Energy Conversion and Management 49 (2008) 2069–2077

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A unified model for energy and environmental performance assessment of natural gas-fueled poly-generation systems

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ARTICLE INFO

Article history:
Received 29 June 2007
Accepted 25 February 2008
Available online 15 April 2008

Keywords:
Cogeneration
Trigeneration
Multi-generation
Energy saving
Environmental assessment
Emission reduction

ABSTRACT

Poly-generation systems for combined production of manifold energy vectors such as electricity, heat at different enthalpy levels (for instance, in the form of hot water and steam), and cooling power from a unique source of primary energy (typically natural gas) are increasingly spreading, above all on a small-scale basis (below 1 MW_e), owing to their enhanced energy, environmental and economic characteristics. Availability of suitable tools for assessing the performance of such systems is therefore fundamental. In this paper, a unified general model is proposed for assessing the energy and CO_2 emission performance of any type of poly-generation system with natural gas as the energy input. In particular, the classical energy saving model for cogeneration systems is extended to include in the analysis further energy vectors by defining the novel PPES (Poly-generation Primary Energy Saving) indicator. In addition, equivalent efficiencies for CO_2 emission assessment are defined and used in the formulation of the new PCO2ER (Poly-generation CO_2 Emission Reduction) indicator, specifically introduced for environmental analysis. The formal analogy between the PPES and the PCO2ER indicators is highlighted. Numerical applications are provided to show the effectiveness of the proposed models and to quantify the typical benefits that poly-generation systems can bring. In particular, the new indicators are of relevant interest for both energy planners and policy makers, above all in the outlook of formulating financial incentive strategies, as it already occurs for cogeneration systems, or of participating to specific energy-related markets such as the ones for trading white certificates or emission allowances.

1. Introduction

Cogeneration (or Combined Heat and Power, CHP) [1] is widely acknowledged as an effective technique allowing for fuel primary energy saving with respect to the Separate Production (SP) of electricity (from power plants) and heat (from boilers). In the last decade, the diffusion on a small-scale size (below 1 MW_e) of thermal-based Distributed Generation (DG) [2,3] technologies has allowed cogeneration to be economic-effective also for sizes well below those of traditional bigger industrial and district heating applications [1]. In addition, the last years have witnessed an increasing trend in energy consumption for air conditioning purposes, above all in the summertime. From this point of view, coupling thermally-activated cooling technologies [4] to cogeneration systems gives the possibility to set up the so-called trigeneration systems [5–7], also known with the acronym CHCP (Combined Heat Cooling and Power) [8] or CCHP (Combined Cooling Heat and Power) [9,10], mostly based upon absorption chillers fed with waste heat produced in cogeneration. Different types of trigeneration systems can be set up by exploiting cooling generation equipment other than absorption chillers fed by cogenerated heat (for instance, engine-driven chillers [10–12]), so leading to a generalized approach to trigeneration system planning and evaluation [13–15].

Besides their energy saving potential [1,7,8,14,15], CHP and CCHP plants can also bring significant CO_2 emission reduction, especially in those countries where the separate production of heat and above all electricity is characterized by high level of CO_2 emissions, mostly from fossil fuels [16,17]. This is even more true if considering that small-scale DG technologies are mainly fueled by natural gas, which is "cleaner" than coal or oil owing to its lower carbon content [3,18].

From a more general point of view, it is possible to extend the analyses from CHP and CCHP systems to the so-called *poly-generation* or *multi-generation* systems [19,20] (that entail CHP and CCHP ones as sub-cases). These energy systems can provide different types of energy vectors (for instance, a *quad-generation* plant with electricity, cooling, and heat in the form of hot water and steam) from a unique source of fuel such as natural gas. In this respect, the integration of various energy sources and energy vectors is a topic of current interest, with emerging concepts like virtual power plants [21] or hybrid energy hubs [22,23].

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doi:10.1016/j.enconman.2008.02.015

Nomenclature

Acronyms
CCHP Combined Cooling Heat and Power
CHCP Combined Heat Cooling and Power
CHP Combined Heat and Power
COP Coefficient Of Performance
DG Distributed Generation
FESR Fuel Energy Saving Ratio
ICE Internal Combustion Engine
LHV Lower Heating Value
PES Primary Energy Saving
PPES Poly-generation Primary Energy Saving
PCO2ER Poly-generation CO_2 Emission Reduction
SP Separate Production
TPES Trigeneration Primary Energy Saving

Subscripts
c cooling
e electricity
f fuel
h hot water
s steam
t thermal
x generic end use

Superscripts
d demand
p poly-generation
SP separate production
y cogeneration

Letters
m mass (g)
$\boldsymbol{D}$ set of demand energy vectors and types of energy
F fuel thermal content (kWh_f)
H hot water (kWh_t)
Q heat (kWh_t)
R cooling (refrigeration) (kWh_c)
S steam (kWh_t)
W electricity (kWh_e)
X generic energy vector (kWh)
η efficiency
μ emission factor (g/kWh)

The spread of cogeneration is often boosted from a regulatory outlook. In fact, in several countries cogeneration is regulated within well-established frameworks [24,25], with the rationale of pushing towards higher-efficiency energy generation techniques. Thus, an extension to explicitly consider trigeneration and more in general poly-generation within regulatory frameworks is suitable for the next future. In addition, new markets are arising worldwide to comply with the Kyoto Protocol commitments, by applying for instance *emission trading* schemes [26], or trading the so-called *white certificates* (*efficiency market*) (see for instance [27] for Italy). Poly-generation systems could be protagonist in these markets, owing to their enhanced high-efficiency and low-emission characteristics. Therefore, availability of tools and procedures enabling the operators to effectively assess both the energy saving and the CO_2 emission reduction brought by adopting a poly-generation system is of key interest.

On these premises, following the classical approach to cogeneration system evaluation through the PES (Primary Energy Saving) indicator [25], in this paper the energy system evaluation is extended to poly-generation systems by introducing the novel PPES (Poly-generation Primary Energy Saving) indicator. In addition, an equivalent model is formulated for assessing the CO_2 emission reduction owing to combined poly-generation systems by introducing the novel PCO2ER (Poly-generation CO_2 Emission Reduction) indicator. In particular, suitable equivalent efficiencies are defined for assessing the CO_2 emissions from conventional means for producing separate energy vectors. In this way, the formulation of the PCO2ER becomes structurally identical to the one of the PPES, thus obtaining a unified model for the evaluation of the energy saving and greenhouse gas emission reduction from combined poly-generation systems based on a unique fuel source such as natural gas, with respect to the conventional separate production of the relevant energy vectors. The effectiveness of the proposed evaluation models is assessed through specific case study applications that highlight the potential of the indicators introduced and quantify the energy and environmental benefits it is possible to pursue by exploiting currently available technologies. In addition, the key role played by proper selection of the *reference values* for separate production is pointed out, which could be particularly useful for assisting the development of adequate policy frameworks concerning poly-generation systems.

2. Components, models and characteristics of poly-generation systems

A poly-generation plant can be *conceptually* seen as composed of different combined structures interacting among each other [13,15]. Focusing on small-scale applications, with reference to Fig. 1, the poly-generation plant can be generally represented as the combination of the following main blocks:

- The *cogeneration side*, containing a CHP group [1], based upon DG technologies such as Internal Combustion Engines (ICEs) or microturbines [2,3,18], and a combustion heat generator group, typically boilers for hot water or steam generation [11,18], targeted for both back-up and thermal peak-shaving operation. Typically, equipment for small-scale applications are natural gas-fueled, also owing to the broad availability of natural gas through distribution systems at relatively cheap rates.
- The *cooling side*, which can be made up of different alternatives, also taking into account the physical connection with the cogeneration side [11,13]. Typical equipment that can be adopted are electric chillers, absorption chillers (direct-fired by natural gas or fed by cogenerated heat), absorption/electrical heat pumps (in case reversible), engine-driven chillers and engine-driven heat pumps (also often reversible) [4,11,28,29].
- An *energy buffer* [30–32], composed by a cooling storage system and/or a thermal storage system, enabling a more effective and profitable management of the plant.
- The *user side*, with loads representing the various types of energy demand and possible connections to external energy networks (i.e., the electrical grid, district heating and district cooling networks). The connection to the electrical grid allows for satisfying the energy needs in any condition (including the stops for outages and maintenance) and gives wider opportunities to profitably run the plant, for instance in the competitive electricity market [13].

The energy flows illustrated in Fig. 1 are related to electricity W, heat Q, cooling energy R, and primary energy F contained in the fuel (for instance on the basis of the fuel LHV). In particular, the thermal power Q could be supplied at different enthalpy levels