones corresponding to four Italian cities, two electric demand profiles, as well as two control strategies micro-cogeneration unit were considered. The assessment of environmental impact was performed by using the standard emission factors approach, neglecting the effects of local pollutants. The operating costs due to both natural gas and electric energy consumption were evaluated in detail, whereas both the capital and maintenance costs were neglected; the revenue from selling the electric energy surplus was also taken into account.

The performance of the proposed system was also compared with those of a conventional system composed of a natural gas-fired boiler (for thermal energy production) and a power plant mix connected to the national central grid (for electricity production) in order to assess its suitability in comparison to the systems based on separate energy production from both environmental and economic point of views.

The analyses were carried out with respect to the Italian scenario, by considering the most meaningful indexes suggested in current literature.

1. Introduction

In recent years, the energy conversion systems have evolved towards increasing the adoption of local generation sources connected to various points of the electricity distribution systems, commonly defined as distributed generation. Micro-cogeneration plants, also known as combined heat and power systems with an electric output lower than 50 kW_{el}, are widely acknowledged for their excellent overall efficiency in terms of fuel consumption with respect to the separate production of the same cogenerated energy vectors. However micro-cogeneration units, as a consequence of their enhanced energy performance, can also bring important benefits from both environmental and economic point of views.

Therefore the diffusion of micro-cogeneration systems was accompanied by a number of research programmes and scientific studies around the world, aimed at analyzing the performance of small-scale energy systems. In the companion paper (Part I: Energy analysis) [1] a residential building-integrated micro-cogeneration system (BICS) coupled with a multi-family house was described; its performance during the winter upon varying the boundary conditions (tank volume, climatic conditions, electric demand profile, as well as the control strategy of the MCHP unit) was investigated by means of whole-building simulation software and compared with those of a conventional system from an energy point of view; the energy assessment [1] showed that the proposed system can contribute to a significant reduction of primary energy

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http://dx.doi.org/10.1016/j.enconman.2013.09.058

Nomenclature

Latin letters

B	boiler
BICS	building-integrated micro-cogeneration system
CU	unit cost (€/S m^3)/(€/kW h_{el})
D	diverter
DHW	domestic hot water
E	energy (kJ)
EU	European Union
EV	electric vehicle
IEA	International Energy Agency
IF	inlet flow
IHE	internal heat exchanger
LHV	lower heating value (kJ/kg)
MFH	multi family house
m	mass (kg)
MCHP	micro-combined heat and power
OC	operating cost (€)
OF	outlet flow
P	power (kW)/pump
PES	primary energy saving (%)
PHE	plate heat exchanger
SFH	single family house
SHC	solar heating and cooling
T	temperature (°C)/thermostat
u	energy output-based emission factor
V	valve
VAT	Value Added Tax

Greeks

Δ	difference
η	efficiency
ρ	density (kg/m^3)

Superscripts

CS	conventional system
E	energy
E_p	primary energy
E_{el}	electric energy
PS	proposed system

Subscripts

buy	purchased from the central electric grid
B	boiler
CO_2	carbon dioxide
el	electric
MCHP	micro-combined heat and power
ng	natural gas
p	primary
sell	sold to the central electric grid
th	thermal
x	generic pollutant

consumption. However assessing the environmental impact of cogeneration systems is particularly relevant in today's scenario in order to evaluate their suitability for preserving the fossil sources, cutting down the production of greenhouse gases [2,3] (in particular claimed by the Countries signing the Kyoto's Protocol), and creating a more mature awareness of several environmental and sustainable development aspects. The results of the environmental analysis could be also fruitfully used for energy planning (e.g., assessment of the air quality change due to widespread diffusion of CHP systems, to be compared to other energy scenarios [4,5]) or regulatory purposes (e.g., to set up suitable emission tests or establish adequate emission limits [6]).

Taking into account that a micro-cogeneration system would require a higher investment for the user as compared to the conventional separate production of heating and electricity, a detailed economic analysis is also mandatory; aiming at a more widespread diffusion of MCHP technology, a reasonable reduction of operating costs should be obtained and some incentives should be adopted by the governments for cogeneration units to be financially feasible.

For the above-mentioned reasons, in this framework both the environmental and economic performance of the system proposed in the companion paper (Part I: Energy analysis) [1] were evaluated.

The assessment of the environmental impact of cogeneration technology was performed by taking into account only the global effects through the evaluation of equivalent carbon dioxide emissions. The standard emission factors approach, which takes into account the pollutant emissions due to energy consumption (either directly due to fuel combustion or indirectly via fuel combustion associated with electricity and heat usage) was used. As known, the introduction of MCHP systems within urban areas, where the problem of air quality standards is significantly prominent, requires that the effects of local pollutants, such as NO_X, CO, SO_X, particulate matter, and unburned hydrocarbons, should also be taken into account [7]. In fact, in urban contexts dispersion in the atmosphere of pollutants from small-scale generators sited among buildings may be more difficult than, for instance, for bigger power plants with high stacks [8]. In addition, also due to the high population density, there is a sensitive population group (elderly and sick people, children, etc.), with other potential impacts of pollutant emissions referred to ecosystems, monuments, and so forth [9]. The concentration of these pollutants is mainly affected by the fuel, MCHP technology, combustion dynamics, part-load operation characteristics, and, secondly, by the morphology of the territory and climatic conditions. Thus, their estimation could be quite complex and how to estimate the dynamics of such phenomena still represents an open debate [7]. Taking this into consideration, the local effects were neglected in this paper also due to the fact that the emission data of the specific equipment under investigation were not given by the manufacturers or gathered through field measurements. Further analysis could be performed on the environmental impact introducing a method based on life cycle analysis (LCA) of greenhouse gas emissions [10]. This approach includes not only the emissions of the final combustion, but also all emissions of the supply chain; it also includes emissions from the exploitation, transport and processing (e.g. refinery) steps. The approach considered in this paper, although it does not reflect the total environmental impact related to the use of an energy carrier, has several advantages with respect to the LCA approach [11]. In particular, it is compatible with the monitoring of progress towards the EU's 20–20–20 target and, above all, the required emission factors are easily available thanks to the fact that they depend on the carbon content of the fuels and therefore do not vary significantly from case to case. On the contrary, obtaining information on the emissions upstream in the production process required by the LCA approach may be challenging and considerable differences may occur even for the same type of fuel [12].