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

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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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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

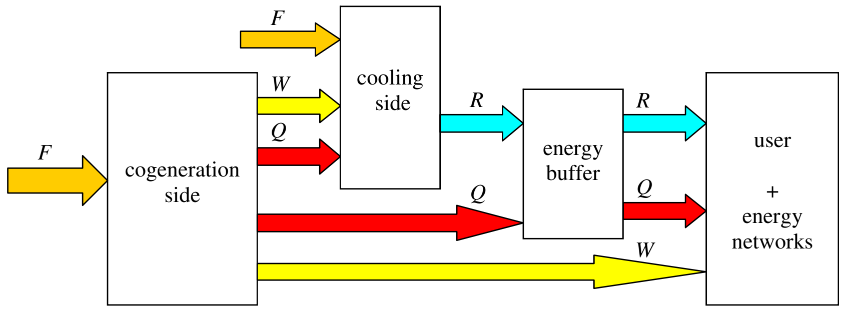

Fig. 1. General poly-generation plant layout and energy flows.

(for instance, hot water for space heating and steam to fire an absorption chiller or for industrial uses).

3. Energy performance assessment of poly-generation systems

3.1. Performance evaluation of cogeneration and trigeneration systems

Among various possible approaches to cogeneration performance evaluation [1,18], the comparison of the energy produced in a combined system with respect to the separate production of the same amount of the cogenerated energy vectors is particularly appropriate and effective [24]. Such an approach is typically based on the PES indicator [25], also known in the literature as FESR (Fuel Energy Saving Ratio) [1,18]. Through the PES, the primary energy saving brought by adopting cogeneration is evaluated with respect to the separate production of electricity and heat in conventional reference generation systems with electrical efficiency η_e^{SP} and thermal efficiency η_t^{SP}, respectively. In line with this approach, it is natural to extend the analysis to take into account the manifold energy vectors produced in a combined plant. Specific indicators have been proposed to extend the evaluation to classical trigeneration systems fed by cogenerated heat, for instance simply using the PES evaluated in a trigeneration case [8], or defining a specific energy saving index [14,33].

3.2. Performance evaluation of poly-generation systems: the PPES indicator

The complexity of the issues related to adopting poly-generation systems calls for working out synthetic indicators for characterizing their energy and environmental performance. In particular, with the approach proposed in this paper, the plant is interpreted as a *black-box* (Fig. 2), of which it is possible to build an equivalent performance model on the basis of the only input–output energy flows, without entering into the detailed representation of the internal components.

For notation purposes, the various energy entries are calculated over a given time span (for instance, hourly, daily, annual) depending on the purpose of the study. The set $\boldsymbol{D}$ contains the pairs (X,x), each of which is formed by an energy vector X with the corresponding type of energy x characterizing the useful output (demand).

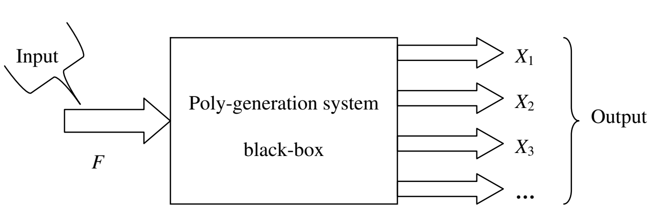

Fig. 2. Black-box model and energy flows for a poly-generation system.

Following the lines drawn for co- and tri-generation [14], an indicator that can be applied to any kind of poly-generation system is introduced here. This indicator is called PPES (Poly-generation Primary Energy Saving) and is expressed in a compact form as

$$\mathrm{PPES} = \frac{F^{SP} - F^{p}}{F^{SP}} = 1 - \frac{F^{p}}{\sum_{(X,x)\in \boldsymbol{D}} \frac{X^{p}}{\eta_x^{SP}}} \quad (1)$$

where the superscript p points out poly-generation, and the set $\boldsymbol{D}$ contains, as introduced above, the useful output (demand) of various types of energy from the poly-generation system (including different forms of the same energy type, for instance hot water or steam in the case of heat generation). The relevant energy entries bear the following meaning:

- $F^{SP}$is the primary energy generated through conventional SP systems to satisfy the same demand of different energy types in the poly-generation system.
- F^{p} is the fuel thermal input (primary energy) to the whole poly-generation system, including for instance the fuel to feed the CHP unit, the boilers, and in case the cooling generation equipment directly fed by fuel.
- The entry X^{p} represents the *actual energy output value* of a generic energy vector (e.g., electricity W^{p}, heat Q^{p}, or cooling R^{p}). For instance, in a classical trigeneration system a share of hot water can be produced to feed a single-effect absorption chiller, the remainder being used for thermal purposes. Therefore, the heat considered in Q^{p} is only the one corresponding to the hot water generation for thermal purposes, while the part to feed the chiller is accounted for through the evaluation of the cooling output R^{p}. Thus, with the black-box approach, no matter what happens *inside* the plant, the only energy flows to take into account are the ones visible from the *outside* (Fig. 2).
- Each term η_x^{SP} represents the separate production efficiency (*conventional* value) for the generic energy vector X produced. The relevant efficiency of each energy vector is taken as *reference* to evaluate the primary energy (thermal energy contained in the fuel) that would be necessary to produce the same amount of the different energy vectors produced in the combined plant through conventional SP means. Of course, the *numerical* values to assign to these efficiencies and their definition itself represent matter of discussion for the development of a regulatory framework (as for the PES at the European level [24,25]). In particular, choosing a reference efficiency as opposed to another one can consistently change the results of the energy efficiency assessment for the specific energy vector and for the whole system [14]. In general, two limit-case approaches are possible, one making reference to average performance for the SP equivalent

equipment, the other one making reference to state-of-the-art SP efficiency values. A comprehensive example highlighting these aspects is provided in Section 5.

4. Environmental performance assessment of poly-generation systems

4.1. The emission factor model for evaluating CO_2 emissions from combustion devices

The assessment of any type of emissions from any combustion device can be carried out through an approach based on the evaluation of the relevant *emission factors* [17,18,34,35]. Focusing on CO_2 emissions, the mass $m^X_{CO_2}$ (typically in (g)) of CO_2 emitted to produce the useful energy output X can be estimated according to a model such as [16–18,34,35]:

$$m^X_{CO_2} = \mu^X_{CO_2} \cdot X \tag{2}$$

where

- the useful output X in general can be electrical energy W (kWh$_e$), heat Q (kWh$_t$), or cooling energy R (kWh$_c$);
- $\mu^X_{CO_2}$ is the CO_2 *emission factor* to produce the generic useful energy output X, that is, the mass of CO_2 emitted per unit of X, and represents the CO_2 *specific emissions* typically expressed in (g/kWh).

More specifically, the carbon dioxide emitted when burning a given typology of fuel can be assessed according to the characteristics of the relevant chemical reaction, and depends in particular on the carbon content and the *LHV* of the specific fuel [18,35]. Hence, the model (2) can be rewritten by introducing the emission factor $\mu^F_{CO_2}$ referred to the primary energy generated while burning the fuel, that is, the CO_2 emission factor referred to the fuel thermal content F in *input*, which depends on the specific fuel [17,18,35]. Then, since the relation between the fuel input and the generic energy output is given by the relevant efficiency, it is possible to draw an emission factor model for the conventional CO_2 emissions referred to the energy output as [35]

$$m_{CO_2} = \mu^F_{CO_2} \cdot F = \mu^X_{CO_2} \cdot X \Rightarrow \mu^X_{CO_2} = \frac{\mu^F_{CO_2}}{\eta_x}, \quad \text{for } (X,x) \in \boldsymbol{D} \tag{3}$$

where η_x is the relevant equivalent efficiency to generate the corresponding output X from the input F (for instance, the electrical efficiency η_e for generating electricity W in a power plant).

4.2. Environmental evaluation of poly-generation systems: the PCO2ER indicator

In the literature, a few models have been proposed for evaluating the emission reduction brought by cogeneration and seasonal trigeneration (where all the cogenerated heat is used to fire an absorption chiller) systems [16], or for highlighting the key variables involved in the energy and environmental assessment of trigeneration systems [17]. The generalization of these models to any type of poly-generation systems and in a more general and compact form is proposed here, resorting to the same approach illustrated in Section 3.2 and in analogy to the deduction of the PPES (1), by introducing the PCO2ER (Poly-generation CO_2 Emission Reduction) indicator as

$$\text{PCO2ER} = \frac{(m^F_{CO_2})^{SP} - (m^F_{CO_2})^{p}}{(m^F_{CO_2})^{SP}} = 1 - \frac{(\mu^F_{CO_2})^{p} \cdot F^{p}}{\sum_{(X,x)\in\boldsymbol{D}} (\mu^X_{CO_2})^{SP} \cdot X^{p}} \tag{4}$$

where

- $(m^F_{CO_2})^{p}$ (g) is the CO_2 mass emitted by the poly-generation system while producing the demand energy vectors in $\boldsymbol{D}$, and that can be estimated according to the model (3).
- The term $(m^F_{CO_2})^{SP}$ (g) represents the carbon dioxide mass that would be emitted if the same amounts of the demand energy vectors in $\boldsymbol{D}$ were produced in separate production. The estimate of these CO_2 emissions, of course conventional, passes through the evaluation of the different terms $(\mu^X_{CO_2})^{SP}$, that is, the *reference* emission factors to produce the relevant energy vectors X^p in separate production. For instance, in a cogeneration plant the energy vectors to evaluate would be the cogenerated electricity W^y and the cogenerated heat Q^y. Consequently, the emission factor to consider would be $(\mu^F{}_{CO_2})^y$ (g/kWh$_f$) for the fuel input to the CHP system, $(\mu^W_{CO_2})^{SP}$ (g/kWh$_e$) for the conventional separate production of electricity, and $(\mu^Q_{CO_2})^{SP}$ (g/kWh$_t$) for the conventional separate production of heat.

Apparently, the structure of the PCO2ER indicator is in all similar to the one of the PPES, with the role of reference efficiencies for the separate production now covered by the inverse of the reference emission factors. Actually, the analogy between the expressions (1) and (4) can be further highlighted by introducing the CO_2 *emission equivalent efficiency* $(\eta_{CO_2})^{SP}_x$, in correspondence of the relevant pairs $(X,x) \in \boldsymbol{D}$, defined as

$$(\eta_{CO_2})^{SP}_x \equiv \frac{\mu^F_{CO_2}}{(\mu^X_{CO_2})^{SP}} \tag{5}$$

The *equivalent* efficiency (5) has indeed the dimension of an efficiency (for instance, it is measured in (kWh$_e$/kWh$_f$) in the case of electricity). In the environmental impact assessment of a poly-generation system, it plays the same role as the "classical" efficiency for energy analysis. However, while the primary energy saving evaluation through (1) depends only upon the relevant efficiencies referring to *sheer* energy, when evaluating (5) it is possible to consider different types of fuels and equipment characteristics, with subsequent different CO_2 emission profiles, that change case by case the numerical value of (4). For instance, the reference emission factor for electricity production $(\mu^W_{CO_2})^{SP}$ could be calculated as an average value accounting for the various emission factor figures from the different types of power plants in the power system, or it could be evaluated as referred to a specific power plant typology (e.g., natural gas-fueled combined cycle). In addition, the relevant CO_2 emission equivalent electrical efficiency $(\eta_{CO_2})^{SP}_e$, calculated on the basis of (5), would depend on the specific fuel input to the poly-generation system through $\mu^F_{CO_2}$. In any case, the conceptual analogy between (1) and (4) is straightforward, and can be highlighted by rewriting (4) in the form

$$\text{PCO2ER} = 1 - \frac{F^{p}}{\sum_{(X,x)\in\boldsymbol{D}} \frac{X^{p}}{(\eta_{CO_2})^{SP}_x}} \tag{6}$$

Given a poly-generation system, positive values of the indicators (1) and (6) correspond to positive energy saving and emission reduction with respect to the conventional SP references considered. Some numerical applications pointing out the above concepts with different analyses and approaches are provided in the sequel.

5. Case study applications

5.1. Description of the case study applications and general evaluation models

Let us consider a poly-generation plant composed of a small-scale CHP ICE [36] coupled to an absorption chiller fed by cogenerated heat. In particular, the ICE is characterized by the relevant electrical and thermal efficiencies, while the absorption chiller is characterized by its COP = R/Q [4,11,28,29], in which R is the chiller output (cooling energy) and Q is the chiller input (thermal energy), in this specific case cogenerated by the ICE. Since all the energy and environmental evaluations performed refer to *relative* values, it is possible to avoid considering explicitly the specific sizes of the various equipment, thus making reference only to the relevant performance characteristics (set to average values for small-scale equipment available in the market). Similarly, the relevant energy entries are calculated over a common assigned time window, for instance annual, assuming constant values for the system performance parameters in the operational time window.

The cogeneration ICE produces both hot water at 80 °C (from the engine coolant and lubricant circuits) and steam at 10 bar and 183 °C (from the exhaust gases in a heat recovery steam generator). Thus, it is possible to model the heat production through two equivalent thermal efficiencies, one for hot water production, $\eta_h = 0.28$, and one for steam production, $\eta_s = 0.13$, the sum of which clearly representing the overall thermal efficiency. The electrical efficiency is $\eta_e = 0.33$.

As far as the absorption chiller is concerned, let us consider alternatively the presence of a single-effect chiller [4,11,28,29], fed by cogenerated hot water, with COP = 0.65 (Case 1), and of a double-effect chiller [4,11,28,29], fed by cogenerated steam, with COP = 1.1 (Case 2), both producing chilled water at 7 °C. For the two cases, let us hypothesize that only a share of the relevant thermal energy vector is used to fire the chiller, while the rest is exploited for the user's needs. In particular, as illustrated in the sequel, the relative share of cogenerated heat (hot water or steam) used to fire the chiller can be indicated through an approach based upon suitable *dispatch factors*, whose general framework is described in [22].

According to the energy saving evaluation model (1), the system considered can be evaluated out by writing the PPES indicator as

$$\mathrm{PPES} = \frac{F^{\mathrm{SP}} - F^{\mathrm{P}}}{F^{\mathrm{SP}}} = 1 - \frac{F^{\mathrm{P}}}{\frac{W^{\mathrm{P}}}{\eta_{\mathrm{e}}^{\mathrm{SP}}} + \frac{H^{\mathrm{P}}}{\eta_{\mathrm{h}}^{\mathrm{SP}}} + \frac{S^{\mathrm{P}}}{\eta_{\mathrm{s}}^{\mathrm{SP}}} + \frac{R^{\mathrm{P}}}{\eta_{\mathrm{c}}^{\mathrm{SP}}}} \quad (7)$$

In (7), F^{P} is the fuel thermal input (kWh$_{\mathrm{f}}$) to the poly-generation system, while W^{P} is the electricity output (kWh$_{\mathrm{e}}$), H^{P} the thermal output (kWh$_{\mathrm{t}}$) in the form of hot water (at 80 °C), S^{P} the thermal output (kWh$_{\mathrm{t}}$) in the form of steam (at 10 bar), R^{P} the cooling output (kWh$_{\mathrm{c}}$) in the form of chilled water at 7 °C. The equivalent fuel thermal input F^{SP} that would be needed adopting SP conventional means is worked out through the relevant reference efficiencies. Thus, $\eta_{\mathrm{e}}^{\mathrm{PS}}$ is the reference efficiency for conventional electricity-only generation, $\eta_{\mathrm{h}}^{\mathrm{PS}}$ the reference efficiency for hot water-only conventional thermal generation, $\eta_{\mathrm{s}}^{\mathrm{PS}}$ the reference efficiency for steam-only conventional thermal generation, and $\eta_{\mathrm{c}}^{\mathrm{PS}}$ the reference efficiency for cooling-only conventional generation. More specifically, the reference electrical and thermal efficiencies can be related to SP models occurring, respectively, in power plants and boilers (for hot water or steam production). Similarly, the most common way of producing cooling power is through electrical chillers, so that it is possible to further specify the model (1) by explicitly considering, within the equivalent cooling generation efficiency $\eta_{\mathrm{c}}^{\mathrm{PS}}$, the COP^{SP} of the reference electrical chiller, as also indicated in [8,33] for CCHP systems. Thus, it is possible to draw a more practical model for carrying out the poly-generation primary energy saving evaluation as

$$\mathrm{PPES} = \frac{F^{\mathrm{SP}} - F^{\mathrm{P}}}{F^{\mathrm{SP}}} = 1 - \frac{F^{\mathrm{P}}}{\frac{W^{\mathrm{P}} + \frac{R^{\mathrm{P}}}{COP^{\mathrm{SP}}}}{\eta_{\mathrm{e}}^{\mathrm{SP}}} + \frac{H^{\mathrm{P}}}{\eta_{\mathrm{h}}^{\mathrm{SP}}} + \frac{S^{\mathrm{P}}}{\eta_{\mathrm{s}}^{\mathrm{SP}}}} \quad (8)$$

In particular, setting $R^{\mathrm{P}} = 0$ in (8), and considering thermal production in the form of hot water-only ($S^{\mathrm{P}} = 0$) or steam-only ($H^{\mathrm{P}} = 0$), the expression for the PPES turns into the classical PES [1,18,25] for cogeneration systems.

Following the same approach, and according to the model (6) and to the related considerations carried out in Section 4.2, it is possible to calculate the PCO2ER indicator as

$$\mathrm{PCO2ER} = 1 - \frac{F^{\mathrm{P}}}{\frac{W^{\mathrm{P}} + \frac{R^{\mathrm{P}}}{COP^{\mathrm{SP}}}}{(\eta_{\mathrm{CO_2}})_{\mathrm{e}}^{\mathrm{SP}}} + \frac{H^{\mathrm{P}}}{(\eta_{\mathrm{CO_2}})_{\mathrm{h}}^{\mathrm{SP}}} + \frac{S^{\mathrm{P}}}{(\eta_{\mathrm{CO_2}})_{\mathrm{s}}^{\mathrm{SP}}}} \quad (9)$$

in which $(\eta_{\mathrm{CO_2}})_{\mathrm{e}}^{\mathrm{SP}}$, $(\eta_{\mathrm{CO_2}})_{\mathrm{h}}^{\mathrm{SP}}$ and $(\eta_{\mathrm{CO_2}})_{\mathrm{s}}^{\mathrm{SP}}$ are the equivalent CO_2 emission efficiencies for conventional generation of electricity, hot water and steam, respectively. All the CO_2 emission equivalent efficiencies are specified with reference to the relevant fuel input to the considered poly-generation system, according to the definition (5). In particular, comparison between (8) and (9) emphasizes for this specific case the general formal analogy between (1) and (6).

In the sequel, the fuel input to the poly-generation system, i.e., to the ICE, is assumed to be natural gas, to which corresponds a carbon dioxide emission factor equal to about $\mu_{\mathrm{CO_2}}^{F} \cong 200$ g/kWh$_{\mathrm{f}}$, calculated with respect to the fuel LHV [16,18].

5.2. Case 1: Plant and evaluation models for the poly-generation system with single-effect absorption chiller

Considering the single-effect absorption chiller, the relevant plant model can be represented as in Fig. 3. In this case, all the cogenerated electricity W^y and the cogenerated steam S^y are used to supply the user's demand, part of the cogenerated heat H^y supplies the hot water demand H^{d}, and the remaining part H^R is used to fire the chiller to satisfy the cooling demand R^{d}. In particular, the relative share of cogenerated hot water used as thermal input to the chiller is described through the *heat-to-cooling dispatch factor* α_R [15], so as to yield $H^R = \alpha_R \cdot H^y$ and $H^{\mathrm{d}} = (1 - \alpha_R) \cdot H^y$.

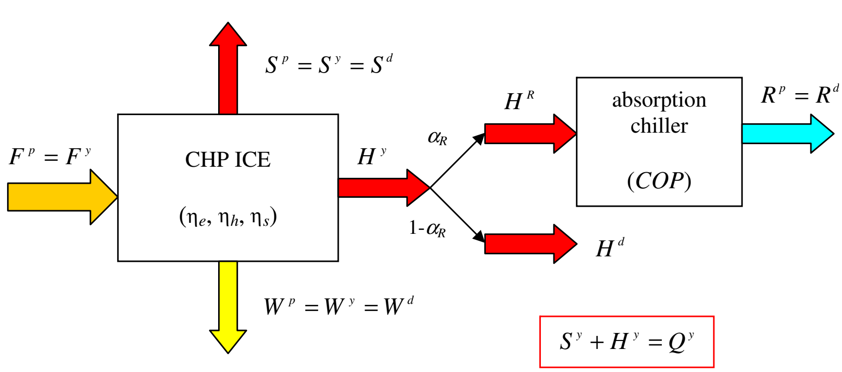

Fig. 3. Poly-generation system model with single-effect absorption chiller.

Thus, with reference to the expression (8) and to the energy flows in Fig. 3, in this specific case the PPES can be expressed as

$$\mathrm{PPES} = 1 - \frac{F^y}{\frac{W^y + \alpha_R \cdot H^y \frac{\mathrm{COP}}{\mathrm{COP}^{\mathrm{SP}}}}{\eta_e^{\mathrm{SP}}} + \frac{(1-\alpha_R)\cdot H^y}{\eta_h^{\mathrm{SP}}} + \frac{S^y}{\eta_s^{\mathrm{SP}}}} \tag{10}$$

In addition, by exploiting the relevant definitions of electrical efficiency and thermal efficiencies (for both hot water and steam generation) given in Section 5.1 for the considered ICE, the expression (10) can be rewritten equivalently as

$$\mathrm{PPES} = 1 - \frac{1}{\frac{\eta_e}{\eta_e^{\mathrm{SP}}} + \frac{\eta_h}{\eta_h^{\mathrm{SP}}} + \frac{\eta_s}{\eta_s^{\mathrm{SP}}} - \alpha_R\left(\frac{\eta_h}{\eta_h^{\mathrm{SP}}} - \frac{\eta_h}{\eta_e^{\mathrm{SP}}}\frac{\mathrm{COP}}{\mathrm{COP}^{\mathrm{SP}}}\right)} \tag{11}$$

In analogy with the expression (11), the relevant PCO2ER (9) in this specific case can be readily worked out as

$$\mathrm{PCO2ER} = 1 - \frac{1}{\frac{\eta_e}{(\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}}} + \frac{\eta_h}{(\eta_{\mathrm{CO_2}})_h^{\mathrm{SP}}} + \frac{\eta_s}{(\eta_{\mathrm{CO_2}})_s^{\mathrm{SP}}} - \alpha_R\left(\frac{\eta_h}{(\eta_{\mathrm{CO_2}})_h^{\mathrm{SP}}} - \frac{\eta_h}{(\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}}}\frac{\mathrm{COP}}{\mathrm{COP}^{\mathrm{SP}}}\right)} \tag{12}$$

5.3. Case 2: Plant and evaluation models for the poly-generation system with double-effect absorption chiller

In analogy with Case 1, let us consider the user in Fig. 4, with the double-effect absorption chiller fired by part of the cogenerated steam (again described through the relevant dispatch factor α_R), while all the cogenerated hot water is used to supply the user's needs.

In this case, it can be readily worked out that the relevant expressions for the energy saving and the emission reduction are respectively

$$\mathrm{PPES} = 1 - \frac{1}{\frac{\eta_e}{\eta_e^{\mathrm{SP}}} + \frac{\eta_h}{\eta_h^{\mathrm{SP}}} + \frac{\eta_s}{\eta_s^{\mathrm{SP}}} - \alpha_R\left(\frac{\eta_s}{\eta_s^{\mathrm{SP}}} - \frac{\eta_s}{\eta_e^{\mathrm{SP}}}\frac{\mathrm{COP}}{\mathrm{COP}^{\mathrm{SP}}}\right)} \tag{13}$$

$$\mathrm{PCO2ER} = 1 - \frac{1}{\frac{\eta_e}{(\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}}} + \frac{\eta_h}{(\eta_{\mathrm{CO_2}})_h^{\mathrm{SP}}} + \frac{\eta_s}{(\eta_{\mathrm{CO_2}})_s^{\mathrm{SP}}} - \alpha_R\left(\frac{\eta_s}{(\eta_{\mathrm{CO_2}})_s^{\mathrm{SP}}} - \frac{\eta_s}{(\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}}}\frac{\mathrm{COP}}{\mathrm{COP}^{\mathrm{SP}}}\right)} \tag{14}$$

5.4. Numerical applications and results

A number of analyses have been performed in order to point out the role of the variables and of the parameters involved in the energy efficiency and environmental evaluation, by plotting the PPES and PCO2ER indicators with respect to the relevant dispatch factor α_R as the independent variable for different numerical values for the reference efficiencies. In this respect, as far as the energy efficiency evaluation is concerned, two sets of values have been assumed for the separate production references:

- *Set A1*, corresponding to average values of the reference efficiencies, with $\eta_e^{\mathrm{SP}} = 0.4$ (close to the Italian average production efficiency of the power system, including transmission and distribution losses), $\eta_h^{\mathrm{SP}} = 0.85$ (average boiler efficiency for residential hot water generation), $\eta_s^{\mathrm{SP}} = 0.8$ (average boiler efficiency for industrial steam generation), and $\mathrm{COP}^{\mathrm{SP}} = 3$ (average COP for small/medium-scale electrical chillers).
- *Set A2*, with numerical values of the reference efficiencies close to the ones of the today's best available technologies for the separate production, that is, $\eta_e^{\mathrm{SP}} = 0.55$ (large combined cycles), $\eta_h^{\mathrm{SP}} = 0.99$ (for hot water generation in condensing boilers, with reference to the fuel LHV), $\eta_s^{\mathrm{SP}} = 0.9$ (for steam generation in large industrial boilers), and $\mathrm{COP}^{\mathrm{SP}} = 5$ (for medium/large-scale electrical chillers).

As far as the emission evaluation is concerned, it is generally possible to adopt the same kind of approach. Therefore, it is possible to consider two sets of reference values for separate production:

- *Set B1*, again with reference to the Italian case, with average CO_2 emission factor for the thermal units operated in the power system $(\mu_{\mathrm{CO_2}}^W)^{\mathrm{SP}} \cong 700$ g/kWh$_e$ [37]; this corresponds to a CO_2 emission equivalent electrical efficiency $(\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}} \cong 0.29$, on the basis of (5) and with natural gas as input to the ICE. Similarly, average emission factor values can be used as references for the production of hot water and steam, for instance $(\mu_{\mathrm{CO_2}}^Q)_h^{\mathrm{SP}} \cong 280$ g/kWh$_t$, corresponding to $(\eta_{\mathrm{CO_2}})_h^{\mathrm{SP}} \cong 0.71$, and $(\mu_{\mathrm{CO_2}}^Q)_s^{\mathrm{SP}} \cong 350$ g/kWh$_t$, corresponding to $(\eta_{\mathrm{CO_2}})_s^{\mathrm{SP}} \cong 0.57$, assuming a mix of fuels as input to make up the model for the reference equivalent boilers (emission data from different boilers taken from [18]). In addition, to complete the evaluation of the expression (14), the value $\mathrm{COP}^{\mathrm{SP}} = 3$ has been considered, as above.
- *Set B2*, corresponding to adopt values closer to the state-of-the-art. In this case, natural gas (the cleanest one in terms of CO_2 emissions among the commonly and widely adopted fossil fuels [2,18,34,35]) is assumed to be the input to the same state-of-the-art SP means as in *Set A2*, and the CO_2 emission characteristics can be calculated on the basis of the model (3). Therefore, since also the ICE is fed by gas, comparing (3)–(5) leads to the conclusion that the conventional reference efficiencies for energy evaluation and CO_2 emission evaluations are numerically the same, namely, $\eta_e^{\mathrm{SP}} = (\eta_{\mathrm{CO_2}})_e^{\mathrm{SP}} \cong 0.55$, $\eta_h^{\mathrm{SP}} = (\eta_{\mathrm{CO_2}})_h^{\mathrm{SP}} \cong 0.99$, and $\eta_s^{\mathrm{SP}} = (\eta_{\mathrm{CO_2}})_s^{\mathrm{SP}} \cong 0.9$. This is a logical consequence of the fact that, according to the unified model introduced, given the same fuel and thus the same emission factor $\mu_{\mathrm{CO_2}}^F$ for both the poly-generation system and the SP references, the energy saving and CO_2 emission reduction characteristics are the same. Hence, there will be no numerical difference between the PPES and the PCO2ER indicators, as shown above.

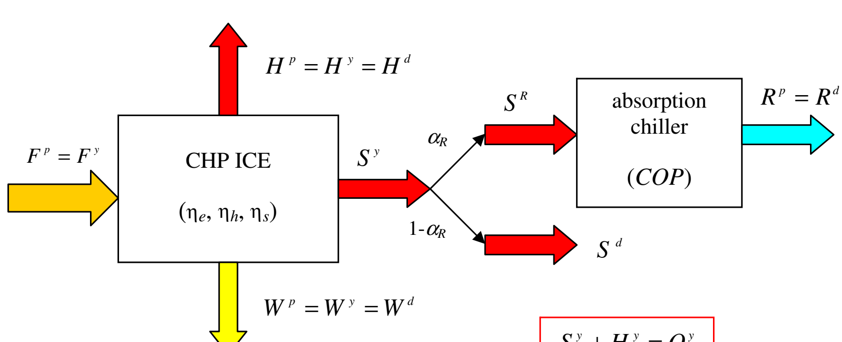

Fig. 4. Poly-generation system model with double-effect absorption chiller.

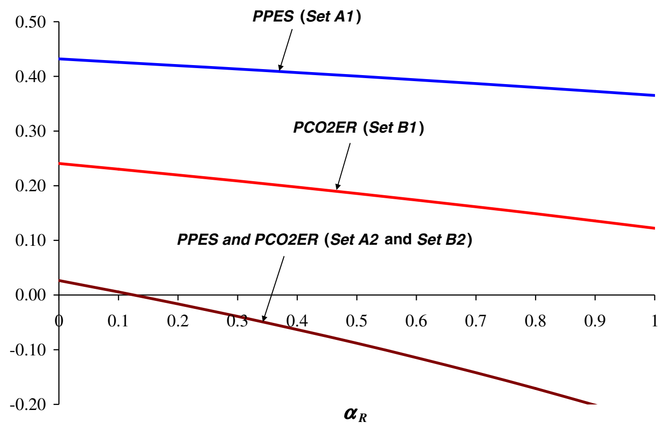

Fig. 5. PPES and PCO2ER for the poly-generation system with single-effect absorption chiller.

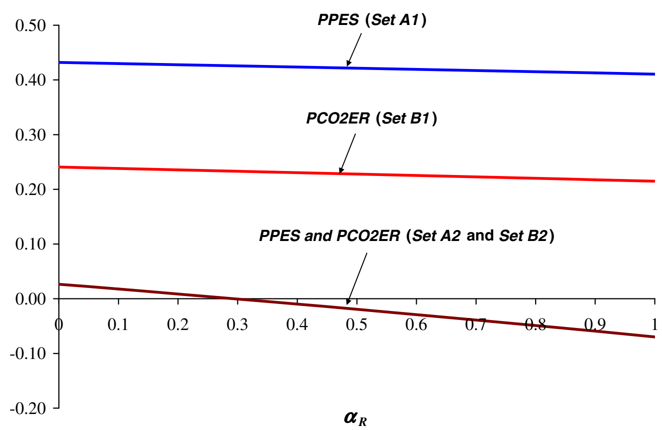

Fig. 6. PPES and PCO2ER for the poly-generation system with double-effect absorption chiller.

The numerical results for the PPES and the PCO2ER indicators according to the approaches outlined are shown in Fig. 5 for the plant based on the single-effect absorption chiller of Fig. 3, and in Fig. 6 for the plant based on the double-effect absorption chiller of Fig. 4.

5.5. Discussion on the numerical results

The results in Figs. 5 and 6 clearly show how the plant performance depends on the relevant dispatch factor. In particular, the extreme cases for $\alpha_R = 0$ and $\alpha_R = 1$ correspond, respectively, to trigeneration of electricity, hot water and steam, and to trigeneration of electricity, cooling and steam (Case 1) *or* hot water (Case 2). In this sense, it can be pointed out that the more the heat employed for cooling production purposes (i.e., with higher α_R), the lower the energy saving and the CO_2 emission reduction brought by the combined poly-generation. This is implicitly due to the fact that the cooling separate production is carried out through electrical chillers with a combination of reference electrical efficiency and reference COP relatively high with respect to the absorption chiller COP. In fact, with the *Set A2* ($COP^{SP} = 5$ and $\eta_e^{SP} = 0.55$) the performance reduction for increasing values of α_R is steeper than in the case with the *Set A1* ($COP^{SP} = 3$ and $\eta_e^{SP} = 0.4$). In addition, in Fig. 6, with performance of the double-effect absorption chiller almost doubled with respect to the single-effect one, the performance reduction for increasing values of α_R is far less evident than in Fig. 5, above all for the *Set A1*. Furthermore, the possible adoption of higher-performance absorption chillers (triple-effect, with expected *COP* of about 1.5 or even higher [29,38]) could even lead to *positive* performance curve slopes by increasing α_R, as confirmed by simulations for similar cases in [39], at least with the lower SP references.

As general comments, with average SP reference values (*Set A1* and *Set B1*), the performance of the poly-generation systems considered in the case study is excellent. In particular, primary energy saving above 20% and CO_2 emission reductions above 40% (with respect to the Italian power system) can be reached. However, the energy and environmental benefits are basically absent when the SP reference values become close to the state-of-the-art (*Set A2* and *Set B2*).

5.6. Considerations on the selection of the reference efficiencies for separate production

The energy and environmental assessment model introduced is completely general and enables to run different types of analyses. In particular, it is important to point out that, starting from the same evaluation model, the specific SP references selected as input data can reflect different approaches. Focusing on the environmental performance, generally speaking the comparison assuming the same fuel (namely, natural gas) as input to both the separate generation equipment and the cogenerator addresses the rationale of assessing the benefits brought by the poly-generation system owing to the high-efficiency of the combined production. Indeed, in this case since the same CO_2 emission characteristics per fuel energy unit hold for both combined production and separate production, there is no structural difference between *producing energy* or *emitting* CO_2, as pointed out by the unified model introduced. On the contrary, approaches using different input data (making reference for instance to average SP figures for the CO_2 emission characteristics) would be useful to evaluate the emission reduction within a specific energy framework (a region, a country, and so on) in terms of global environmental impact.

In principle, even better numerical values than the ones used here could be set up for the SP reference efficiencies, in particular about the CO_2 emission from centralized electricity generation. For instance, this could be the case of considering the average emissions from a whole power system based upon renewable sources, such as Norway, or nuclear fuel, such as France, as discussed in [16]. Hence, the poly-generation system considered in this case study could bring excellent benefits in a country such as Italy, with a power system mostly based upon thermal power plants, with *average* production efficiency relatively low with respect to the updated combined cycles, and supplied by a mix of fuels such as coal, oil, gas, and so on, with emissions far higher than from natural gas only. Instead, as it is easy to work out through the model (9), the same poly-generation plant would bring basically no environmental benefit in a country such as France, where the average emission factor is equal to about $(\mu^W_{CO_2})^{SP} \cong 80\ \mathrm{g/kWh_e}$ [40], corresponding to $(\eta_{CO_2})_e^{SP} \cong 2.5$. This latter value higher than unity must not be surprising, given the particular definition of CO_2 emission efficiency (9), when dealing with nearly zero-emission technologies such as the nuclear ones (neglecting the manufacturing process [28,41]).

Apart from the specific figures of the generation systems in a given region, in general it could be arguable what approaches are most suitable for setting up the numerical references for the separate production for both the energy and the environmental assessment, in line with the considerations drawn in several studies for cogeneration systems [24,25,42–44]. More specifically, the general reasoning streamlines are that on the one hand poly-generation systems could substitute the production from a wide range of systems, so that definition of average figures for the reference efficiencies (for both energy generation and CO_2 emissions) would be suitable; on the other hand, updated technologies could be installed instead of the poly-generation plant, so that definition of SP references close to the state-of-the-art would be more consistent. In any case, it has also to be considered that updating the technologies averagely available for the separate production of different energy vectors to the state-of-the-art takes time, above all for what concerns large power plants (e.g., combined cycles). Meanwhile, small-scale poly-generation systems could be fast installed and bring consistent energy and environmental benefits, as shown here.

6. Concluding remarks

Natural gas-fueled poly-generation systems are increasingly spreading worldwide, above all on a small-scale basis, owing to the energy and environmental (as well as economic) benefits they can bring. In this sense, this paper has introduced and discussed a novel and unified model for assessing the energy and environmental performance of poly-generation systems fueled by a unique source of primary energy such as natural gas. Within this general framework, the new PPES and PCO2ER indicators, structurally identical, have been introduced to assess, respectively, the primary energy saving and the CO_2 emission reduction brought by exploiting the combined generation of manifold energy vectors as opposed to the conventional separate production of the same energy vectors. Various existing indicators such as the FESR for cogeneration systems, as well as other indicators for co- and trigeneration energy and CO_2 emission performance evaluation, are entailed as sub-cases within the proposed framework.

Comprehensive case study applications, with *quad-generation* systems for combined production of electricity, hot water, steam and cooling, have shown the potential and the effectiveness of the proposed indicators in highlighting the relevant variables and parameters involved in the plant evaluation. The analyses run and the considerations on the numerical results from the case studies point out the importance of setting up appropriate reference values for the conventional SP efficiencies. The numerical values of the reference efficiencies represent matter of policy discussions, which may depend on the specific country, above all for what concerns the greenhouse gas emissions from thermal power plants.

From this outlook, the regulation in the future should explicitly take into account the definition of adequate energy and environmental performance indicators for poly-generation systems, as it already occurs for cogeneration systems [24,25]. In this respect, the indicators proposed here represent a standpoint also for further policy development, aimed at fostering the diffusion of high-efficiency and low-emission poly-generation systems. These issues become even more relevant considering that, owing to their enhanced energy and environmental performance, the economic profitability of poly-generation systems could consistently increase if the plants were allowed to participate to various *energy-related* markets [45] arising at the European and national levels for emission trading [26], white certificates [27], green certificates [27], and so forth.

These aspects are being included within a comprehensive framework for technical and economic assessment of poly-generation systems with additional output typologies (for instance, *dehumidification* [46,47]) and also accounting for *multiple input* energy vectors, thus bringing up the concept of *poly-generation energy hub* [22,23]. In particular, the authors are now working on entailing within the models formulated the possibility of exploiting different fuel typologies as the thermal energy input (such as gas from biomasses or hydrogen). The peculiar energy and environmental characteristics of these fuels call for more detailed analyses including an energy and environmental *life cycle assessment* and accounting for the processes to generate gas or hydrogen as the final input to the poly-generation system [48–55]. The related results will be reported in future contributions.

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References

[1] Horlock JH. Cogeneration-combined heat and power. Malabar, FL, USA: Krieger; 1997.
[2] Borbely AM, Kreider JF, editors. Distributed generation: the power paradigm of the new millennium. Boca Raton, Florida, USA: CRC Press; 2001.
[3] Willis HL, Scott WG. Distributed power generation: planning and evaluation. New York: Dekker; 2000.
[4] US DOE. Review of thermally activated technologies. Distributed energy program report, July 2004. Available (June 2007) at: <http://www.eere.energy.gov/de/pdfs/thermally_activated_techreview04.pdf>.
[5] Cardona E, Piacentino A. A method for sizing a trigeneration plant in Mediterranean areas. Appl Therm Eng 2003;23:1665–80.
[6] Ziher D, Poredos A. Economics of a trigeneration system in a hospital. Appl Therm Eng 2006;26:680–7.
[7] Hernandez-Santoyo J, Sanchez-Cifuentes A. Trigeneration: an alternative for energy savings. Appl Energy 2003;76:219–27.
[8] Havelsky V. Energetic efficiency of cogeneration systems for combined heat, cold and power production. Int J Refrig 1999;22:479–85.
[9] Maidment GG, Tozer RM. Combined cooling heat and power in supermarkets. Appl Therm Eng 2002;22:653–65.
[10] Resource Dynamics Corporation: Cooling, Heating, and Power for Industry: A Market Assessment. Final Report prepared for US Department of Energy and Oak Ridge National Laboratory. Vienna, VA, August 2003. Available (June 2007) at: <http://www.eere.energy.gov/de/pdfs/chp_industry_market_assessment_0803.pdf>.
[11] American Society of Heating, Refrigerating and Air-conditioning Engineers. ASHRAE HVAC systems and equipment handbook. SI ed. USA: ASHRAE; 2000.
[12] Lazzarin R, Noro M. District heating and gas engine heat pump: economic analysis based on a case study. Appl Therm Eng 2006;26:193–9.
[13] Chicco G, Mancarella P. From cogeneration to trigeneration: profitable alternatives in a competitive market. IEEE Trans Energy Conver 2006;21:265–72.
[14] Chicco G, Mancarella P. Trigeneration primary energy saving evaluation for energy planning and policy development. Energy Policy 2007;35(12):6132–44.
[15] Mancarella P. From cogeneration to trigeneration: energy planning and evaluation in a competitive market framework. Doctoral Dissertation. Politecnico di Torino, Torino, Italy, April 2006.
[16] Meunier F. Co- and tri-generation contribution to climate change control. Appl Therm Eng 2002;22:703–18.
[17] Minciuc E, Le Corre O, Athanasovici V, Tazerout M. Fuel savings and CO_2 emissions for trigeneration systems. Appl Therm Eng 2003;23:1333–46.
[18] EDUCOGEN. The European Educational Tool on Cogeneration (2nd ed.), December 2001. Available (June 2007) at: <http://www.cogen.org/Downloadables/Projects/EDUCOGEN_Tool.pdf>.
[19] Chicco G, Mancarella P. Beyond the electricity-only production: towards a distributed multi-generation world. In: Proceedings of international conference on power engineering, energy and electrical drives (POWERENG). Setúbal, Portugal, 12–14 April 2007. p. 219–24.
[20] Li H, Nalim R, Haldi PA. Thermal-economic optimization of a distributed multi-generation energy system – a case study of Beijing. Appl Therm Eng 2006;26:709–19.
[21] Pudjianto D, Ramsay C, Strbac G. Virtual power plant and system integration of distributed energy resources. IET Renew Power Generat 2007;1:10–6.
[22] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 2007;22:145–55.
[23] Chicco G, Mancarella P. A comprehensive approach to the characterization of trigeneration systems. In: Proceedings of VI world energy system conference, Torino, Italy, July 10–12 2006. p. 544–51.
[24] Cardona E, Piacentino A. Cogeneration: a regulatory framework toward growth. Energy Policy 2005;33:2100–11.
[25] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Official Journal of the European Union, 21.2.2004;L 52:50–60. Available (June 2007) at: <http://europa.eu.int/eur-lex/pri/en/oj/dat/2004/l_052/l_05220040221en00500060.pdf>.
[26] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003, Establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Official Journal of the EU, 25.10.2003, L 275, 32-46. Available (June 2007) at:

<http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_275/l_27520031025en003 20046.pdf>.
[27] Italian Market Operator (Gestore del Mercato Elettrico – GME), Web site <http://www.mercatoelettrico.org>.
[28] Danny Harvey LD. A handbook on low energy buildings and district energy systems. Sterling, USA: Quicksilver Drive; 2006.
[29] Wu DW, Wang RZ. Combined cooling, heating and power: a review. Prog Energy Combust Sci 2006;32:459–95.
[30] Hasnain SM. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. Energy Convers Manage 1998;39:1127–38.
[31] Hasnain SM. Review on sustainable thermal energy storage technologies, Part II: cool thermal storage. Energy Convers Manage 1998;39:1139–53.
[32] Wulfinghoff DR. Energy efficiency manual. Wheaton, Maryland, USA: Energy Institute Press; 1999.
[33] Heteu PMT, Bolle L. Economie d'énergie en trigenération. Int J Therm Sci 2002;41:1151–9.
[34] US EPA. Catalogue of CHP Technologies. Available (June 2007) at: <http://www.epa.gov/CHP/pdf/catalog_entire.pdf>.
[35] Cârdu M, Baica M. Regarding the greenhouse gas emissions of thermopower plants. Energy Convers Manage 2002;43:2135–44.
[36] Internal combustion engine technical data from commercial catalogues. April 2006.
[37] Macchi E, Chiesa P. Scenario studies for the electricity generation in Italy in the next 20 years (in Italian: Studi di scenario sulla generazione elettrica in Italia nei prossimi 20 anni). Rapporto CESI n. 71/00298, 31/03/2002. Available (June 2007) at: <www.ricercadisistema.it>.
[38] Foley G, De Vault R, Sweetser R. Future of absorption technology in America: a critical look at the impact of BCHP and innovation. Oak Ridge National Laboratory; June 2000. Available (June 2007) at: <http://www.eere.energy.gov/de/publications.html>.
[39] Chicco G, Mancarella P. Enhanced energy saving performance in composite trigeneration systems. In: IEEE powertech 2007 conference, Lausanne, Switzerland, 1–5 July 2007.
[40] Intergovernmental Panel on Climate Change, Working Group III. Data on carbon dioxide intensities. Available (June 2007) at: <http://arch.rivm.nl/env/int/ipcc/pages_media/SROC-final/Tables/t0305.pdf>.
[41] Voorspools KR, Brouwers EZ, D'haeseleer WD. Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: results for the Low Countries. Appl Energy 2000;67:307–30.
[42] COGEN EUROPE. Position statement on the definition of harmonised efficiency reference values; February 2005. Available (June 2007) at: <http://www.cogen.org/Downloadables/Publications/Position_Paper_CHP_Reference_Values.pdf>.
[43] Strachan N, Farrell A. Emission from distributed vs. centralized generation: the importance of system performance. Energy Policy 2006;34:2677–89.
[44] Allison J, Lents J. Encouraging distributed generation of power that improves air quality: can we have our cake and eat it too? Energy Policy 2002;30:737–52.
[45] Chicco G, Mancarella P. Exploiting small-scale cogeneration in energy-related markets. In: IEEE powertech 2007 conference, Lausanne, Switzerland, 1–5 July 2007.
[46] Henning HM, Pagano T, Molla S, Wiemken E. Micro tri-generation system for indoor air conditioning in the Mediterranean climate. Appl Therm Eng 2007;27:2188–94.
[47] Zaltash A, Petrov AY, Rizy DT, Labinov SD, Vineyard EA, Linkous RL. Laboratory R& D on integrated energy systems (IES). Appl Therm Eng 2006;26:28–35.
[48] Fiaschi D, Carta R. CO_2 abatement by co-firing of natural gas and biomass-derived gas in a gas turbine. Energy 2007;32:549–67.
[49] Chevalier C, Meunier F. Environmental assessment of biogas co- or tri-generation units by life cycle analysis methodology. Appl Therm Eng 2005;25:3025–41.
[50] Bickel P, Friedrich R, editors. ExternE: externalities of energy, methodology 2005 update. European Communities, 2005. Available (June 2007) at: <http://www.externe.info/brussels/methup05.pdf>.
[51] González A, Sala JM, Flores I, López LM. Application of thermoeconomics to the allocation of environmental loads in the life cycle assessment of cogeneration plants. Energy 2003;28:557–74.
[52] Pehnt M. Life-cycle assessment of fuel cell stacks. Int J Hydrogen Energy 2001;26:91–101.
[53] Wietschel M, Hasenauer U, De Groot A. Development of European hydrogen infrastructure scenarios – CO_2 reduction potential and infrastructure investment. Energy Policy 2006;34:1284–98.
[54] Matsuhashi R, Hikita K, Ishitani H. Model analyses for sustainable energy supply taking resource and environmental constraints into considerations. Energy Convers Manage 1996;37:1253–8.
[55] Bargigli S, Raugei M, Ulgiati S. Comparison of thermodynamic and environmental indexes of natural gas, syngas and hydrogen production processes. Energy 2004;29:2145–59.