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Distributed Cogeneration:
Modelling of Environmental Benefits and Impact

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1. Introduction

Radical changes occurred in the energy scenario in recent years, with a clear trend towards shifting part of the energy production from large centralized plants to relatively small decentralized systems. The growing diffusion of distributed generation systems for Combined Heat and Power (CHP) production represents a significant part of these changes. In particular, CHP generation could bring substantial improvements in energy efficiency and energy saving, as well as economic benefits, with respect to the separate production (SP) of electricity in the centralized power system and of heat in local boilers (Horlock, 1997). The development of CHP systems is particularly relevant for relatively small-scale applications (e.g., below 10 MW$_e$) in urban areas, including potential coupling to heat networks for larger capacities as well as micro-cogeneration (Pehnt et al., 2006; Pehnt, 2008) for domestic applications. The adoption of CHP systems can even be more effective when it is possible to supply, in periods with little or no heat demand, absorption chillers to satisfy the cooling demand (for instance, for air conditioning), thus obtaining high-efficiency seasonal tri-generation systems (Meunier, 2002; Mancarella, 2006). Moreover, CHP systems can be conveniently used in a distributed multi-generation framework, to supply various types of chillers to better fit the overall characteristics of the demand of various energy vectors (Chicco & Mancarella, 2009a).

Higher energy efficiency can also correspond to lower environmental impact in terms of CO_2 emissions with respect to SP, mainly depending on the generation characteristics of the power system in the specific country (Mancarella & Chicco, 2008a), particularly where electricity generation prevailingly occurs from fossil fuels. On the other hand, distributed cogeneration could worsen the air quality on the local level, due to emissions of various hazardous pollutants such as NO_x, CO, SO_x, Particulate Matter (PM), Unburned Hydrocarbons (UHC), and further substances conveying the pollution into the human body. In particular, in urban areas the environmental pollution is more critical because of a host of reasons, among which:
a) high concentration of background pollutants, in particular due to road traffic pollution;
b) difficult dispersion in the atmosphere of the pollutants produced from small-scale generators located in urban sites, with respect to large power plants with high stacks;
c) relatively high number of receptors, due to the population density;

d) presence of relative weak receptors, such as children, elders and sick people; and,
e) detrimental effects on non-human receptors (monuments, green urban areas and ecosystems), that could also contribute to keeping the pollutants within the area.

On the above reasons, the local air quality regulation could often be quite stringent, especially in urban areas, with environmental assessments tending to be conservative and leaving reduced margins to the deployment of cogeneration in heavily polluted zones. These limitations call for a thorough appraisal at the cogeneration system planning stage. In addition, it is important to consider that the emissions of certain pollutants may worsen even significantly in the off-design operation at partial load of the cogeneration unit. Hence, the environmental assessment of cogeneration systems has to be carried out not only on the basis of the full-load performance, but in actual operating conditions. This aspect is even more relevant considering that in today's and emerging energy systems the cogeneration units are not generally used in on/off operation only, but can be controlled to achieve specific objectives of electrical or heating load tracking, or with more refined strategies in which the cogeneration unit is combined into trigeneration or more generally multi-generation systems (Mancarella & Chicco, 2009b) and microgrids (Hatziargyriou et al., 2007). Further environmental benefits could refer to micro-cogeneration solutions.
This chapter addresses the manifold sides of potential environmental benefits and impact related to modelling and analysis of distributed cogeneration solutions. Section 2 recalls the energy efficiency benefits of adopting cogeneration systems. Section 3 deals with the modelling of global and local emissions. Section 4 describes the characterization of the emissions from typical CHP technologies already widely applied today. Section 5 presents specific indicators for environmental impact assessment. Section 6 discusses the role of environmental impact in the formulation of optimization methods. Section 7 illustrates the identification and determination of the environmental external costs from distributed cogeneration. Section 8 addresses the potential deployment of cogeneration in energy-related markets. Section 9 draws the conclusions and indicates directions of future research.

2. Energy efficiency of distributed cogeneration

A suitable characterization of cogeneration equipment and systems is conducted by using a black-box modelling approach, in which the performance of CHP units is represented by relevant input-output efficiency models (Mancarella, 2006; Chicco & Mancarella, 2009b). In particular, a cogeneration prime mover is represented by using its electrical efficiency η_W, thermal efficiency η_Q, and their sum known as Energy Utilisation Factor (*EUF*) (Horlock, 1997). By denoting with *W* the electrical energy (kWh$_e$), *Q* the thermal energy (kWh$_t$), and *F* the fuel thermal input (kWh$_t$) in a specified time interval, the energy efficiency indicators are expressed as:

$$\eta_W = \frac{W}{F} \; ; \; \eta_Q = \frac{Q}{F} \; ; \; EUF = \eta_W + \eta_Q \qquad (1)$$

The terms *W*, *Q* and *F* can also be interpreted as average powers within the specified time interval. For instance, this interpretation is useful for the sake of comparison of the energy production (represented as average power within a time interval in which the power

variation is relatively low) with the rated power of the equipment, to check whether the operational limits are exceeded, provided that significant power variations during the specified time interval can be excluded.

The fuel thermal input F is generally based on the Lower Heating Value (*LHV*) of the fuel. The efficiencies indicated above depend on many factors, such as the equipment technology, the loading level, the outdoor conditions, the enthalpy level at which heat is produced, the characteristics of the heat recovery system, and so forth (Danny Harvey, 2006).

The outcomes of the CHP system energy efficiency assessment can be represented in a synthetic way through suitable indicators. A classical way to define such indicators is to compare the production of the same energy outputs (electricity and heat) from the cogeneration system and from conventional systems for separate production of electricity and heat used as reference (Horlock, 1997). The SP systems are typically the electricity distribution system (EDS) for electricity production (associated to a reference electrical efficiency η_e^{SP}), and conventional boilers for heat production (associated to a reference thermal efficiency η_t^{SP}).

Considering the fuel thermal input F^{SP} to the conventional separate production system, the resulting energy efficiency indicator is the Primary Energy Saving (*PES*), also known as Fuel Energy Savings Ratio (*FESR*), expressed as:

$$PES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{\frac{W}{\eta_e^{SP}} + \frac{Q}{\eta_t^{SP}}} = 1 - \frac{1}{\frac{\eta_W}{\eta_e^{SP}} + \frac{\eta_Q}{\eta_t^{SP}}} \tag{2}$$

Energy efficiency benefits of cogeneration appear for positive values of the *PES* indicator, and the break-even condition is found for *PES* = 0. The simple and meaningful structure of the *PES* indicator makes it particularly useful to quantify the energy efficiency of a cogeneration system for regulatory purposes (Cardona & Piacentino, 2005). Extensions of the *PES* indicator have been proposed to encompass trigeneration systems (Chicco & Mancarella, 2007a) and more general multi-generation systems (Chicco & Mancarella, 2008b). A further indicator characterising the operation of a cogeneration system is the heat-to-power cogeneration ratio, typically denoted with the letter lambda (Horlock, 1997), that according to (1) can be also seen as the ratio of the thermal to electrical efficiency:

$$\lambda = \frac{Q}{W} = \frac{\eta_Q}{\eta_W} \tag{3}$$

3. Modelling of global and local emissions

3.1 Emission factors

The emissions of a generic pollutant p from a combustion device can be characterised through suitable *emission factors*, referred to the useful energy produced by the generic energy vector X. The corresponding emission factor model is expressed in the form

$$m_p^X = \mu_p^X \cdot X \tag{4}$$

where the term m_p^X represents the mass [g] of the pollutant p emitted to produce the energy vector X [kWh], and μ_p^X is the *emission factor* or *specific emissions* [g/kWh] of the pollutant p referred to X.

The emission factor depends on the type of generator and varies in different operating conditions (e.g., at full load or partial load), with the equipment aging and with the state of maintenance of the generator. The emission performance of the generator can be characterised through dedicated measurements in actual operating conditions.

In the definition of the emission factors for cogeneration applications, the energy vector X can be chosen in different ways, thus originating different definitions of the emission factor. For instance, X can represent the input fuel energy F [kWh$_t$], or the electricity production W [kWh$_e$] or the heat production Q [kWh$_t$]. The corresponding formulations can be written by expressing the mass of pollutant m_p on the basis of the emission factor adopted in different ways:

$$m_p = \mu_p^F \cdot F = \mu_p^W \cdot W = \mu_p^Q \cdot Q \qquad (5)$$

In particular, the emission factor μ_p^F depends primarily on the characteristics of the chemical reactions and on the type of fuel used (Cârdu & Baica, 2002). It is then possible to evaluate the emission factor referred to the energy produced through the expression

$$\mu_p^X = \frac{\mu_p^F}{\eta_X} \qquad (6)$$

where η_X is the efficiency equivalent to the production of the useful energy X using the fuel F. For instance, for a cogeneration system the term η_X can be the electrical efficiency η_W for electricity production, or the thermal efficiency η_Q for heat production.

3.2 Emission balances

The emission factors can be used to formulate *global* or *local* emission balances (Mancarella & Chicco, 2009a).

The *global* emission balance does not take into account the location of the emission source with respect to the receptors. For a given time interval (e.g., one hour) in which the variation of the energy production from the cogenerator is low (in such a way to assume almost constant values of the variables involved in the analysis), it is possible to compare the mass of the pollutant emitted by the cogeneration system with the mass of pollutant emitted from separate production of the same electrical and thermal energy (Mancarella & Chicco, 2009a; Mancarella & Chicco, 2009b).

With reference to the electricity production, taking into account the cogeneration ratio (3) and considering the total mass of pollutant emitted in global separate production (GSP) as the sum of the mass of pollutant emitted in the production of electricity and heat, it is possible to elaborate the previous expressions to get (Mancarella & Chicco, 2009a):

$$m_p^{\mathrm{GSP}} = m_p^{Q,\mathrm{SP}} + m_p^{W,\mathrm{SP}} = \mu_p^{Q,\mathrm{SP}} \cdot \lambda \cdot W + \mu_p^{W,\mathrm{SP}} \cdot W = \left(\mu_p^{Q,\mathrm{SP}} \cdot \lambda + \mu_p^{W,\mathrm{SP}} \right) W \qquad (7)$$

From (7) it is possible to define the *global* equivalent emission factor referred to the electricity production

$$\mu_p^{W,\mathrm{GSP}} = \mu_p^{Q,\mathrm{SP}} \cdot \lambda + \mu_p^{W,\mathrm{SP}} \qquad (8)$$

The emission factor $\mu_p^{W,\mathrm{GSP}}$ is directly comparable with the corresponding emission factor μ_p^{W} of the cogeneration system. This is a major upside of the emission balance model developed, which allows emission comparison on a common basis (for instance, *specific* emissions with respect to the same useful energy output) and thus unbiased environmental impact appraisal of different generation rationales such as cogeneration and separate production. In fact, by comparing the emissions per unit of useful kWh produced, the fact that cogeneration can produce the same amount of useful energy burning less fuel (thus producing less pollutants) is intrinsically made apparent in the model. Hence, the environmental impact benefits (in terms of reduced specific emissions) arising from enhanced cogeneration efficiency are explicitly acknowledged as well. Conversely, comparisons carried out by considering only the concentration of pollutant (in mg/m^3) contained in the gases exhausted off to the ambient would be unable to take into account the energy efficiency benefits of cogeneration, as further remarked in Section 5.4. These concepts form the basis to adopt energy-output related specific emissions to define the emission reduction indicators illustrated in Section 5.1.

The *local* emission balance takes into account that the large power plants for electricity production are typically located far from urban areas. In the analysis of the effects of emitting pollutants with propagation in a relatively limited area (for instance, NO$_x$, CO and volatile organic compounds), it is possible to adopt an approximated model, neglecting both the propagation of these substances outside the area and the possible introduction of the same substances emitted by sources located outside the area. For instance, for an urban area the local emission balance considers only the local separate production (LSP) from residential boilers belonging to the area. In this case, the mass of the pollutant p emitted is only the one originated by the thermal production and is expressed as (Mancarella & Chicco, 2009a)

$$m_p^{\mathrm{LSP}} = m_p^{Q,\mathrm{SP}} = \mu_p^{Q,\mathrm{SP}} Q = \mu_p^{Q,\mathrm{SP}} \lambda\, W \qquad (9)$$

The local equivalent emission factor, referred to the electricity production, is then defined as

$$\mu_p^{W,\mathrm{LSP}} = \frac{m_p^{\mathrm{LSP}}}{W} = \mu_p^{Q,\mathrm{SP}} \lambda \qquad (10)$$

More detailed evaluations can be conducted with reference to specific models of the pollutant dispersion in the atmosphere (Arya, 1999). However, the local emission balance model is useful for a preliminary assessment of the local emission impact through the dedicated indicators illustrated in Section 5.2. Of course, the local emission approximation

can be more or less relevant, also depending on the specific pollutant and dispersion conditions, and represents a conservative ("pessimistic") evaluation of the actual impact due to the distributed energy system. On the other hand, the global emission approximation may often represent an "optimistic" evaluation of the impact from distributed sources (apart from the evaluation of greenhouse gases (GHGs), whose effect is essentially global to every extent, neglecting possible contribution to micro-climates). However, the simultaneous appraisal of local and global emission balances provides meaningful insights on the upper and lower bounds of the real environmental pressure (Mancarella & Chicco, 2009a). In particular, the indications yielded by these models are independent of the specific site and can be used to compare different scenarios of development of the cogeneration systems. The information provided can be useful for regulatory purposes, with the aim of setting up local emission limits, assuming conventional values for the separate production efficiencies and emission factors, as discussed in Section 5.3.

4. Characterization of the emissions from cogeneration technologies

The analysis of the emissions of various pollutants from specific cogeneration technologies takes into account different types of fuel (mainly natural gas, or alternative fuels such as biomasses) and operation in partial-load conditions, with potential remarkable worsening of the emission of pollutants such as NO_x and CO at relatively low loading level. The illustrations included here refer to technologies that have reached a wide commercial stage, such as the ones based on microturbine (MT) or internal combustion engine (ICE) prime movers. The same concepts can be extended to other technologies, such as fuel cells.

Generally, different cogeneration units, also with the same type of technology, could exhibit emission characteristics quite different from each other, because of the specific design of the combustion device, the possible presence or abatement system, and so forth. It is then tough to draw general emission models. For general studies, it is typically preferred to consider average values of emissions taken from inventories prepared by the various environmental protection agencies and research groups worldwide (e.g., EPRI, 2009; US Environmental Protection Agency, 2009), or elaborations of data provided by manufacturers.

Operation at partial load can be determined by the implementation of specific control (or load tracking) strategies, such as electrical load-following or heat load-following ones, as well as economically driven strategies such as based on the evaluation of the "spark spread" between natural gas cost and electricity cost.

The emissions in real operation conditions depend on the characteristics of the combustion occurring in the cogeneration prime mover. Experimental results provided by the cogeneration unit manufacturers and obtained during specific researches and on-site measurements have shown that the emissions of some pollutants (for instance, NO_x and CO) can worsen significantly during partial load operation. Furthermore, at decreasing loading level the evolution of these emissions is not linear and in some cases could exhibit non-monotonic behaviour, especially for microturbine units (Canova et al., 2008; Mancarella & Chicco, 2009a). These aspects make the emission impact assessment of cogeneration systems more complicated. In addition, below a certain loading level (e.g., 50%) the performance of the cogeneration unit could become so worse to suggest switching the unit off. In this case, the domain of definition of the operating conditions of the cogeneration unit becomes non-connected, including the discrete switch-off condition and a continuous operation range

between the technical limits of minimum and maximum loading. These aspects impact on the characterization of the cogeneration systems and call for adopting dedicated analysis techniques, for instance based on mixed integer and linear/nonlinear programming or heuristic methods, in some cases developed for energy efficiency analyses not including environmental aspects (Horii et al., 1987; Illerhaus & Verstege, 1999; Tsay et al., 2001; Gómez-Villalva & Ramos, 2003).

Concerning the types of analysis, one of the key distinctions occurs between time-domain simulations and methods in which the succession of the time instants in the cogeneration system operation is not exploited. Time-domain simulations are needed when it is important to consider the coupling-in-time of events, for instance to take into account the integral effect of the emissions within a specified period, or the operational limits dependent on the time domain, such as the maximum number of switch-on/switch-off operations of the cogeneration unit (Freschi & Repetto, 2008). If the coupling-in-time is not strictly relevant, general evaluations can be carried out by using integral models, such as for instance the *equivalent load* approach illustrated in Mancarella & Chicco, 2009a. This approach is based on the construction of a discrete (multi-level) version of the load duration curve representing the electricity demand, containing pre-defined levels of partial-load operation. Each loading level is represented by a pair hourly energy-duration (number of hours), from which the equivalent electrical load is calculated as the weighted average of the hourly energies, assuming the load level durations as weights. Each level of the duration curve is then associated to a value of specific emissions, used to determine the mass of pollutant and the equivalent emission factors for the cogeneration system and for separate production.

The equivalent load approach can be used for different time horizons and with different levels of detail of the load duration curve. This makes the approach suitable both for planning analyses over one year or more, as well as to represent the local emissions occurring in the short-term (e.g., minute by minute) during the application of load-tracking strategies, in order to quantify the cumulative duration for which the emission limits have been exceeded. Furthermore, the structure of the equivalent load approach provides *smooth* trends of variation of the specific emissions when the equivalent load changes, even in the case of high non-linearity of the specific emissions from the cogeneration units. The equivalent load approach could be adopted by regulatory bodies to establish a conventional technique for taking into account partial-load operation of the cogeneration units.

5. Indicators for environmental impact assessment

Specific system-based indicators are aimed at promoting policy developments, as well as determining the break-even conditions for which CHP systems are equivalent to the conventional separate production in terms of global or local emissions. The use of synthetic indicators for assessing the benefits of exploiting cogeneration technologies with respect to separate production is common in energy efficiency studies, as recalled in Section 2. Comparison between distributed and centralized systems can be resorted to also in terms of emission analysis (Strachan & Farrell, 2006). Similar concepts can be extended and applied in the framework of the global and local emission balance approach (Section 3.2). In particular, the indicators listed in the following subsections are particularly useful to obtain

general indications independent of the characteristic of the individual site, thus of possible interest for regulatory purposes.

5.1 Global emission indicators

Let us consider the case of CO_2 emission assessment as a relevant example of application of the global emission balance approach, given the global warming impact of CO_2 as GHG. The CO_2 emission reduction due to cogeneration is expressed in relative terms with respect to the mass of pollutant emitted in global separate production. The resulting CO_2 Emission Reduction (*CO2ER*) indicator applied to global CO_2 emissions (Mancarella & Chicco, 2009a) is a sub-case of the *PCO2ER* indicator introduced in Chicco & Mancarella, 2008a for multi-generation systems:

$$CO2ER = \frac{m_{CO_2}^{GSP} - m_{CO_2}}{m_{CO_2}^{GSP}} = 1 - \frac{\mu_{CO_2}^{F} \cdot F}{\mu_{CO_2}^{W,SP} \cdot W + \mu_{CO_2}^{Q,SP} \cdot Q} = 1 - \frac{\mu_{CO_2}^{F}}{\mu_{CO_2}^{W,SP} \cdot \eta_W + \mu_{CO_2}^{Q,SP} \cdot \eta_Q} \qquad (11)$$

where the emission balance is carried out by considering the mass m_{CO_2} of CO_2 emitted from the combustion of the fuel F to cogenerate useful electricity and heat, and the mass $m_{CO_2}^{GSP}$ of CO_2 emitted by the separate production of the same useful outputs (electricity W and heat Q) from conventional technologies. Exploiting cogeneration is environmentally effective for positive values of *CO2ER*, while *CO2ER* = 0 indicates the break-even condition. As a further step, it is possible to introduce the *CO_2 emission equivalent efficiencies* (Chicco & Mancarella, 2008b)

$$\eta_{CO_2}^{W,SP} = \frac{\mu_{CO_2}^{F}}{\mu_{CO_2}^{W,SP}} \text{, and } \eta_{CO_2}^{Q,SP} = \frac{\mu_{CO_2}^{F}}{\mu_{CO_2}^{Q,SP}} \qquad (12)$$

thus expressing the *CO2ER* (11) as

$$CO2ER = 1 - \frac{1}{\frac{\eta_W}{\eta_{CO_2}^{W,SP}} + \frac{\eta_Q}{\eta_{CO_2}^{Q,SP}}} \qquad (13)$$

and obtaining an expression with formal analogy with the *PES* indicator (2) used in energy efficiency studies.

Considering the *global* equivalent emission factor referred to the electricity production defined in (8), the *CO2ER* expression can be further written in terms of the electricity production

$$CO2ER = 1 - \frac{\mu_{CO_2}^{F} \cdot F}{\mu_{CO_2}^{W,GSP} \cdot W} = 1 - \frac{\mu_{CO_2}^{F}}{\mu_{CO_2}^{W,GSP} \cdot \eta_W} \qquad (14)$$

Both equation (13) and the last expression in equation (14) show that the *CO2ER* indicator can be expressed in terms of cogeneration efficiencies and emission factors only. The emission factor $\mu_{CO_2}^F$, referred to the cogeneration thermal *input F*, can be considered at first approximation *independent* of the loading level, estimating it as a function of the fuel carbon content and of its *LHV* (Educogen, 2001). As an example, the value $\mu_{CO_2}^F \cong 200$ g/kWh$_e$ can be assumed for natural gas referred to the *LHV*.

The electrical and thermal efficiencies of the cogeneration unit can be evaluated depending on the loading level, giving the possibility of applying the indicator for explicit assessments under actual operating conditions of the cogeneration unit.

Taking into account equation (6), a further relevant result can be obtained if the cogeneration system and the separate production use the *same fuel*. In this case, it is possible to write equation (13) as

$$CO2ER = 1 - \frac{1}{\dfrac{\eta_W}{\eta_e^{SP}} + \dfrac{\eta_Q}{\eta_t^{SP}}} \tag{15}$$

In this way, the *CO2ER* indicator becomes equal to the *PES* indicator (2), that is, the environmental benefits can be evaluated by using *only* energy efficiencies, providing emission reduction results numerically coincident with the ones obtained from the energy saving analysis, as widely discussed in Chicco & Mancarella, 2008a, and Chicco & Mancarella, 2008b.

The underlying hypothesis leading to (15) is that complete combustion occurs, which is an excellent approximation in most cases (Educogen, 2001) and leads to a conservative model of the CO$_2$ emissions. In fact, with incomplete combustion part of the hydrocarbons produce pollutants other than CO$_2$ (for instance, CO), so that the CO$_2$ produced is lower than the one estimated by using the emission factor model.

The generalisation of the indicators to assess the *global* emission reduction for a generic pollutant *p* is straightforward, yielding to the *class* of indicators

$$pER = 1 - \frac{\mu_p^F \cdot F}{\mu_p^{W,SP} \cdot W + \mu_p^{Q,SP} \cdot Q} = 1 - \frac{\mu_p^F}{\mu_p^{W,SP} \cdot \eta_W + \mu_p^{Q,SP} \cdot \eta_Q} = 1 - \frac{\mu_p^F}{\mu_p^{W,GSP} \cdot \eta_W} \tag{16}$$

thus obtaining for instance indicators named *NO$_X$ER* for the case of NO$_X$, *COER* for the case of CO, and so forth, with the same conceptual implications described above for the CO$_2$ case.

Concerning global warming impact, in cogeneration applications CO$_2$ is the main GHG of interest. However, in certain cases also methane emissions could be of concern, particularly because methane could represent up to 90% of the total UHC emitted in natural gas-fuelled units. Thus, a further formulation is presented to enable assessing the global emission reduction for a generic GHG or for a GHG set **G**. This formulation is based on the fact that the effect of a generic GHG can be compared with the effect of CO$_2$ in terms of *Global Warming Potential* (GWP). Since by definition $GWP_{CO_2} = 1$ in the case of CO$_2$, the *GWP* for the other GHGs is expressed in relative terms with respect to CO$_2$ (see also Chicco &

Mancarella, 2008a, for details). The equivalent emission factor introduced for the generic GHG $p \in \boldsymbol{G}$ is defined as

$$\mu_{CO_2eq,p}^X = GWP_p \cdot \mu_p^X \tag{17}$$

where GWP_p represents the mass of CO_2 equivalent to the emission of a unity of mass of the GHG p, while μ_p^X is the emission factor defined in equation (6). The expression of the equivalent indicator $GHGER$ containing the effect of a set of GHG referred to the cogeneration system is

$$GHGER = 1 - \frac{\sum_{p \in \boldsymbol{G}} \mu_{CO_2eq,p}^F F}{\sum_{p \in \boldsymbol{G}} \left(\mu_{CO_2eq,p}^{W,SP} W + \mu_{CO_2eq,p}^{Q,SP} Q \right)} \tag{18}$$

5.2 Local emission indicators

Since the local emission balance model of Section 3.2 neglects the amount of pollutants produced by the electrical system considered to be sufficiently "far" from the area of interest, the local emission reduction indicators are defined starting from the global emission indicators and deleting the amount referred to the separate production of electricity. The *class* of *generalised local* emission reduction indicators for a generic pollutant p is then expressed as

$$pLER = 1 - \frac{\mu_p^F \cdot F}{\mu_p^{Q,SP} \cdot Q} = 1 - \frac{\mu_p^F}{\mu_p^{Q,SP} \cdot \eta_Q} = 1 - \frac{\mu_p^F}{\mu_p^{W,LSP} \cdot \eta_W} \tag{19}$$

where the last expression is obtained by taking into account the definition of the local equivalent emission factor referred to the electricity production in (10). The corresponding indicators are named NO_XLER for the case of NO_X, $COLER$ for the case of CO, and so forth.

5.3 Conventional separate production efficiencies and emission factors

The results obtained from the application of the emission reduction indicators depend on the choice of the efficiencies and emission factors referred to separate production of electricity and heat. The rationale for setting up the conventional values has to be addressed in a systematic way, highlighting the implications of different choices that could be adopted. Different settings of the values could lead to different numerical outcomes of the indicators introduced above. Since these indicators are expressed in relative values (per unit or per cent), the relevant shareholder typically pays attention to the resulting numerical outcome to get an idea of the potential emission reduction. For instance, a numerical outcome of 20% emission reduction has different meanings depending on the set of separate production efficiencies used to determine it.

Among the different ways to set up the conventional reference values, it is possible to mention:

1) The definition of the conventional values on the basis of the *average values* of the emission factors, that is, $\mu_p^{W,\text{SP}}$ for electricity production and $\mu_p^{Q,\text{SP}}$ for heat production. In this case, these values are assigned by considering on the electrical side the average emissions from the power plants used to produce electricity, and for the thermal side the average emissions from different boilers, also supplied with different fuels. The average values are calculated as weighted sums of the emissions from different units with respect to the unit sizes and types, and can in case refer to the marginal units operating in the bulk power system generation scheduling. This kind of definition allows obtaining indications on the real emission reduction that could occur in a given energy scenario, for instance in a given country (Meunier, 2002).

2) Considering cogeneration systems supplied by a given fuel (for instance, natural gas), the conventional values can be defined by taking into account the emission factors of technologies supplied by the same fuel (that is, in the case of CO_2, with the same carbon content and thus basically with the same CO_2 emissions per unit of burned fuel). This approach is aimed at assessing the emission saving potential of CHP systems *intrinsic* in the plant characteristics. It is then possible to adopt the model (6) with separate production efficiencies η_e^{SP} and η_t^{SP} for electricity and heat, respectively, to determine the equivalent emissions. In turn, the separate production efficiencies can be chosen according to different rationales, taking into account:

   a) *average technologies* for sizes *similar* to the one of the cogeneration system under analysis (ASST – Average Same-Size Technologies); or,

   b) the *best available technologies* for sizes *similar* to the one of the cogeneration system under analysis (BSST – Best Same-Size Technologies); or,

   c) the *best available technologies* (BAT) without size limits (with natural gas, corresponding to high-efficiency boilers and combined cycle power plants subtracting the electricity transmission and distribution losses).

The numerical values of the separate production efficiencies and emission factors are given by system-wide assessments, and need to be updated after some years in order to account for possible changes in the energy generation mix. An example of values referred to average CO_2 emissions in the Italian system (year 2003) yields $\mu_{CO_2}^{W,\text{SP}} \cong 525$ g/kWh$_e$ and $\mu_{CO_2}^{Q,\text{SP}} \cong 275$ g/kWh$_t$ (Mancarella & Chicco, 2009a). On the basis of equation (6), it can be noted that when increasing the SP efficiencies in the *CO2ER* indicator cogeneration loses competitiveness with respect to separate production. In fact, the adoption of the best technologies as references clearly penalizes the numerical outcome of the indicator, making cogeneration look less convenient. However, if the indicators are used for regulatory purposes, for instance setting thresholds above which it is possible to obtain incentives, the regulatory body can set the thresholds taking into account the conceptual meaning of the reference values. The above approaches are useful to boost the investments into high-efficiency cogeneration systems, with possible economic incentives within nation-wide energy and environmental policies (European Union, 2004; Cardona & Piacentino, 2005).

5.4 Emission limits and promotion of energy efficiency

The emissions measured on-site, or suitable emission reduction indicators, are typically compared with the limits to the various pollutants established by regulatory bodies. The rationale for setting up the emission limits can play a key role to promote or limit the diffusion of energy efficient technologies. For instance, the emission limits could be established considering the concentration of pollutant contained in the gas released to the ambient (e.g., expressed in mg/m^3). This approach could intuitively seem suitable to avoid exceeding the emission thresholds. However, it is not adequate to promote energy efficiency. In fact, a generator with high efficiency and a given concentration of pollutant in the exhaust gases would be penalized with respect to another generator less efficient but with slightly lower concentration of pollutant in the exhaust gases, regardless of the fact that the actual emissions per unit of output of the generator with higher efficiency could be lower than for the other unit.

A viable alternative consists of setting up emission limits on the basis of the specific emissions μ_p^X referred to the *useful energy output* (for instance, expressed in mg/kWh). In this case, it is possible to promote both reduction of the real environmental impact (referred to the useful outputs) and increase of energy efficiency.

Another limiting factor to the development of cogeneration solutions is the way in which the interactions among different causes of pollution are taken into account in the environmental regulation, especially at the local level. In the presence of a remarkably high level of pollution due for instance to road traffic, the strict application of the emission limits when planning the installation of new cogeneration systems would make it hard to promote the diffusion of new efficient technologies introducing (even relatively low) new local emissions, since the burden of exceeding the emission limits would be totally charged to the *marginal plants* to be installed. Promoting the diffusion of energy efficient technologies at the planning stage thus requires a comprehensive re-assessment of the causes of pollution and the identification of measures for limiting the impact of each of these causes.

5.5 Indicators for comparative emission assessment

Generally, the fuel adopted to supply the cogeneration system is different with respect to the fuel considered to represent the separate production, especially when taking into account the mix of fuels used to produce electricity in the power plants at regional or nation-wide level. Thus, focusing on CO_2 emissions, on average the same cogeneration technologies can be effective in terms of emission reduction in a system with prevailing production of electricity from fossil fuels (above all if with heavily polluting marginal plants), while they could provide no benefit in systems with prevailing production from hydroelectric or nuclear sources (Meunier, 2002; Chicco & Mancarella, 2008b). These aspects have been outlined in Mancarella & Chicco, 2008a, by introducing additional environmental impact indicators on the basis of which it is possible to provide a quantitative assessment of the effectiveness of adopting a certain type of cogeneration within a given regional or national context. In particular, the use of the indicators denoted as CO_2 Emission Equivalent Efficiency (*CO2EEE*) and CO_2 Emission Characteristic Ratio (*CO2ECR*) enables the determination of the break-even conditions for which CHP systems are equivalent to the conventional separate production in terms of GHG emissions. The *CO2ECR* indicator is defined as

$$CO2ECR = \frac{\mu_{CO_2}^{F}}{\left(\mu_{CO_2}^{W}\right)^{SP}} \quad (20)$$

The *CO2ER* expression (11) can be rewritten by explicitly showing the term *CO2ECR* as

$$CO2ER = 1 - \frac{CO2ECR \cdot F}{W + \frac{\mu_{CO_2}^{Q,SP}}{\mu_{CO_2}^{W,SP}} \cdot Q} = 1 - \frac{CO2ECR}{\eta_W + \frac{\mu_{CO_2}^{Q,SP}}{\mu_{CO_2}^{W,SP}} \cdot \eta_Q} \quad (21)$$

It is then possible to define the indicator *CO2EEE* as the value of *CO2ECR* obtained by applying the break-even condition *CO2ER* = 0 (Mancarella & Chicco, 2008a):

$$CO2EEE = \frac{W}{F} + \frac{\mu_{CO_2}^{Q,SP}}{\mu_{CO_2}^{W,SP}} \cdot \frac{Q}{F} = \eta_W + \frac{\mu_{CO_2}^{Q,SP}}{\mu_{CO_2}^{W,SP}} \cdot \eta_Q \quad (22)$$

In this way, the indicators *CO2ECR* and *CO2EEE* can be easily calculated on the basis of the emission factor of the fuel used, of the efficiencies of the cogenerator and of the emission factors in separate production. Adopting cogeneration is then convenient in terms of reducing the CO_2 emissions if the following inequality holds:

$$CO2EEE \geq CO2ECR \quad (23)$$

In analogy to equation (6), for separate production it is possible to define the expressions

$$\mu_{CO_2}^{W,SP} = \frac{\mu_{CO_2}^{F,SP}}{\eta_e^{SP}} \; ; \qquad \mu_{CO_2}^{Q,SP} = \frac{\mu_{CO_2}^{F,SP}}{\eta_t^{SP}} \quad (24)$$

Assuming that the same fuel is used to supply the cogeneration unit, the external boiler and the power system generation mix, the *CO2EEE* indicator can be expressed in a way depending only on the cogeneration unit and separate production efficiencies:

$$CO2EEE = \eta_W + \frac{\eta_e^{SP}}{\eta_t^{SP}} \cdot \eta_Q \quad (25)$$

In the general case, in which the fuels are not the same, the general scheme of analysis can be applied with some practical adjustments. For this purpose, suitable correction factors can be defined. Considering the emission factor $\mu_{CO_2}^{F,SP,e}$ for the equivalent fuel supplying the electricity separate production system, and the emission factor $\mu_{CO_2}^{F,SP,t}$ for the fuel supplying the boiler for separate production of heat, the correction factors are defined as

$$\varepsilon_e = \frac{\mu_{CO_2}^F}{\mu_{CO_2}^{F,SP,e}} \; ; \qquad \varepsilon_t = \frac{\mu_{CO_2}^F}{\mu_{CO_2}^{F,SP,t}} \tag{26}$$

Thus, the emission factors referred to the separate production of electricity and heat become, respectively,

$$\mu_{CO_2}^{W,SP} = \frac{\mu_{CO_2}^{F,SP,e}}{\eta_e^{SP}} = \frac{\mu_{CO_2}^F}{\varepsilon_e\,\eta_e^{SP}} \; ; \qquad \mu_{CO_2}^{Q,SP} = \frac{\mu_{CO_2}^{F,SP,t}}{\eta_t^{SP}} = \frac{\mu_{CO_2}^F}{\varepsilon_t\,\eta_t^{SP}} \tag{27}$$

and the expression of the *CO2EEE* indicator becomes

$$CO2EEE = \eta_W + \frac{\varepsilon_e\,\eta_e^{SP}}{\varepsilon_t\,\eta_t^{SP}} \cdot \eta_Q \tag{28}$$

thus highlighting the use of the corrected electrical efficiency $\varepsilon_e\,\eta_e^{SP}$ for separate production of electricity, and of the corrected thermal efficiency $\varepsilon_t\,\eta_t^{SP}$ for separate production of heat. Comparisons at regional or nation-wide level by using the *CO2ECR* and *CO2EEE* indicators have been reported in Mancarella & Chicco, 2008a.

5.6 Emission maps

In order to represent effectively the outcomes from break-even analyses, specific *emission mapping models* can be introduced. For instance, it is possible to work out the break-even conditions (in terms of pollutant emissions) with reference to the unitary production of electricity or heat, in terms of emission factors as defined in equation (5), taking the electrical and thermal efficiencies of the CHP prime mover as variables. The relevant break-even emission values so obtained in these *emission break-even maps* can be then compared to the actual emissions from every specific cogeneration unit and for every given pollutant. In this way, it is straightforward to estimate the environmental impact of cogeneration on the basis of the relevant emission balance considered, so that the maps drawn allow for general (not only break-even) emission assessment, as illustrated below. For specific analyses it could be possible to simulate the actual dispatch of the relevant cogeneration units to assess *punctually* their environmental impact with respect to the marginal plants operating in the bulk power system, as done for instance in Hadley & Van Dyke, 2003, or for bigger systems in Voorspools & D'haeseleer, 2000, and Voorspools & D'haeseleer, 2003.

Apart from the specific emission balance considered, several different maps can be drawn depending upon the *reference* emission characteristics assigned to the separate generation. The conventional reference values can be set up as indicated in Section 5.3. The reference numerical values considered for separate production may change significantly the outcomes of the analysis, so that these values must be carefully selected according to the specific systems under study and to the specific goal to pursue, above all for policy purposes.

Alternative models could be developed to account for the marginal operation of cogeneration units in different hours in an equivalent fashion, as done for instance by Tsikalakis & Hatziargyriou, 2007. However, for general and synthetic assessments, such as

for general policy regulation development, simulation-based or equivalently detailed approaches seem less feasible, above all in the presence of large power systems.

Once drawn the relevant break-even emission maps, given the cogeneration efficiencies (1) and the corresponding emissions for *every* operating point of the cogeneration system under analysis, it is possible to evaluate the local and global emission balances (Section 3.2), and thus the environmental performance with respect to the conventional separate generation of the same amount of electricity and/or heat, according to the emission evaluation model used. More specifically, given a certain pollutant, to which corresponds a certain emission break-even map on the basis of the separate production emission references selected for the analysis, the environmental impact comparison between conventional generation and cogeneration can be carried out on the basis of the following steps:

- assign the electrical and thermal efficiency of the analysed cogeneration system under a determined operation condition;
- in correspondence of these values of η_W and η_Q, determine on the (local and/or global) emission break-even map the relevant (local and/or global) emissions from the conventional separate production technologies taken as references;
- compare the emission values found to the *actual* emissions from the considered cogeneration system under the same operational conditions;
- on the basis of the separate production emissions and the actual cogeneration emissions, evaluate the relevant emission balance.

A specific example of use of the emission maps is shown here, considering the case of NO_x with average reference emission factors $\mu_{NO_x}^{W,SP}$ = 0.5 g/kWh$_e$ for electricity generation and $\mu_{NO_x}^{Q,SP}$ = 0.5 g/kWh$_t$ for heat generation.

In the *local* emission balance analysis, Fig. 1 shows the emission break-even curves, in terms of specific emissions expressed in mg/kWh$_e$. The curves are drawn in function of the cogeneration electrical efficiency, for discrete values of the thermal efficiency used as the curve parameter.

The mapping in Fig. 1 can be exploited by following the procedure outlined above, with reference to specific cogeneration prime movers. For instance, let us consider a MT and an ICE with rated characteristics indicated in Table 1.

unit	rated power [kW$_e$]	η_W	η_Q	λ_y	NO$_x$ specific emissions	
					[mg/kWh$_e$]	[mg/kWh$_t$]
MT	100	0.29	0.48	1.65	170	101
ICE	180	0.34	0.49	1.44	1500	1041

Table 1. Rated characteristics for MT and ICE units.

The location within the map of the *actual* specific emissions (in mg/kWh$_e$) of the MT and the ICE units is reported in Fig. 1. For each unit, the rated electrical and thermal efficiency pair of values corresponds, on the map, to the emission break-even condition, that is, the maximum specific emissions (referred in this case to the kWh$_e$) that the unit should feature in order to guarantee an environmental impact lower than the conventional heat generation reference in the local emission balance. In particular, while the emission map in Fig. 1 is drawn with reference to the specific NO$_x$ emissions per kWh$_e$, the break-even conditions are

worked out so as to compare the cogeneration heat production with the same thermal energy produced by local boilers. Indeed, an equivalent emission break-even map might be drawn as well with reference to specific emissions per kWh_t produced. As the last step in the evaluation, once pointed out in the map the relevant break-even unitary emissions, the local emission balance can be graphically worked out by pointing out the *actual* emissions from the machine under analysis.

Considering the MT, the values of electrical efficiency (0.29) and thermal efficiency (0.48) are entered in the emission map, providing a break-even emission factor value of about 330 mg/kWh_e. Comparing the break-even emission value to the actual full-load MT emissions of about 170 mg/kWh_e (Table 1), the MT brings NO_x emission reduction per kWh_e produced of about 330–170=160 mg/kWh_e. A similar calculation could be readily developed with respect to the kWh_t produced. In this case, the MT would emit 101 mg/kWh_t (Table 1), to be compared with 200 mg/kWh_t emitted by the reference boiler; this brings NO_x emission reduction equal to 97 mg/kWh_t, again corresponding to 97·1.65=160 mg/kWh_e.

Considering the ICE, entering the electrical efficiency (0.34) and the thermal efficiency (0.49) in the emission map, the break-even NO_x emissions value for the reference boiler is of about 280 mg emitted per kWh_e of electrical energy cogenerated. Considering actual specific emissions of 1500 mg/kWh_e (Table 1), the local emissions using the ICE unit *increase* with respect to the local emissions from conventional reference boilers by about 1220 mg/kWh_e.
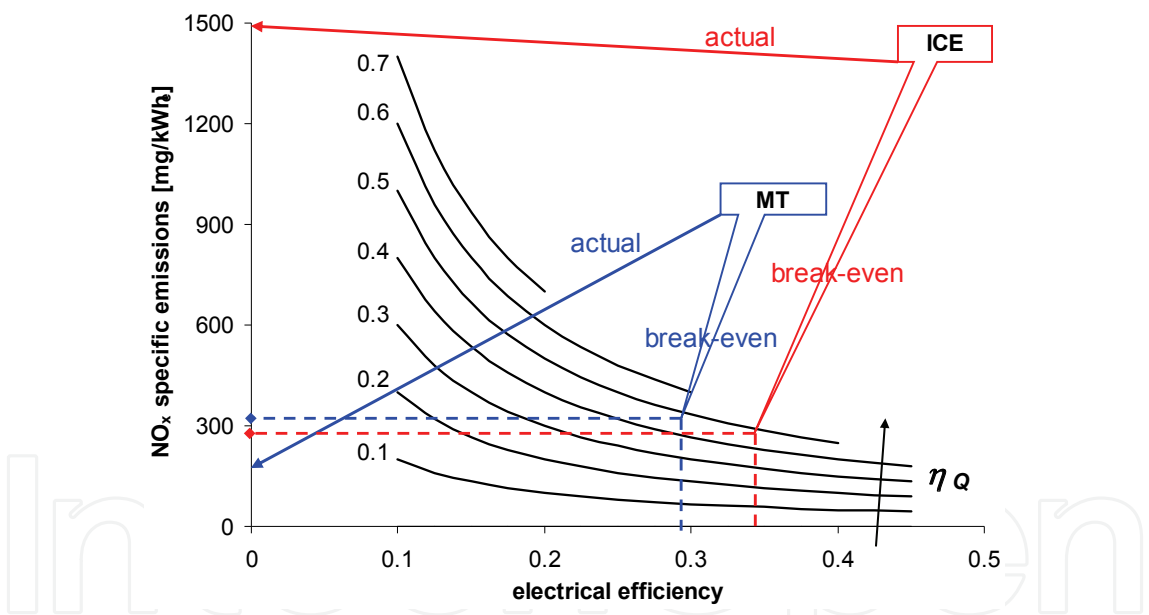

Fig. 1. Local NO_x emission balance assessment with MT and ICE (average separate production references).

The same considerations apply to the *global* emission map for NO_x, comparing the break-even conditions with the actual emission characteristics of the MT and ICE of Table 1. In this case, a similar representation (not shown here) can be adopted, in which the global emission balance yields a global emission *reduction* of about 650 mg/kWh_e for the MT, and a global emission *increase* of about 750 mg/kWh_e for the ICE.

Besides single cogeneration units, the emission mapping models can be used to evaluate more general solutions, such as particular scenarios of diffusion of cogeneration with

different types of equipment. The general approaches introduced enable to undertake *scenario analyses* aimed at assessing the environmental impact from given types of equipment, number of units, and so forth. For instance, the scenario analyses can be formulated according to the lines indicated in Chicco & Mancarella, 2008c:

- different technologies are taken into account, with their energy and emission characteristics;
- a set of scenarios is defined, each of which is characterized by a given mix of technologies, that can be envisioned for the future, and by the level of penetration of cogeneration with respect to the (electrical and thermal) energy demand; each scenario also contains a specific set of reference values for separate production of electricity and heat;
- for each mix of technologies, the equivalent energy and emission performance is determined by weighting the contribution of each technology to the overall mix with a predefined model (e.g., linear);
- the *PES* and *CO2ER* indicators, as well as the local emission balance outcomes, can be used to evaluate the energy efficiency and the environmental impact for different pollutants.

In addition, a comprehensive environmental impact mapping of given cogeneration systems can be obtained by merging scenario analyses with off-design assessments.

6. Role of environmental impact in the formulation of optimisation methods

Minimization of the emissions from cogeneration plants has been included in the formulation of planning and operation problems in various literature studies. The simplest way to take into account emissions is to include the emission limits within the optimization problem constraints. More generally, emissions are taken into account in the definition of *multi-objective* optimisation problems of different types:

1. Problems in which an *equivalent objective function* is defined as the weighted sum of a set of objective functions; one of the objective functions (or more than one, for instance when local and global emissions are considered separately) refers to emission impact minimization.
2. Problems with *conflicting objectives* (typical problems in the case of considering different types of emissions) solved through the evaluation of compromise solutions with Pareto-front calculation techniques. The *Pareto front* contains all the non-dominated solution points of the multi-objective optimization problem. With reference to objective minimisations, a solution is *non-dominated* if no other solution exhibits lower values for *all* the individual objective functions. Non-dominated solutions in which none of the individual optima is achieved may be of interest because of providing compromise alternatives among the various objectives. For problems with non-convex Pareto front, the ε-constrained method (Yokoyama et al., 1988) optimizes the preferred objective by introducing the other objectives as constraints and leaving a margin of acceptable solutions bounded by a user-defined threshold ε. Conceptually, the components of the Pareto front could be obtained more extensively by varying the threshold ε. More recently, some literature methods have been proposed to find directly a number of compromise solutions belonging to the *best-known* Pareto front (Shukla & Deb, 2007).

3. Long-term or design problems solved through a *multi-criteria* approach (Giannantoni et al., 2005; Carpaneto et al., 2007). When the level of uncertainty becomes very large, the decision-maker can assume a wider discretion in defining a set of scenarios to be considered. These scenarios are then analysed by means of *multi-attribute* decision-making approaches, providing multiple results, among which the decision-maker can determine the preferred solution by evaluating the Pareto front through a suitable numerical technique, as described in Li, 2009, or exploiting risk-based tools (Carpaneto et al., 2008).

Some sample references including environmental aspects in cogeneration optimization are recalled here. Curti et al., 2000, introduce in the objective function a specific term representing the pollution cost rate determined for each pollutant, depending on the emission level, the specific damage cost referred to the pollutant, and a user-defined penalty factor. In the multi-objective approach with minimization of cost and multiple emissions presented in Tsay, 2003, the emissions of each pollutant (CO_2, SO_x, and NO_x) are modelled as a function of the fuel enthalpy dependent on the emission factor. In Aki et al., 2005, optimum energy pricing is obtained as a Pareto solution for a multi-objective model considering both CO_2 emissions and economic impact on consumers. The CO_2 emission limits are also used as a constraint in the optimization model to minimize the individual cost to the consumers. Pelet et al., 2005, introduce the CO_2 emissions among the multiple objectives of integrated energy systems, obtaining the best-known Pareto front through a dedicated heuristic. Boicea et al., 2009, determine the best-known Pareto front for a cluster of microturbines operating with electrical load-following control strategy.

Environmental objectives are also included in the optimization of tri-generation or multi-generation systems (for instance, Burer et al., 2003; Rong & Lahdelma, 2005; Li et al., 2006).

7. Identification and determination of the environmental external costs and role of Life Cycle Assessment

External costs can be defined as the costs determined by the activities of a subject that do not appear in the economic balance of that subject. Another definition refers to external costs as arising "*when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group.*" (Bickel & Friedrich, 2005).

For cogeneration plants, internal costs are typically referred to construction and operation of the plant. Cogeneration plant emissions impact on the environment and on the society because of the effects of the pollutants emitted on the human health or on other receptors (Gulli, 2006). Some of the costs to reduce the pollutant emissions, such as the ones for installing abatement systems, are included in the internal balance. The remaining costs referred to the impact on the environment and the society are external cost components. Environmental external costs are related to both local and global effects, and need to be compared to separate production externalities. External costs can generally be internalized, that is, included in the economic evaluation to complete the environmental analysis. When the net external cost balance is positive in favour of distributed systems, internalization can be carried out through fiscal incentives, discounts on purchasing of products, taxes, relaxation of the air quality constraints, and so forth. For instance, adopting classical economic indicators (Biezma & San Cristóbal, 2006), ICE technologies could result more

convenient than microturbines on the basis of economic analysis, but MTs could exhibit emissions of CO and NO_X lower than the ones of the ICEs in a local emission balance. By internalizing the external costs due to global emissions, the margins of convenience of ICEs with respect to MTs could decrease substantially.

The analysis and assessment of external costs for energy system applications can be addressed as in the ExternE project (Bickel & Friedrich, 2005), based on a bottom-up approach in which the final impacts of the energy production are tracked back to their initial causes by determining the chain of events denoted as "impact pathways". The four stages of the ExternE model address the following aspects:

1. The description of the *technology* and characterisation of the related emissions. This requires the identification of the parameters referred to the emissions, like the flux of substances emitted in the environment and the concentration of pollutants inside these substances, as well as the stack height, and so forth. If the planning analysis refers to comparing different alternatives without specifying the technical details (Canova et al., 2008), it is possible to resort to the use of the emission factors within the emission balance approach illustrated in Section 3.

2. The analysis of the territorial *dispersion* of the emissions, with the objective of identifying the concentration of pollutants in the areas in which the receptors are located. The analysis is carried out by means of either *statistical* models based on the time series of environmental data measured in meteorology centres, or *deterministic* models, based on tracing the dispersion of the pollutants according to theoretical representation of the phenomena linked to their diffusion in the atmosphere (Arya, 1999).

3. The identification of the *receptors* and of the corresponding dose-response functions to assess the potential damages. The dose-response functions are defined in incremental terms, representing the increase of damage due to the increase of concentration of the pollutant. With reference to the human health, the dose-response functions can represent the increase in the number of subjects affected by a given pathology as a consequence of the exposure to the pollutants reaching the areas in which the subject is located (Bickel & Friedrich, 2005).

4. The determination of the *economic value* of the damages, taking into account permanent or temporary damages. Permanent damages refer to effects leading to premature death, generally evaluated by means of the Years of Lost Life (*YOLL*) to obtain the Value of Life Years Lost (*VOLY*) indicator (Krewitt et al., 1998; Bickel & Friedrich, 2005). Temporary damages refer to the quantification of illness, evaluated either by determining the cost incurred by the society to care the patients affected, denoted as Cost of Illness (*COI*), or by identifying the Willingness to Pay (*WTP*) of the individuals to avoid the occurrence or persistence of the causes, also taking into account further aspects of personal judgement like the opportunities lost because of illness (Dickie & Gerkin, 1989; Stieb et al., 2002).

A more comprehensive approach to the evaluation of the overall effects of introducing cogeneration systems in the energy context resorts to the concepts of Life Cycle Assessment (LCA), as discussed and applied in dedicated studies (Dincer, 1999; González et al., 2003; Chevalier & Meunier, 2005; Bickel & Friedrich, 2005).

For distributed cogeneration applications, in the overall LCA environmental balance the construction of MTs or ICEs (in terms of materials, manufacturing process, transport and installation) impacts to a minor extent with respect to the energy generated by the unit during its operational lifetime (Riva et al., 2006). This highlights the practical importance of

studies addressing energy and environmental issues of cogeneration, especially when comparisons are made among technologies using the same fuel, in which further aspects concerning the construction and exploitation of the fuel transportation system have the same impact and thus can be removed from the analysis without changing the nature of the results. Conversely, LCA considerations could be needed when comparing technological alternatives adopting different fuels, especially when the fuel production and transportation infrastructure has different characteristics with respect to the one used for natural gas, as in the case, for instance, of biomasses or hydrogen (Chevalier & Meunier, 2005; Pehnt, 2001). More generally, the inclusion of external costs in the objective functions of regional energy planning studies could show more incisively the benefits of adopting cogeneration, as well as other energy efficient technologies, in the energy production system (Cormio et al., 2003).

8. Cogeneration deployment in energy-related markets

Cogeneration can already be exploited under specific tariff systems or within a competitive electricity market structure. In addition, it could be possible to trade energy-related commodities (Chicco & Mancarella, 2007b) relevant to cogeneration, such as:

- GHG *emission allowances*, introduced within an emission trading framework aimed at limiting the GHG emissions from energy consumers; currently, each entity participating in the emission trading mechanism is assigned a certain number of emission allowances, with the possibility of trading the positive or negative allowance spread on the relevant market (Boonekamp, 2004); the unitary price ρ_{CO_2} of the allowances is expressed in m.u./tonCO$_2$eq, where m.u. means monetary units; the allocation of CO$_2$ emissions for energy systems with multiple products and multiple inputs is illustrated and discussed in Rosen, 2008.

- *Energy efficiency* (*white*) *certificates*, corresponding to acknowledged primary energy saving obtained from actions aimed at reducing the electricity and/or gas consumption; the unitary price ρ_y of the white certificates is expressed in m.u./toe.

Currently, a limited number of relatively large actors can participate in such markets, also depending on the country-specific applications. However, it can be envisaged that in the future participation will be enlarged to smaller producers. Profitability of potentially deploying CHP technologies within such market frameworks (provided that the policy structure allows it) should be evaluated through energy-environmental economic models. If the focus is specifically set on the cost of electricity production, an application example is illustrated in Mancarella & Chicco, 2009a, whose approach defines an average production cost of electricity (in m.u./kWh$_e$) based on the average fuel cost for electricity production. For this purpose, the fuel component related to the electricity produced is discounted by an equivalent amount relevant to the cogenerated heat in an *incremental* fashion, according to the classical incremental heat rate model (Horlock, 1997). The average production cost of electricity defined by this approach can be compared to the actual electricity prices, providing preliminary hints to assess profitability of exploiting the cogeneration system. Furthermore, multi-scenario analyses are run to calculate the sensitivities of electricity production cost to emission allowance prices, white certificate prices, gas prices, and conventional separate production references (Chicco & Mancarella, 2007b). The outcomes from such an exercise enlighten how the competitiveness of distributed cogeneration could

increase substantially if adequate pricing or market framework were set up to acknowledge the positive environmental externalities brought about by the enhanced performance intrinsic in the combined production.

9. Conclusions

This chapter has illustrated a number of aspects referred to the environmental impact of cogeneration systems, mainly focused on recent literature references and on the authors' work. In particular, specific models for evaluation of global and local pollutants have been discussed, introducing relevant emission reduction indicators to quantify the potential benefits of distributed cogeneration relative to classical separate production of heat in boilers and electricity in centralised power plants. Openings aimed to internalise environmental externalities within an LCA framework or potential energy-related markets, have also been illustrated. Starting from the concepts presented, there are several extensions for present and future research at both theoretical and application levels. On the technology side, the diffusion of new solutions of different type (for instance, fuel cells) and/or supplied by different fuels (e.g., biomasses) can change the scenario of convenience and profitability of adopting cogeneration in evolving energy systems. Other overall benefits could come from the interactions of various types of cogeneration prime movers with district heating, storage, and more generally multi-generation solutions for simultaneous production of different energy vectors. Broader availability and interaction of technologies can be accompanied by their more flexible exploitation under off-design conditions, introducing new uncertainty in the energy system analysis. Large uncertainty also appears at the planning and design stages because of the need of making hypotheses and of constructing very different scenarios of evolution of the electricity and gas prices in time horizons spanning over at least one decade. Further elements of uncertainty are introduced by the presence of energy-related markets for trading white certificates or emission allowances, and by a continuously changing policy framework, whose evolution depends on political decisions and on arbitrariness at the regulatory level. From the point of view of the decision-maker, helpful responses could come from the development of tools exploiting the concept of risk and formulating suitable strategies to hedge risks.

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11. Acronyms

ASST	Average Same-Size Technologies
BAT	Best Available Technologies
BSST	Best Same-Size Technologies
CHP	Combined Heat and Power
CO2ER	CO_2 Emission Reduction
COI	Cost of Illness
DG	Distributed Generation
FESR	Fuel Energy Savings Ratio
GHG	GreenHouse Gases
GSP	Global Separate Production
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LSP	Local Separate Production
MT	Microturbine
m.u.	monetary units
NG	Natural Gas
PCO2ER	Poly-generation CO_2 Emission Reduction
PES	Primary Energy Saving
PM	Particulate Matter
SP	Separate Production
toe	tonne of oil equivalent
UHC	Unburned Hydro-Carbons
VOLY	Value of Life Years Lost
WTP	Willingness to Pay
YOLL	Years of Lost Life

Distributed Generation

Edited by D N Gaonkar

In the recent years the electrical power utilities have undergone rapid restructuring process worldwide. Indeed, with deregulation, advancement in technologies and concern about the environmental impacts, competition is particularly fostered in the generation side, thus allowing increased interconnection of generating units to the utility networks. These generating sources are called distributed generators (DG) and defined as the plant which is directly connected to distribution network and is not centrally planned and dispatched. These are also called embedded or dispersed generation units. The rating of the DG systems can vary between few kW to as high as 100 MW. Various new types of distributed generator systems, such as microturbines and fuel cells in addition to the more traditional solar and wind power are creating significant new opportunities for the integration of diverse DG systems to the utility. Interconnection of these generators will offer a number of benefits such as improved reliability, power quality, efficiency, alleviation of system constraints along with the environmental benefits. Unlike centralized power plants, the DG units are directly connected to the distribution system; most often at the customer end. The existing distribution networks are designed and operated in radial configuration with unidirectional power flow from centralized generating station to customers. The increase in interconnection of DG to utility networks can lead to reverse power flow violating fundamental assumption in their design. This creates complexity in operation and control of existing distribution networks and offers many technical challenges for successful introduction of DG systems. Some of the technical issues are islanding of DG, voltage regulation, protection and stability of the network. Some of the solutions to these problems include designing standard interface control for individual DG systems by taking care of their diverse characteristics, finding new ways to/or install and control these DG systems and finding new design for distribution system. DG has much potential to improve distribution system performance. The use of DG strongly contributes to a clean, reliable and cost effective energy for future. This book deals with several aspects of the DG systems such as benefits, issues, technology interconnected operation, performance studies, planning and design. Several authors have contributed to this book aiming to benefit students, researchers, academics, policy makers and professionals. We are indebted to all the people who either directly or indirectly contributed towards the publication of this book.

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