Energies **2013**, *6*, 2686-2708; doi:10.3390/en6052686

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Energy-Exergy, Environmental and Economic Criteria in Combined Heat and Power (CHP) Plants: Indexes for the Evaluation of the Cogeneration Potential

Marco F. Torchio

Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; E-Mail: marco.torchio@polito.it; Tel.: +39-011-0904501; Fax: +39-011-0904499

Received: 27 February 2013; in revised form: 6 May 2013 / Accepted: 17 May 2013 / Published: 22 May 2013

Abstract: In the first part of this work, combined heat and power (CHP) criteria pertaining to energy, exergy, environmental (pollutant emission) and economic aspects, have been investigated and compared. Although the constraints in legislation usually refer to energy efficiency, primary energy savings and greenhouse gas savings, other criteria should also be taken into account in order to obtain a better evaluation of a cogeneration plant. Here particular attention has been paid to saving indexes for both an individual CHP-unit and for a CHP-system, that is the complete system with all the cogeneration units and the auxiliary plants necessary to cover the users' demand. Five indexes, named potential indexes, have been introduced to evaluate the cogeneration potential: one for energy saving, one for exergy, two for environmental aspects (global and local scale) and one for economic aspects. Finally, some indexes analysed in the paper have been applied to a case study concerning a district heating cogeneration system, and the different behaviour of the energy-exergy, environmental and economic aspects has been discussed.

Keywords: combined heat and power (CHP); energy indexes; exergy indexes; environmental indexes; economic indexes

Nomenclature

Latin Symbols

C	cost
d	interest rate
Ex	exergy
Ex^F	exergy associated with fuel F

Ex^Q	exergy associated with heat Q
$\hat{E}x$	rate of exergy
ExS	exergy saving
F	fuel energy supply (lower heating value)
$\hat{F}$	rate of fuel energy supply
m	mass
N	lifetime of the system
NC	number of CHP-units
NB	number of auxiliary boilers
PES	primary energy saving
POS	pollutant saving
PV	present value
PVS	present value saving
Q	heat
$\hat{Q}$	rate of heat
R	revenues
T	thermodynamic temperature
W	electric or mechanical energy
$\hat{W}$	rate of electric or mechanical energy

Greek Symbols

α	weight factor
ε	efficiency expressed as exergy ratio
$\hat{\varepsilon}$	efficiency expressed as exergy rate ratio
η	efficiency expressed as energy ratio
$\hat{\eta}$	efficiency expressed as energy rate ratio
λ	electric-to-thermal ratio of the CHP-unit (refer to energy)
$\hat{\lambda}$	electric-to-thermal ratio of the CHP-unit (refer to rate of energy)
μ	emission factor
π	potential index

Subscripts

A	absolute
B	auxiliary boilers
CPP	central power plants
env	value associated with the environment
ef	effective
el	electric
fu	fuel
k	k-th year
O&M	operation and maintenance

R	relative
SYS	CHP-system
th	thermal
we	weighted
0	initial time in the economic evaluation

Superscripts

F	referring to fuel
in	input
loss	loss due to irreversibility
j	j-th pollutant
L	local scale
out	output
Q	referring to heat
W	referring to electric or mechanical energy

Abbreviations

CHP	Combined Heat and Power (synonymous of cogeneration)
CHP-unit	a single cogeneration plant
CHP-system	a system composed of CHP-units, auxiliary boilers and central power plants
SHP	Separated Heat and Power

1. Introduction

Several criteria have been proposed, over the last few decades, to evaluate the advantages of cogeneration and different aspects have been taken into account. Cogeneration was initially mainly proposed for industrial applications, and attention was mainly focused on improving energy efficiency and on the resulting economic impact. Another advantage of cogeneration was due to the possibility of increasing the autonomy in power production with respect to the grid. Combined heat and power (CHP) was then expanded to other sectors: residential (mainly district heating) and tertiary (offices, hospitals, supermarkets, hotels). With the liberalization of the electricity market (which was introduced in the European Union in 1996), the production of power from CHP underwent a further expansion. Moreover, increasing attention towards sustainable development has highlighted the advantages of CHP, in terms of primary energy savings and pollutant reduction. CHP has also been considered one of the possible ways of reducing greenhouse gas.

Different criteria can be adopted to quantify the improvements made with CHP solutions or to compare different solutions. Classical indexes are based on energy analysis, in which all the useful energies (work and heat) have the same weight. The criteria of the second law of thermodynamics have been proposed (exergy efficiency) to improve information on CHP. In this approach, it is important not only how much heat is available but also at what temperature it is available.

The main environmental factor that has to be taken into account is the impact of pollutant emissions, and this factor is closely connected to both the fuel that is used and to the prime mover technology. CHP can reduce pollutant emissions in certain conditions: a high total efficiency intrinsically reduces emissions, but the emission factors of CHP need to be analysed to understand whether there will be a real advantage. It is in fact possible to obtain a reduction in emissions for one pollutant, but an increase for another.

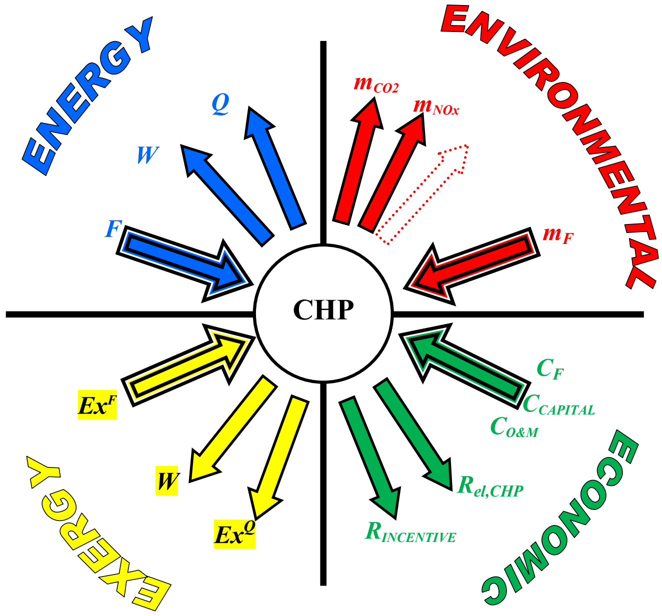
However, the economic aspect should also be taken into account. The main issues affecting this aspect are: fuel and power prices, prime mover capital costs, maintenance costs, fiscal incentives, effective power, heating requirements, *etc*.

These topics have often been discussed in technical literature [1–15]. Feng *et al.* [1] proposed a new performance index for cogeneration systems that takes into account the effect of "anergy" in heating, and compared it with four well-known criteria: energy utilization factor, artificial thermal efficiency, fuel energy saving ratio and exergy efficiency. Nussbaumer and Neuenschwander [2] analysed CHP from an economic point of view and introduced two dimensionless numbers: dimensionless capital costs and dimensionless fuel costs. Their approach allows CHP technologies, with different fuels, to be easily compared in different countries, and with different currencies. Bhatt [3] has identified nine different parameters that characterize a CHP-unit, and has also underlined the importance of comparing the heat-to-power ratio of the prime mover with the heat-to-power ratio of the load. Pilavachi *et al.* [4] have applied a multi-criteria method to a CHP plant and obtained a General Index of Sustainability. Seven factors are considered to assess their index: efficiency, installation costs, fuel costs, electricity costs, heat costs, CO_2 emissions and energy footprint. These factors are normalised with the weight coefficients and sixteen systems, with different CHP technologies and plant sizes, are compared. The authors stated that the results obtained with their method could be used to establish the most important factors that can influence the performance of a system. Nesheim and Ertesvag [5] have analysed the energy indexes that are adopted in the legislation of different countries and indexes based on exergy. Two plants have been simulated and compared using the aforementioned indexes. The authors have also discussed the importance of reference plants for separate electric and heat generation, and two possible choices have been underlined: best available technology (BAT) and an average of existing installations. Ertesvag [6] has continued the work he started in [5] and introduced a second law index named relative avoided irreversibility; industrial CHP and district heating CHP have been analysed as case studies, and both natural gas and biomass have been considered. He observed that some indexes overstate or underestimate improvements and, in some cases, exergetically poor systems could be favoured. In [7], Mancarella and Chicco have analysed global and local emissions in distributed cogeneration, and suggested some specific indicators. In [8], the same authors have introduced a new environmental index, trigeneration CO_2 emission reduction, which can be used to compare a trigeneration plant with conventional separate production of heat and power, and they have considered CHP as a subcase of the trigeneration analysis. They presented case studies, based on current technologies (microturbines, internal combustion engines, gas turbines, combined cycles), and discussed CO_2 emission reductions: the results mainly depend on the technology that was used for the combined production and on the composition of the energy generation mix. Kanoglu and Dincer [9] have analysed four cogeneration plants in which the heat is supplied to buildings: steam-turbine, gas-turbine, diesel-engine and binary geothermal plants. The adopted criteria were energy and exergy efficiencies, and the latter was more suitable when there were geothermal systems in the comparison. Ruan *et al.* [10] have studied CHP for commercial buildings (hotels, hospitals, stores and offices) and proposed an overall evaluation index that takes into account primary energy savings, CO_2 reduction, and payback. Sanaye and Ardali [11] have focused attention on microturbine CHP with the aim of estimating the optimal power and the number of units that maximize the annual profit, that is, the objective function; the payback period was also estimated. Kavvadias *et al.* [12] have discussed the design of a trigeneration system for a hospital building: two different electricity tariffs and different strategies to cover the loads were analysed. Different seasonal energy profiles were also taken into account. Particular attention was paid to energy indexes (overall efficiency, primary energy savings, system load coverage) and two economic indexes (annual operating profit and return of investment); no environmental or exergy indexes were considered. Wheeley *et al.* [13] have compared CHP systems for different industrial manufacturing applications using the simple payback, the internal rate of return and the net present value. The authors checked the effects of some factors on these indexes, such as operating hours, electric utility rate, facility thermal load, fuel type and fuel costs.

Compernolle *et al.* [14] have analysed a CHP system for greenhouse cultivation using the net present value approach and the local and global scale balance for CO_2, CO and NO_x. The authors concluded that CHP can be a cost effective technology for greenhouse cultivation and can help to reach emission reduction targets. However, tailored policies and support measures are necessary to promote CHP in the agricultural sector because new technical and management skills are necessary for the farmer, and higher investment are required. Maes and Van Passel [15] have studied an interesting policy aspect: the interference between different public policies promoting energy efficiency and CO_2 reduction. In fact, when authorities favour a technology, other energy technologies may in find themselves a less favourable position on the market. The authors analysed this aspect in a case study in which a hybrid energy system combined two complementary heating techniques: CHP and thermal solar panels. Two regions, the Netherlands and Flanders, were compared, and critical results were obtained for the latter: CHP has been favoured so much that solar panels are no longer of interest to investors. However, as far as the authorities are concerned, a more balanced policy would result in a larger CO_2 reduction for a lower cost.

In the first part of the present work, CHP criteria pertaining to energy, exergy, environmental (pollutant emission) and economic aspects have been investigated and compared. For each aspect, particular attention has been paid to the saving indexes. The main quantities concerning the energy, exergy, emission and economic balances are summarised in Figure 1. The importance of obtaining information for both the individual CHP-unit and the CHP-system has been underlined. CHP-system is here intended as the whole system consisting of all the cogeneration units and the auxiliary plants necessary to cover the users' demands. Five indexes have been introduced to evaluate the cogeneration potential: one for energy saving, one for exergy, two for environmental aspects (global and local scale) and one for the economic aspects. Finally, the main indexes analysed in the paper have been applied to a case study concerning a district heating cogeneration system, and the different behaviour of the saving and potential index has been evaluated and discussed.

Figure 1. The main quantities concerning the energy, exergy, emission and economic balances used to analyse the CHP (see the nomenclature for the meaning of the symbols).



2. CHP Energy Criteria

It is worth noting that some indexes could be expressed either as instantaneous values or as integral values. Both these values are important: the former are distinctive features of CHP-units, while the latter take into account how CHP-units actually work and are calculated over a conventional period of time (many regulations refer to integral indexes).

2.1. Classical Efficiency and Electric-to-Thermal Ratio of a CHP-Unit

A typical first law efficiency that can be used to characterise a CHP-unit is the total CHP efficiency (some of the synonyms are total system efficiency, overall efficiency, energy utilization factor, *etc.*):

$$\hat{\eta}_{CHP} = \frac{\hat{W} + \hat{Q}}{\hat{F}_{CHP}} \tag{1}$$

where $\hat{W}$ is the electric power; $\hat{Q}$ is the useful rate of heat; and $\hat{F}$ is the rate of supplied fuel energy. Another fundamental characteristic of a CHP-unit is the *electric-to-thermal ratio*:

$$\hat{\lambda} = \frac{\hat{W}}{\hat{Q}} \tag{2}$$

The total efficiency (1) is often divided into two parts in prime mover datasheets: instantaneous electric efficiency and thermal efficiency:

$$\hat{\eta}_{CHP} = \hat{\eta}_{el,CHP} + \hat{\eta}_{th,CHP} \tag{3}$$

$$\hat{\eta}_{el,CHP} = \frac{\hat{W}}{\hat{F}_{CHP}} \qquad \hat{\eta}_{th,CHP} = \frac{\hat{Q}}{\hat{F}_{CHP}} \tag{4}$$

From which it is easy to obtain:

$$\hat{\eta}_{el,CHP} = \hat{\eta}_{CHP} \cdot \left(\frac{\hat{\lambda}}{1+\hat{\lambda}} \right) \qquad \hat{\eta}_{th,CHP} = \hat{\eta}_{CHP} \cdot \left(\frac{1}{1+\hat{\lambda}} \right) \tag{5}$$

These efficiencies are functions of the load and are usually lower at part-load. The efficiencies and the electric-to-thermal ratio can be defined referring to a given period of time (an hour, a day, a season, a year, *etc*.), and can be reformulated as energy ratios:

$$\eta_{CHP} = \frac{W + Q}{F_{CHP}} = \eta_{el,CHP} + \eta_{th,CHP} \tag{6}$$

$$\lambda = \frac{W}{Q} \tag{7}$$

where W, Q and F are the electric, thermal and fuel energies, respectively. Therefore if the CHP-unit works at part load, the integral indexes will be lower than the instantaneous ones. In addition to the electric-to-thermal ratio of a CHP-unit, it is also possible to define an electric-to-thermal ratio for the load (*i.e.*, which refers to the user). These two ratios do not usually coincide because a CHP-unit does not match the electric and heat demands perfectly.

2.2. Modified Efficiencies

The well-known limit of the total efficiency is that there is no difference between the electric and thermal outputs. There are two possible ways of taking this aspect into account: adopting a modified first law efficiency, or using the exergy method (see section 3). The following approaches have been proposed for the former:

2.2.1. Weighted efficiency

$$\eta_{we} = \frac{\alpha_{el} \cdot W + \alpha_{th} \cdot Q}{\alpha_{fu} \cdot F} \tag{8}$$

where α is the weight factor of the three energy forms (work, heat and chemical). In the past has been proposed electrical and thermal energy sale values for α_{el} and α_{th}, respectively, and the fuel price for α_{fu}. As observed by [5], the weighted approach is adopted in some regulations, where α_{el} and α_{fu} are often assumed equal: US PURPA [16] has taken $\alpha_{el} = \alpha_{fu} = 1$ and $\alpha_{th} = 0.5$ as the standard efficiency. Brazilian legislation is similar, and, in fact, $\alpha_{el} = \alpha_{fu} = 1$, but the heat weight factor is not constant: $\alpha_{th} = \eta_{el,SHP} / \eta_{th,SHP}$. The product, $(\alpha_{th} \cdot Q)$, refers to the potential surplus of electricity. Because of the useful heat that is produced by a CHP-unit, the users do not use fuel in local boilers ($Q/\eta_{th,SHP}$) and this fuel could be used in a central power plant ($\eta_{el,SHP}$) to obtain a surplus of electricity. In general, the weighted efficiency is a simplified exergy efficiency without the real exergy content of the heat being taken into account. Therefore, if the weight factors are not chosen carefully, they can lead to distorted results.

2.2.2. Effective Electrical Efficiency

This efficiency is also known as *artificial thermal efficiency* [1], *fuel utilization efficiency* [16], *CHP electric effectiveness* [17], or the *Ecabert method* [18]. It is defined as:

$$\eta_{ef} = \frac{W}{F_{CHP} - \dfrac{Q}{\eta_{th,SHP}}} \tag{9}$$

where the CHP fuel energy; F_{CHP}, is reduced by the portion of fuel that theoretically should be used if the heat is obtained from separate heat production (*e.g.*, boilers). The advantage of this efficiency is that it can easily be compared with power plant efficiency.

2.3. Energy Saving Indexes

2.3.1. Introduction on Separated Heat and Power (SHP) Production

A CHP plant is often proposed in place of SHP production. It is therefore important to estimate the improvement that can be made when CHP is chosen instead of SHP. Many energy indexes are not only functions of CHP technology, but also of SHP technology, and it is therefore useful to define two conversion efficiencies related to SHP, one referring to heat and the other to work.

As far as heat is concerned, a typical option is the use of boilers (conventional, high efficiency, condensing), but heat pumps (electrical or absorption) can be considered an interesting alternative. Other alternatives could be considered in particular cases, for example the district heating, if it is available near the user. As far as electric power is concerned, reference is usually made to a mix of the power plants of a region (*e.g.*, country-Mix, EU-Mix, *etc.*), but other solutions could also be adopted, *e.g.*, Best Available Technologies for power plants.

Electric and thermal conversion from separate plants is here described with these efficiencies:

$$\eta_{el,SHP} = \frac{W}{F_{el,SHP}} \qquad \eta_{th,SHP} = \frac{Q}{F_{th,SHP}} \tag{10}$$

where $F_{th\text{-}SHP}$ and $F_{el\text{-}SHP}$ are the fuel energies supplied to the separate plants. It is useful to define the total fuel energy supply to SHP as:

$$F_{SHP} = F_{el,SHP} + F_{th,SHP} = \frac{W}{\eta_{el,SHP}} + \frac{Q}{\eta_{th,SHP}} \tag{11}$$

Finally, a total efficiency can also be defined for SHP plants:

$$\eta_{SHP} = \frac{W+Q}{F_{SHP}} = \frac{W+Q}{\dfrac{W}{\eta_{el,SHP}} + \dfrac{Q}{\eta_{th,SHP}}} \tag{12}$$

2.3.2. Absolute Primary Energy Saving

One of the most important comparisons between CHP and SHP concerns their primary energy consumptions. It should be noted that the acronym *PES* is used by some authors in the literature as an absolute value, but by others as a relative value. Therefore, the subscripts *A* (for absolute) and *R* (for relative) are used in this paper to avoid misunderstandings. The primary energy saving of the CHP-unit is:

$$PES_A = F_{SHP} - F_{CHP} \tag{13}$$

where F_{CHP} and F_{SHP} are fuel energy with and without cogeneration, respectively.

2.3.3. Relative Primary Energy Saving

This is defined by the following ratios:

$$PES_R = \frac{PES_A}{F_{SHP}} = \frac{F_{SHP} - F_{CHP}}{F_{SHP}} = 1 - \frac{F_{CHP}}{F_{SHP}} \tag{14}$$

Another useful expression can be obtained substituting equation (11) in (14):

$$PES_R = 1 - \frac{F_{CHP}}{\left(\dfrac{W}{\eta_{el,SHP}} + \dfrac{Q}{\eta_{th,SHP}}\right)} = 1 - \frac{1}{\dfrac{W}{\eta_{el,SHP} \cdot F_{CHP}} + \dfrac{Q}{\eta_{th,SHP} \cdot F_{CHP}}} \tag{15}$$

Finally, substituting the electric and thermal efficiency of the CHP-unit:

$$PES_R = 1 - \frac{1}{\left(\dfrac{\eta_{el,CHP}}{\eta_{el,SHP}} + \dfrac{\eta_{th,CHP}}{\eta_{th,SHP}}\right)} \tag{16}$$

Equation (16) clearly shows the link between the relative saving and the efficiencies (CHP and SHP). PES_R is one of the most important indexes, and it is at present used in European Union legislation [19] to promote cogeneration. Equation (16) can be rewritten as a function of other parameters, such as the electric-to-thermal ratio and the total efficiency, and these formulations are given in Equation (17):

$$PES_R = 1 - \frac{\lambda + 1}{\eta_{CHP} \cdot \left(\dfrac{\lambda}{\eta_{el,SHP}} + \dfrac{1}{\eta_{th,SHP}}\right)} = 1 - \frac{\eta_{SHP}}{\eta_{CHP}} \tag{17}$$

2.4. Potential Index for the Energy Saving

Generally, a CHP-unit does not completely substitute the SHP because the thermal and electric demands are not perfectly matched with those of to the CHP-unit. Therefore, parts of the loads are still coved by the auxiliary boilers and central power plants. This choice is also necessary to both ensure a backup system when the CHP-unit is unavailable (breakdown, maintenance, *etc*.) and to cover the load when the use of the CHP is not cost effective (off-peak load, very low thermal loads, *etc*.). Moreover, more than one CHP-unit could be installed, and different management strategies could be adopted. In this paper, the whole system, consisting of all the cogeneration units, the auxiliary boilers and central power plants, is called "CHP-system" (indicated by the subscript SYS in the next equations). Some particular indexes can be proposed for a CHP-system, and, in a similar way to the CHP-unit, some efficiencies and savings can be defined. The following can in general be written for a CHP-system:

$$\begin{cases} W_{SYS} = \sum_{i=1}^{NC} W_{CHP,\, i} + W_{CPP} \\ Q_{SYS} = \sum_{i=1}^{NC} Q_{CHP,\, i} + \sum_{v=1}^{NB} Q_{B,\, v} \\ F_{SYS} = \sum_{i=1}^{NC} F_{CHP,\, i} + \sum_{v=1}^{NB} F_{B,\, v} + F_{CPP} \end{cases} \tag{18}$$

where NC is the number of CHP-units; NB is the number of auxiliary boilers; and the subscripts SYS and B refer to the CHP-system and the auxiliary boilers, respectively. The primary energy saving referring to the CHP-system is:

$$(PES_R)_{SYS} = \frac{F_{SHP} - F_{SYS}}{F_{SHP}} = 1 - \frac{F_{SYS}}{F_{SHP}} \tag{19}$$

In this paper, the index obtained from the difference between the CHP-unit saving [*i.e.*, pure cogeneration, Equations (14) and (16)] and the CHP-system saving has been proposed to evaluate the cogeneration potential:

$$\pi_{PES} = PES_R - (PES_R)_{SYS} \tag{20}$$

This information should help one to better understand how much of the cogeneration potential is actually exploited.

3. CHP Exergy Criteria

Different forms of energy cross the boundary of a CHP-unit and the first law of thermodynamics does not impose restrictions on the direction of these flows (power, heat rate, mass flow rate of the fuel, *etc*.); the second law of thermodynamics instead introduces these restrictions [20–22].

The exergy analysis takes into account both thermodynamic laws: the exergy is defined as the maximum theoretical useful work obtainable from a system when it is placed in communication with a reference environment (a portion of the surroundings which do not change as a result of the any process under consideration). An exergy transfer corresponds to each energy transfer: the work transfer is equivalent to the exergy transfer, the exergy corresponding to heat transfers can be evaluated with the Carnot efficiency, and the exergy associated with a steady stream of matter can be related to four contributions: kinetic, potential, physical and chemical. The kinetic and potential energy of a stream can be fully converted to work, and are thus equal to kinetic and potential exergy. The physical exergy is equal to the maximum work obtainable when the stream is brought from its initial state to a condition of mechanical and thermal equilibrium with the environment (restricted dead state). The chemical exergy is equal to the maximum work obtainable when the stream that was previously brought to mechanical and thermal equilibrium is also brought to chemical equilibrium (dead state).

Exergy can be transferred between systems, but only in an ideal process is there exergy conservation, while exergy destruction occurs in a real process, that is, energy degradation takes place. As mentioned in the introduction, many authors have adopted exergy to analyse CHP plants, and efficiencies and saving indicators can also be defined for the exergy analysis.

3.1. CHP Exergy Efficiency

This is defined as the ratio between the exergy rate: the useful output (power and exergy rate associated with the heat) and the input (e.g., the fuel exergy):

$$\hat{\varepsilon}_{CHP} = \frac{\hat{W} + \hat{E}x^{Q}}{\hat{E}x^{F}_{CHP}} = \frac{\hat{W} + \hat{Q} \cdot \left(1 - T_{env}/T\right)}{\hat{E}x^{F}_{CHP}} \tag{21}$$

The term $\left(1 - T_{env}/T\right)$ is usually called the Carnot factor. Two thermodynamic temperatures are required for its evaluation: one (T) associated to the useful heat*,* and the other (T_{env}) associated to the environment. The term $\hat{E}x^{F}_{CHP}$ corresponds to the exergy of the stream of fuel, which is mainly the chemical exergy; the tables of standard chemical exergies [21] can be used to evaluate this term.

For a generic thermodynamic system, the exergy balance can be written as:

$$\hat{E}x^{loss} = \sum \hat{E}x^{in} - \sum \hat{E}x^{out} \tag{22}$$

where $\hat{E}x^{loss}$ is the exergy loss due to irreversibility, and the exergy balance for a CHP-unit is:

$$\hat{E}x^{loss} = \hat{E}x^{F}_{CHP} - \left(\hat{W} + \hat{E}x^{Q}\right) \tag{23}$$

Replacing Equation (23) in (21), the exergy efficiency becomes:

$$\hat{\varepsilon}_{CHP} = 1 - \frac{\hat{E}x^{loss}}{\hat{E}x^{F}_{CHP}} \tag{24}$$

Finally, for a given period of time, an exergy efficiency can be defined as:

$$\begin{aligned} \varepsilon_{CHP} &= \frac{W + Ex^{Q}}{Ex^{F}_{CHP}} \\ &= 1 - \frac{Ex^{loss}}{Ex^{F}_{CHP}} \end{aligned} \tag{25}$$

3.2. Exergy Saving Indexes

A comparison between CHP and SHP can also be conducted for the exergy analysis. Like the energy analysis, saving indexes can also be derived for exergy. These indexes are compared with energy indexes in Table 1. The exergy efficiencies for SHP are shown in the first part of the table. The exergy saving equations are then shown and the relative saving is expressed as a function of the exergy efficiency.

Table 1. The main equations for energy and exergy saving evaluation.

Type of index	Energy	Exergy
SHP efficiencies	$\eta_{el,SHP} = \dfrac{W}{F_{el,SHP}}$ $\eta_{th,SHP} = \dfrac{Q}{F_{th,SHP}}$ $\eta_{SHP} = \dfrac{W+Q}{F_{SHP}}$	$\varepsilon_{el,SHP} = \dfrac{W}{Ex^F_{el,SHP}}$ $\varepsilon_{th\_SHP} = \dfrac{Ex^Q}{Ex^F_{th,SHP}}$ $\varepsilon_{SHP} = \dfrac{W+Ex^Q}{Ex^F_{SHP}}$
Absolute saving	$PES_A = F_{SHP} - F_{CHP} = = \left(F_{el,SHP} + F_{th,SHP}\right) - F_{CHP}$	$ExS_A = Ex^F_{SHP} - Ex^F_{CHP} = = \left(Ex^F_{el,SHP} + Ex^F_{th,SHP}\right) - Ex^F_{CHP}$
Relative saving*	$PES_R = \dfrac{PES_A}{F_{SHP}} =$ $= 1 - \dfrac{F_{CHP}}{\dfrac{W}{\eta_{el,SHP}} + \dfrac{Q}{\eta_{th,SHP}}} =$ $= 1 - \dfrac{1}{\dfrac{\eta_{el,CHP}}{\eta_{el,SHP}} + \dfrac{\eta_{th,CHP}}{\eta_{th,SHP}}}$	$ExS_R = \dfrac{ExS_A}{Ex^F_{SHP}} =$ $= 1 - \dfrac{Ex^F_{CHP}}{\dfrac{W}{\varepsilon_{el,SHP}} + \dfrac{Ex^Q}{\varepsilon_{th,SHP}}} =$ $= 1 - \dfrac{1}{\dfrac{\varepsilon_{el,CHP}}{\varepsilon_{el,SHP}} + \dfrac{\varepsilon_{th,CHP}}{\varepsilon_{th,SHP}}}$

* It is interesting to observe that Ertesvag [6] introduced the *RAI* index (*Relative Avoided Irreversibility*), which is defined as $RAI = \left(Ex^{loss}_{SHP} - Ex^{loss}_{CHP}\right) / Ex^F_{SHP}$, and it is possible to demonstrate that *RAI* is equivalent to ExS_R

3.3. Potential Index for Exergy Saving

The CHP-system can also be analysed from an exergy point of view. An exergy saving index can be defined as:

$$(ExS_R)_{SYS} = \frac{Ex^F_{SHP} - Ex^F_{SYS}}{Ex^F_{SHP}} = 1 - \frac{Ex^F_{SYS}}{Ex^F_{SHP}} \tag{26}$$

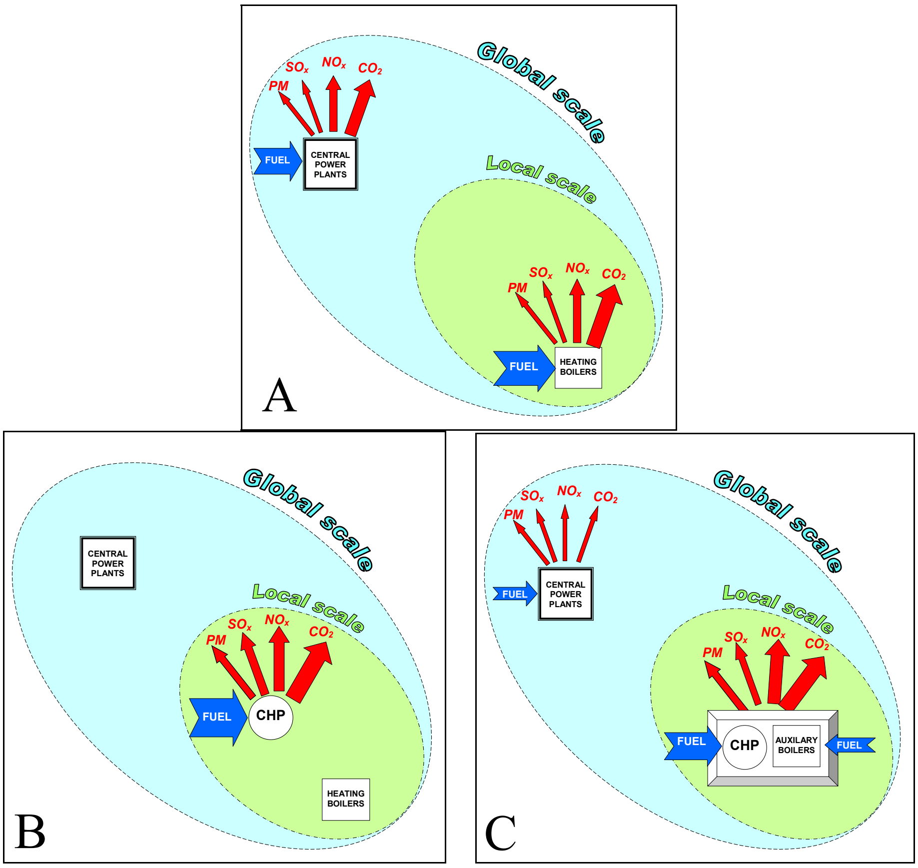
A comparison between the CHP-unit and the CHP-system could be made adopting exergy and as has been done in Equation (20), a potential index can be defined as:

$$\pi_{ExS} = ExS_R - (ExS_R)_{SYS} \tag{27}$$

4. CHP Environmental Criteria

Increasing attention to environmental problems has led to the introduction of more and more stringent restrictions with regard to emissions. At present, a great deal of attention is directed towards greenhouse gases (CO_2, CH_4, N_2O, fluorinated gases), which are expressed in CO_2 equivalents. However, several other pollutants are also important: nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), carbon monoxide (CO), unburned hydrocarbons (HC), *etc*. CHP technologies can reduce emissions due to the increase in efficiency, but in some cases the net emissions can increase, and a dedicated balance should therefore be conducted for each pollutant and each CHP technology. Before conducting a balance, it is necessary to define the boundaries of the area, and two cases are significant [7]: global scale balance, in which both the on-site plants and central power plants are taken into account, and local scale balance, in which only the on-site plants are taken into account. This distinction is important and the pollutant indexes have therefore been presented distinguishing between these two boundaries. A schematic drawing of an SHP is given in Figure 2A, while Figure 2B shows the case of a CHP-unit which is matched exactly to the power and heat demands.

Figure 2. Schematic comparison of the emissions (global and local scale). **A**: SHP; **B**: the CHP-unit is matched exactly to the power and heat demands; **C**: the CHP-unit is not matched exactly to the power and heat demands; a CHP-system (composed of CHP-units, auxiliary boilers, and central power plants) has therefore been considered.



4.1. Pollutant Saving Indicators (Global Scale)

4.1.1. Absolute Pollutant Saving (Global Scale)

A global emission balance can be conducted for each pollutant (subscript *j*):

$$POS_A^j = m_{SHP}^j - m_{CHP}^j \tag{28}$$

In order to obtain an improvement at a global scale, the following conditions should be satisfied for each pollutant:

$$POS_A^j \geq 0 \tag{29}$$

The absolute saving is often cited for GHG emissions, in order to promote the environmental benefits of a technology, but this value is closely linked to the size of the plant and a relative value is more significant.

4.1.2. Relative Pollutant Saving (Global Scale)

$$POS_R^j = \frac{POS_A^j}{m_{SHP}^j} = \frac{m_{SHP}^j - m_{CHP}^j}{m_{SHP}^j} = \\ = 1 - \frac{m_{CHP}^j}{m_{SHP}^j} = 1 - \frac{m_{CHP}^j}{m_{el,SHP}^j + m_{th,SHP}^j} \tag{30}$$

These equations can be written by introducing emission factors, and in particular the CHP emission factor definitions for each j-th pollutant are

$$\mu_{fu,CHP}^j = \frac{m_{CHP}^j}{F} \qquad \mu_{el,CHP}^j = \frac{m_{CHP}^j}{W} \qquad \mu_{th,CHP}^j = \frac{m_{CHP}^j}{Q} \tag{31}$$

and the emission factors definitions for SHP electric production and for SHP-thermal production are

$$\mu_{el,SHP}^j = \frac{m_{el,SHP}^j}{W} \qquad \mu_{fu\_el,SHP}^j = \frac{m_{el,SHP}^j}{F_{el,SHP}} \qquad \mu_{th,SHP}^j = \frac{m_{th,SHP}^j}{Q} \qquad \mu_{fu\_th,SHP}^j = \frac{m_{th,SHP}^j}{F_{th,SHP}} \tag{32}$$

Therefore the Equation (30) can be written as

$$POS_R^j = 1 - \frac{\mu_{fu,CHP}^j \cdot F_{CHP}}{\mu_{el,SHP}^j \cdot W + \mu_{th,SHP}^j \cdot Q} \tag{33}$$

It is useful to rewrite Equation (33), introducing the CHP-unit efficiencies:

$$POS_R^j = 1 - \frac{\mu_{fu,CHP}^j}{\mu_{el,SHP}^j \cdot \frac{W}{F_{CHP}} + \mu_{th,SHP}^j \cdot \frac{Q}{F_{CHP}}} = \\ = 1 - \frac{\mu_{fu,CHP}^j}{\mu_{el,SHP}^j \cdot \eta_{el,CHP} + \mu_{th,SHP}^j \cdot \eta_{th,CHP}} \tag{34}$$

and the SHP efficiencies:

$$POS_R^j = 1 - \frac{\mu_{fu,CHP}^j}{\mu_{fu\_el,SHP}^j \cdot \frac{\eta_{el,CHP}}{\eta_{el,SHP}} + \mu_{fu\_th,SHP}^j \cdot \frac{\eta_{th,CHP}}{\eta_{th,SHP}}} \tag{35}$$

Equation (35) shows that the avoided emissions are functions of several factors: the fuels that are used and the technologies that are adopted for both SHP and CHP. In this case, three different emission factors and four efficiencies are present. Equation (35) is a general equation that can be applied to each j-th pollutant. When CO_2 emissions are analysed, a further simplification can be made by introducing two hypotheses: the same fuel is used for CHP and SHP, and a complete combustion of the fuel is assumed, in this way, the emission only depends on the fuel characteristics. These conditions entail that the same emission factor is present as both the numerator and as the denominator, and Equation (35) can be simplified to:

$$POS_R^{CO2} = 1 - \frac{1}{\frac{\eta_{el,CHP}}{\eta_{el,SHP}} + \frac{\eta_{th,CHP}}{\eta_{th,SHP}}} \tag{36}$$

Equation (36) is the same as Equation (16), and the POS_R^{CO2} index therefore coincides with PES_R. These considerations have been extended to trigeneration systems in [8].

4.1.3. Potential Indexes for Pollutant Saving

When the CHP-system is considered, the following can be written for each j-th pollutant:

$$m_{SYS}^j = \sum_{i=1}^{NC} m_{CHP,i}^j + \sum_{v=1}^{NB} m_{B,v}^j + m_{CPP}^j \tag{37}$$

A schematic representation of the local and global scale pollutant emissions for the CHP-system is shown in Figure2C. This representation can be compared with SHP (Figure 2A), and with the CHP-unit (Figure 2B). Therefore, the CHP-system pollutant saving is:

$$(POS_R^j)_{SYS} = 1 - \frac{m_{SYS}^j}{m_{SHP}^j} \tag{38}$$

and the potential index at a global scale is:

$$\pi_{POS}^j = POS_R^j - (POS_R^j)_{SYS} \tag{39}$$

4.2. Pollutant Saving Indicator (*Local Scale*)

A distinction between global and local scale is fundamental in order to understand whether there is a real environmental improvement due to cogeneration. Greenhouse gases are usually analysed with reference to their global effects (it could also be useful to differentiate between the local and global scale for CO_2 in order to establish where it has been produced). However, the local environmental impact is more important than the global one for other pollutants, because these pollutants could have adverse health effects on the local population. Therefore, a local emission balance should be conducted for each j-th pollutant in order to obtain the local indexes (superscript *L*). The main local saving indexes are shown in Table 2 and compared with the global indexes.

It should be noted that, if the emission factors in $POS_R^{L,j}$ are equal, cogeneration does not improve local emissions (because the thermal efficiency of a CHP-unit is usually lower than that of an SHP). Therefore, in order to obtain an improvement at the local scale, it is necessary for the emission factor ratio to compensate the ratio of these thermal efficiencies.

In addition to the local scale balance, other analyses can be conducted to obtain knowledge on the environmental impact connected to the geographical sites of the plants. For example, it is possible to evaluate the concentration of a pollutant using a dispersion model applied to the area surrounding the plant. The dispersion of a pollutant could be estimated and two maps could be obtained, one with the

CHP plant and one without (i.e. with the SHP heating system). If these maps are compared, it is possible to evaluate whether some parts, and which parts, of an area undergo improvement. An example of this type of analysis is discussed in [23], in which a CHP district heating plant has been analysed using a Gaussian dispersion model and the maps of the concentration of some pollutants (NO_x, SO_x and PM) are discussed. As an alternative to the graphical comparison, an index could be calculated from the mean spatial distribution of the pollutant concentration, that is, a spatial integral is calculated over the area of the dominion. These evaluations are interesting, but require more detailed information (the orography of the site, weather data, the height of the stack, *etc.*) and are more complex.

Table 2. The main equations for the evaluation of the global and local pollutant savings.

Type of index	Global scale	Local scale
Absolute saving	$POS_A^j = m_{SHP}^j - m_{CHP}^j$	$POS_A^{L,j} = m_{th,SHP}^j - m_{CHP}^j$
Relative saving	$POS_R^j = \frac{POS_A^j}{m_{SHP}^j} = \frac{m_{SHP}^j - m_{CHP}^j}{m_{SHP}^j}$ $= 1 - \frac{\mu_{fu,CHP}^j}{\mu_{fu\_el,SHP}^j \cdot \frac{\eta_{el,CHP}}{\eta_{el,SHP}} + \mu_{fu\_th,SHP}^j \cdot \frac{\eta_{th,CHP}}{\eta_{th,SHP}}}$ $(POS_R^j)_{SYS} = 1 - \frac{m_{SYS}^j}{m_{SHP}^j}$	$POS_R^{L,j} = \frac{POS_A^{L,j}}{m_{th,SHP}^j} = 1 - \frac{m_{CHP}^j}{m_{th,SHP}^j}$ $= 1 - \frac{\mu_{fu,CHP}^j}{\mu_{fu\_th,SHP}^j} \cdot \frac{\eta_{th,SHP}}{\eta_{th,CHP}}$ $(POS_R^{L,j})_{SYS} = 1 - \frac{m_{SYS}^{L,j}}{m_{th,SHP}^j}$
Potential index	$\pi_{POS}^j = POS_R^j - (POS_R^j)_{SYS}$	$\pi_{POS}^{L,j} = POS_R^{L,j} - (POS_R^{L,j})_{SYS}$

5. CHP Economic Criteria

5.1. General Criteria

Policymakers are mainly interested in promoting CHP in order to increase energy savings and pollutant savings, but the users and investors are primarily interested in the economic aspects, and economic criteria should therefore also be taken into account to have an overall picture of the CHP. In order to compare SHP and CHP, it is possible to carry out a life-cycle cost analysis, a method that can be applied to any capital investment decision. This kind of analysis is useful when many alternative projects that can perform the same function are available. The same discount rate should be assumed for each analysed project and all future costs and revenues should be discounted to their present value.

The main costs of CHP investment are: the initial investment (for equipment, installations, project), fuel purchase costs, and non-fuel operation and maintenance costs (O&M). There is always a power purchase for SHP, while there could be either a partial power purchase or power sales for CHP. The present value of all the costs and revenues can be written as:

$$PV = C_0 + \sum_{k=1}^{N} \frac{C_k - R_k}{(1 + d_k)^k} \tag{40}$$

where:

C_k = costs at year k (C_0 is the initial investment);

R_k = revenues at year k ;

d_k = interest rate at year k;

N = lifetime of the system

The value of the plant at the end of its life (*i.e.*, at year N) can be positive, but also negative if there is a cost for the disposal of the plant. These cases should be taken into account in NPV equations.

5.1.1. Absolute Present Value Saving

In a similar manner to the previous energy, exergy and environmental analyses, it is also possible to evaluate an economic saving between SHP and CHP for PV:

$$PVS_A = PV_{SHP} - PV_{CHP} \tag{41}$$

$$PVS_A = C_{SHP,0} - C_{CHP,0} + \sum_{k=1}^{N} \frac{C_{SHP,k} - C_{CHP,k}}{(1+d_k)^k} - \sum_{k=1}^{N} \frac{R_{SHP,k} - R_{CHP,k}}{(1+d_k)^k} \tag{42}$$

The term $C_{SHP,0} - C_{CHP,0}$ is usually negative, while the others are positive. CHP should in fact lead to cost savings compared to SHP, e.g., a lower fuel price due to tax exemption for cogeneration, and to an increase in income due to the sold power or to incentives such as white certificates. PVS_A is also called *net present value* and can be obtained summing all the present values of the net cash flow. A greater PVS_A value than zero does not guarantee a real economic advantage, and, two other indicators are often calculated considering Equation (42): the first is the rate of *return of the investment* (*ROI*), which is the root of Equation (42), when the PVS is set equal to zero and d is the unknown value; the second is the *discounted payback period* (*DPB*), which is the length of time necessary for the sum of the discounted net cash flows to be equal to the initial investment. The unknown value is therefore the time. This indicator is used as a screening value to evaluate whether to accept or reject a CHP investment.

5.1.2. Relative Present Value Saving

It is also possible to define a relative value for economic savings:

$$PVS_R = \frac{PV_{SHP} - PV_{CHP}}{PV_{SHP}} = \frac{PVS_A}{PV_{SHP}} \tag{43}$$

5.2. Potential Index for Economic Saving

It is also possible to consider the economic aspect of the CHP-system and the present value of the system becomes:

$$PV_{SYS} = \sum_{i=1}^{NC} PV_{CHP,i} + \sum_{v=1}^{NB} PV_{B,v} + PV_{CPP} \tag{44}$$

Therefore, the present value saving for the CHP-system is:

$$(PVS_R)_{SYS} = \frac{PV_{SHP} - PV_{SYS}}{PV_{SHP}} = 1 - \frac{PV_{SYS}}{PV_{SHP}} \tag{45}$$

and the potential index becomes:

$$\pi_{PVS} = PVS_R - (PVS_R)_{SYS} \tag{46}$$

5.3. Other Indexes and Methods

Other alternative indexes have been proposed for the economic comparison of investments [24,25], but they have not been discussed in this paper. The main indexes are: the saving-to investment ratio, that is, the ratio between the discounted total cumulative savings and the discounted total cumulative investments, where CHP leads to an improvement if this ratio is greater than one; levelized cash flows, where the real variable cash flow is used to calculate a theoretical constant cash flow; direct pricing of electricity and heat, where the calculated prices of the output of a CHP plant are compared with the market prices.

Furthermore, the economic principles and the exergy analysis can be combined and in this case the terms thermoeconomics or exergoeconomics have been adopted [20,22,26,27]. A thermoeconomics analysis allows one to calculate the costs of each product generated by a system with more than one product and it is therefore particularly interesting for CHP. Another line of development includes environmental aspects by internalizing the external costs; the term exergo-enviro-economics analysis has thus been proposed. Some authors have directly connected exergy and the environmental impact: for example Meyer *et al.* [28] proposed that the environmental impact, obtained from LCA, should be assigned to the exergy streams of the analysed system. They called this approach exergoenvironmental analysis. Finally, two other approaches can be mentioned: the Cumulative Exergy Consumption index proposed by Szargut [21], which pertain to the sum of the exergy values of natural resources consumed in all the different steps of a production process, and the Extended Exergy Accounting proposed by Sciubba [29], where aspects such as labour and the environmental impact are also converted into exergy values.

6. Case Study

The savings and potential indexes discussed in the previous sections are presented hereafter applied to a case study. The case study refers to the district heating system with CHP plants studied in [23], where a district heating system was introduced in Northern Italy to substitute the existing heating systems. The environmental aspects were also investigated in [23] through a dispersion model. In the present analysis, in addition to energy and environmental aspects, exergy and economic aspects will also be considered. The main characteristics of the case study concern:

SHP: the thermal loads of the existing buildings are covered by local boilers. The local heating system data have been obtained from the governmental environmental office, which does a periodic check on the heating plant. The main fuels used in the local boilers were oil and natural gas. The yearly thermal energy requirement is 36.4 GWh and the peak load is 21.7 MW. Data from the Italian plant stock has been adopted for central power plant.

CHP SYSTEM: in the district heating generation plant there are both auxiliary boilers and CHP units. In order to take into account the heat losses in the network, the thermal energy requirements have been increased by 5.6%. The fuel is natural gas and the adopted CHP technology is internal combustion engines. The CHP units have a total power generation of 3.6 MW and a heat generation of 3.8 MW. Additional information on the case study can be found in [23]: the daily heating load curves, the monthly distribution of the heating load, the boiler part load efficiencies, *etc.*

As far as the economic aspects are concerned, the following assumptions have been done: the adopted discount rate is 5%; the CHP capital costs and maintenance costs have been obtained from [16] and the data have been updated from consumer price indices. The fuel costs have been calculated considering the Italian market and tax advantages for district heating have been taken into account. The main considered revenues are: sale of the surplus CHP power and an incentive due to the energy efficiency certificates, which are known as “white certificates” [30].

The results of the analysis of the main indexes proposed in the present paper are shown in Figure 3. The blue bars indicate the yearly primary energy. The energy saving for the proposed CHP-System is 10%, while for the CHP-units is 40%. A high potential value, 30%, can therefore be observed. This high value is due to the district heating load coverage; the auxiliary boilers are in fact adopted both in the mid-season and in off peak hours. When the input exergies are compared (yellow bars), the exergy saving is 6% for the CHP-System and 37% for the CHP-units. The potential index is 31% and this value is close to that of the primary energy saving.

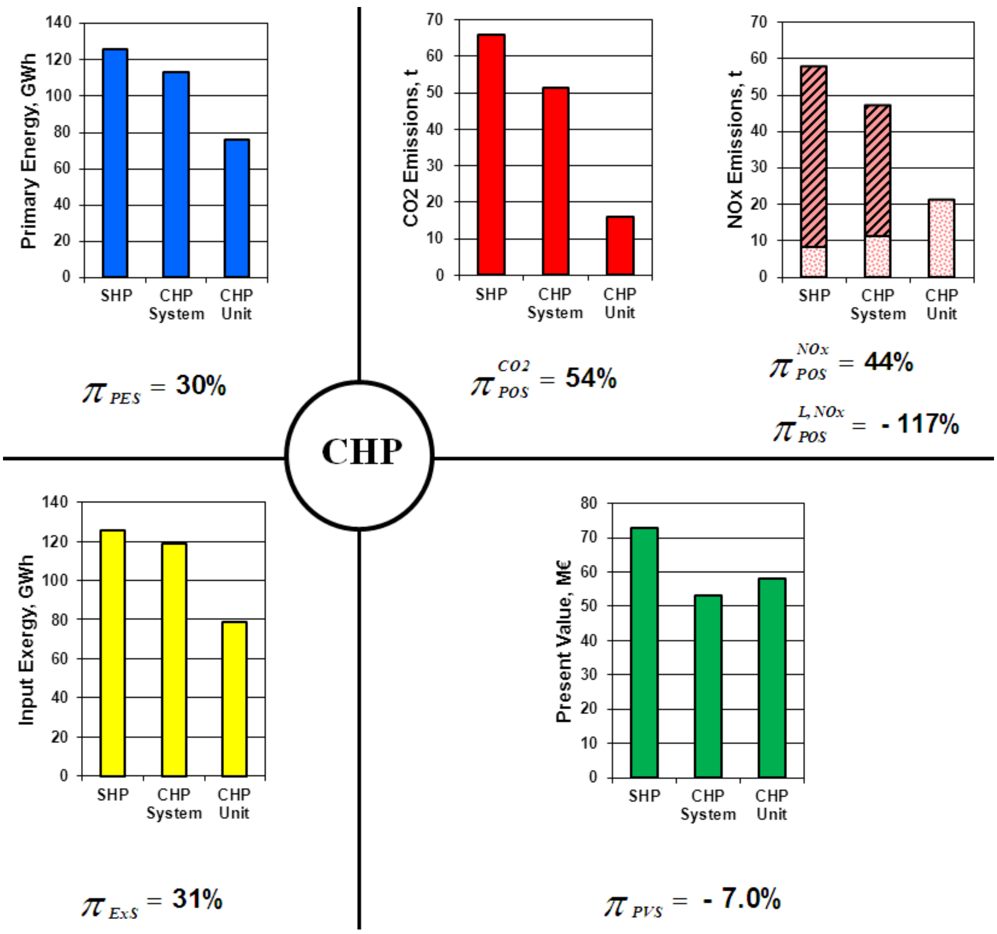
Two environmental evaluations (red bars) have been conducted: one for CO_2 and another for NO_x. The CO_2 savings is 22% for the CHP-System and 76% for CHP-unit. These values are much higher than the primary energy saving because the emission factors of the SHP system are high and the potential index, 54%, is therefore high. As far as the NO_x emissions are concerned, the emissions at a local scale (dotted bars) are distinct from the emissions from the central power plant (hatched bars), as can be seen in the Figure 3. In the global scale balance, the NO_x saving is 19% for the CHP-System and 63% for the CHP-unit. Therefore, a positive potential index of 44% can be observed. The local scale balance instead gives more critical results: the CHP-System shows a negative NO_x saving (−33%), which means the local emissions are increased. This deterioration could further increase to −150% if cogeneration increases. The potential index is therefore negative, −117%, which means that an increase in cogeneration units leads to a deterioration of this environmental aspect.

Finally, the economic saving indexes are discussed. The increase in cogeneration leads to an increase in the capital cost, the fuel purchase and the O&M cost. On the other hand, the revenues also increase, in particular the power sales and the energy efficiency certificates. The green bars in Figure 3 show the present values of all the costs and revenues [Equation (40)]. The CHP-system leads to present value saving of 27%, while the CHP-units give a lower saving of 20%, and a negative potential index of −7% is found from these values. Therefore, an increase in cogeneration could have negative economic implications.

A “snapshot” of the proposed CHP solution can be obtained by looking at all the potential indexes together. From the energy and exergy point of view, there are still significant margins to increase the CHP. The environmental aspect is favourable at the global scale and unfavourable at the local scale. The economic index suggests that caution should be taken when CHP is increased.

The analysis of this snapshot could be useful both to policy-makers and investors, who will both, however, view it from different points of view. National and local governments could benefit from having more comprehensive information. At a national level, indices like the *PES* or POS^{CO2} are usually privileged but for a local government the goal is generally on improving the quality of the conditions of the people who are governed; for example in the case study, Figure 3, there is a deterioration of the NO_x emissions due to the local presence of the CHP. Therefore, the local policy-makers could also constrain the incentives to achieve environmental improvements at a local scale, and the economic indexes could help them to calibrate the incentives. Moreover, these evaluations can be extended to other significant pollutants such as PM, CO, *etc*. However, the investors point of view is primarily focused on economic evaluation, but in a context where new constrains or incentives can be introduced by legislator at a later stage of investment, they should also take into account the energy and environment impact, in order to not penalize these aspects in the design phase. Therefore, they should simultaneously consider all the indexes as a function of different parameters: CHP technologies, fuels used, possible use of pollutant abatement systems, storage systems, *etc*. These analyses could be further extended by introducing a multi-objective optimization technique.

Figure 3. Case study results. Blue bars: primary energies; yellow bars: exergies; red bars: emissions (dotted bars refer to local scale); green bars: present values.



7. Conclusions

Energy-exergy, environmental and economic criteria, which are useful to evaluate cogeneration plants, have been analysed in this paper and new potential indexes have been proposed. Most of the indexes available in literature and legislation refer to energy aspects, and efficiencies and savings have been adopted in particular. Exergy criteria are not included in CHP regulations, even though the operative difference between work and heat has been taken into account in some legislations: efficiencies have been modified assigning different weight factors. As far as environmental aspects are concerned, only air emissions are usually analysed. However, specific indexes that take into account the local balance would be useful for some pollutants. Economic aspects are important to both evaluate an individual CHP investment and to compare different alternatives; the *net present value* and the *discounted payback period* are the two indexes that are most frequently used to compare SHP and CHP. In general, it can be observed that:

- it is possible to define saving indexes (both absolute and relative) for each aspect;
- in most cases, the indexes are also functions of the SHP, therefore, in order to establish the CHP improvements, knowledge of SHP data, that is, power plant efficiency, fuel-mix, heating boiler efficiencies, emission factors, *etc.*, is fundamental;
- high efficiency of the CHP-unit is a necessary, but not sufficient, condition to achieve a real improvement. Therefore, five potential indexes have been introduced to compare the theoretical savings of a CHP-unit with the actual savings of a CHP-system, and are summarised in Table 3;
- further analysis could be conducted extending these indexes to trigeneration systems and/or including other aspects (e.g., social costs).

Table 3. Summary of the main equations used to analyse the CHP-system.

Aspect	CHP-system saving	Potential index
Energy	$(PES_R)_{SYS} = 1 - \frac{F_{SYS}}{F_{SHP}}$	$\pi_{PES} = PES_R - (PES_R)_{SYS}$
Exergy	$(ExS_R)_{SYS} = 1 - \frac{Ex^F_{SYS}}{Ex^F_{SHP}}$	$\pi_{ExS} = ExS_R - (ExS_R)_{SYS}$
Environmental global scale	$(POS^j_R)_{SYS} = 1 - \frac{m^j_{SYS}}{m^j_{SHP}}$	$\pi^j_{POS} = POS^j_R - (POS^j_R)_{SYS}$
Environmental local scale	$(POS^{L,j}_R)_{SYS} = 1 - \frac{m^{L,j}_{SYS}}{m^j_{th,SHP}}$	$\pi^{L,j}_{POS} = POS^{L,j}_R - (POS^{L,j}_R)_{SYS}$
Economic	$(PVS_R)_{SYS} = 1 - \frac{PV_{SYS}}{PV_{SHP}}$	$\pi_{PVS} = PVS_R - (PVS_R)_{SYS}$

As far as the case study analysed in this paper is concerned, different trends were observed: energy, exergy and CO_2 show both a positive relative saving and a positive potential saving; the local scale NO_x emission indicate a negative saving and a negative potential index; the present value saving is positive, but the potential index is negative. These different trends can be useful both to characterize a particular CHP-system, but also to compare different solutions: size of the CHP unit, the number of the units, the CHP technologies, *etc*. From the policy-makers' point of view, all the information from the indexes can be used to better calibrate the CHP incentives, which should take into account energy, environmental and economic aspects.

References

1. Feng, X.; Cai, Y.; Qian, L. A new performance criterion for cogeneration system. *Energy Convers. Manag.* **1998**, *39*, 1607–1609.
2. Nussbaumer, T.; Neuenschwander, P. A new method for an economic assessment of heat and power plants using dimensionless numbers. *Biomass Bioenergy* **2000**, *18*, 181–188.
3. Bhatt, M.S. Mapping of general combined heat and power systems. *Energy Convers. Manag.* **2001**, *42*, 115–124.
4. Pilavachi, P.A.; Roumpeas, C.P.; Minett, S.; Afgan, N.H. Multi-criteria evaluation for CHP system options. *Energy Convers. Manag.* **2006**, *47*, 3519–3529.
5. Nesheim, S.J.; Ertesvag, I.S. Efficiencies and indicators defined to promote combined heat and power. *Energy Convers. Manag.* **2007**, *48*, 1004–1015.
6. Ertesvag, I.S. Exergetic comparison of efficiency indicators for combined heat and power (CHP). *Energy* **2007**, *32*, 2038–2050.
7. Mancarella, P.; Chicco, G. Distributed Cogeneration:Modelling of Environmental Benefits and Impact. In *The Distributed Generation*; Gaonkar, D.N., Ed., In-Teh: Vukovar, Croatia, 2010.
8. Chicco, G.; Mancarella, P. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators. *Energy* **2008**, *33*, 410–417.
9. Kanoglu, M.; Dincer, I. Performance assessment of cogeneration plants. *Energy Convers. Manag.* **2009**; *50*, 76–81.
10. Ruan, Y.; Liu, Q.; Zhou, W.; Firestone, R.; Gao, W.; Watanabe, T. Optimal option of distributed generation technologies for various commercial buildings. *Appl. Energy* **2009**, *86*, 1641–1653.
11. Sanaye, S.; Ardali, M.R. Estimating the power and number of microturbines in small-scale combined heat and power systems. *Appl. Energy* **2009**, *86*, 895–903.
12. Kavvadias, K.C.; Tosios, A.P.; Maroulis, Z.B. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. *Energy Convers. Manag.* **2010**, *51*, 833–845.
13. Wheeley, C.A.; Mago, P.J.; Luck, R. A Comparative Study of the Economic Feasibility of Employing CHP Systems in Different Industrial Manufacturing Application. *Energy Power Eng.* **2011**, *3*, 630–640.
14. Compernolle, T.; Witters, N.; van Passel, S.; Thewys, T. Analyzing a self-managed CHP system for greenhouse cultivation as a profitable way to reduce CO_2-emissions. *Energy* **2011**, *36*, 1940–1947.
15. Maes, D.; van Passel, S. Interference of regional support policies on the economic and environmental performance of a hybrid cogeneration-solar panel energy system. *Energy Policy* **2012**, *42*, 670–680.
16. *Catalog of CHP Technology*; U.S. Environmental Protection Agency: Washington, DC, USA, 2008.
17. Combined Heat and Power Systems. In *HVAC System and equipment Handbook*, 2012 ed.; ASHRAE Press: Atlanta, GA, USA, 2012; Chapter 7.

18. *Energy Statistics Manual*, 2005 ed.; International Energy Agency: Paris France, 2005.
19. *Directive 2004/8/EC Promotion of Cogeneration Based on a Useful Heat Demand in the Internal Energy Market and Amending Directive 92/42/EEC*; European Parliament and Council: Brussel, Belgium, 2004
20. Kotas, T.J. *The Exergy Method of Thermal Plant Analysis*; Butterworths: London, UK, 1985.
21. Szargut, J.; Morris, D.R.; Steward, F.R. *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*; Hemisphere: New York, NY, USA, 1988.
22. Bejan, A.; Tsatsaronis, G.; Moran, M. *Thermal Design and Optimization*; Wiley: New York, NY, USA, 1996.
23. Torchio, M.F.; Genon, G.; Poggio, A.; Poggio, M. Merging of energy and environmental analyses for district heating systems. *Energy* **2009**, *34*, 220–227.
24. Horlock, J.H. *Cogeneration—Combined Heat and Power (CHP): Thermodynamics and Economics*; Krieger Publishing Company: Malabar, Florida, USA, 1997.
25. Owning and Operating Costs. In *HVAC Applications Handbook*, 2011 ed.; ASHRAE Press: Atlanta, GA, USA, 2011; Chapter 37.
26. Lozano, M.A.; Valero, A. Theory of the exergetic cost. *Energy* **1993**, *18*, 939–960.
27. El-Sayed, Y.M. *The Thermoeconomics of Energy Conversions*; Elsevier: New York, NY, USA, 2003.
28. Meyer, L.; Tsatsaronis, G.; Buchgeister, J.; Schebek, L. Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. *Energy* **2009**, *34*, 75–89.
29. Sciubba, E. Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. *Exergy Int. J.* **2001**, *1*, 68–84.
30. *Ministerial Decree 4 August and 5 September 2011 on Promotion of Cogeneration* [in Italian]; Italian Ministry of Economic Development: Rome, Italy, 2011.