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WHAT FRACTION OF THE FUEL CONSUMED BY A HEAT-AND-POWER COGENERATION FACILITY SHOULD BE ALLOCATED TO THE HEAT PRODUCED? OLD PROBLEM, NOVEL APPROACH

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ABSTRACT

The question of what fraction of the fuel consumed by a cogeneration plant is to be allocated to either the heat or the electricity is still open, leading to some arbitrariness in the quantification of the economic value of the different cogenerated goods and of the subsidies often granted to such facilities. In this work, we first evidence the drawbacks of the conventional allocation methods such as Incremental Electricity-Centered Reference (IECR), Incremental Heat-Centered Reference (IHCR) and Separate-Productions Reference (SPR), in that they use fixed partial primary energy factors chosen by some authority to represent the reference efficiencies of heat and /or electricity production technologies that can be different from the local energy portfolio. Here we propose a slightly more elaborate, but self-consistent method whereby the allocation is adaptive and self-tuned to the local energy scenario by sharing the fuel savings on the basis of the average primary energy factors for electricity and heat in the given local area including the cogeneration facility of interest. We call it the Self-Tuned Average-Local-Productions Reference (STALPR) method. We finally show by means of a representative case study that the classical methods might provides unfair, distorted figures that become increasingly important as cogeneration gains higher fractions of the energy market in a given local area.

1 INTRODUCTION

Cogeneration is a sustainable, technically viable and economically convenient strategy to reduce the primary energy demand providing end users with electricity, residential heating, industrial process steam, and/or other energy-intensive products [1]. In this framework one question that remains open is what fraction of the fuel consumed by a CHP facility is to be allocated to heat resources, leading to some arbitrariness in terms of quantifying the benefits associated to the cogeneration to the produced heat and electricity. Although different approaches has been proposed so far to address the allocation problem, none of them presently is universally accepted. For example, the 2007 european standard EN 15316-4-5 [2] provides a method for comparing and rating the efficiencies of different residential heating systems, including the performance and quality of small and large cogeneration-based district heating systems. The same allocation logic used for primary energy is often used also to allocate carbon dioxide and other emissions among the different products [3-13]. In either case the question is whether the resulting allocation fractions are a “fair” representation of the shares of fuel consumption and emissions [14]. Recent regulations are shifting from allocation based on the incremental fuel consumption with respect to either the production of electricity only or of heat only, to allocation based on sharing the fuel savings on the basis of prescribed primary energy factors for electricity and heat usually corresponding to the average efficiencies of separate-production facilities. The latter allocation method is fairer than the former in that it attempts to assign a fair share of the cogeneration benefits to both cogenerated products, as opposed to just one of the two. However, it does so with respect to a prescribed reference set of separate-production efficiencies, and as a result the method results in unfair, distorted figures arising from an inconsistency which becomes increasingly important as cogeneration gains higher fractions of the energy market in a given local area.

In this paper, we propose a slightly more elaborate, but self-consistent method whereby the allocation is adaptive and self-tuned to the local energy scenario by sharing the fuel savings on the basis of the average primary energy factors for electricity and heat in the given local area including the cogeneration facility of interest. We call it the Self-Tuned Average-Local-Productions Reference (STALPR) method. The paper is organized as follows. In Section 2, we define the allocation problem, we review the available methods to define primary energy factors of cogenerated products, and we discuss their drawbacks. In Section 3, we introduce the method we propose to overcome such drawbacks for the simplest case of a local area with only one cogeneration power plant. In Section 4, we analyse the results of the new method for a specific heat and power example and compare them with the results of the traditional methods. In Section 5, we extend the formulation to define the proposed fair allocation of associated carbon dioxide emissions. In Section 6, we draw our conclusions.

2 ALLOCATION PROBLEM DEFINITION

Let us consider a single-fuel CHP facility that consumes $E_{F,chp}$ of fuel energy and delivers $E_{el,chp}$ of electrical energy and $E_{Q,chp}$ of heat through a district heating network; we assume that the CHP facility is part of a certain area - that we call the *local area of interest* - where *n* electricity plants and *m* heat plants are operating on the basis of their specific primary energy factors. We denote by $f_{el,chp}$ and $f_{Q,chp}$ the respective primary energy factors of the electrical and thermal energy of the cogeneration plant, and by $f_{el,sep,i}$ and $f_{Q,sep,i}$ the primary energy factors of electrical and thermal energy obtained by the separate production in the i-th facility. A sketch of the local area of interest and the power plants included therein is represented in Figure 1.

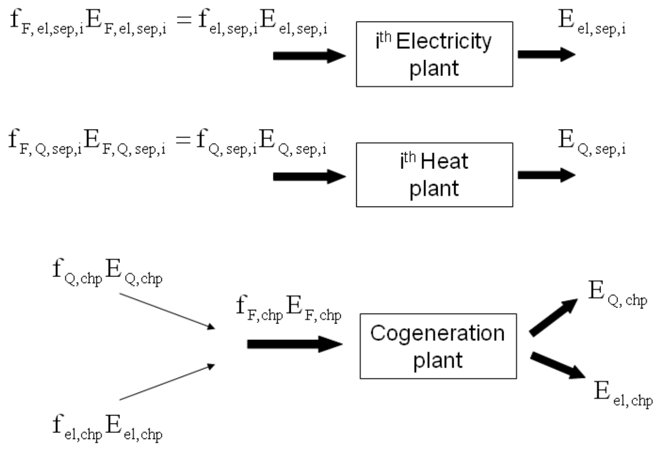

Figure 1: Schematic representation of a local area of interest.

The intent of this analysis is to select a reasonable (fair) rule to determine how the primary energy consumption $f_{F,chp}E_{F,chp}$ of the cogeneration facility should be allocated between the two cogenerated products, i.e., how to split it into the two terms $f_{el,chp}E_{el,chp}$ and $f_{Q,chp}E_{Q,chp}$. Thus, the terms $f_{el,chp}$ and $f_{Q,chp}$, represent the two unknowns of this “fair allocation” problem.

However, they are not independent of one another due to the obvious constraint that the allocation rule itself must conserve primary energy so that with reference to the cogeneration plant shown in Fig. 1 we have

$$f_{F,chp}E_{F,chp} = f_{el,chp}E_{el,chp} + f_{Q,chp}E_{Q,chp} \qquad (1)$$

or, equivalently, the condition $\alpha_{el,chp} + \alpha_{Q,chp} = 1$ where the primary-energy allocation fractions are defined as follows,

$$\alpha_{el,chp} = \frac{f_{el,chp}E_{el,chp}}{f_{F,chp}E_{F,chp}} \quad \text{and} \quad \alpha_{Q,chp} = \frac{f_{Q,chp}E_{Q,chp}}{f_{F,chp}E_{F,chp}} \qquad (2)$$

As a result, the various allocation methods may be characterized by imposing some reasonable relation between $f_{Q,chp}$ and $f_{el,chp}$, which may be expressed in the generic form

$$f\left(f_{el,chp}, f_{Q,chp}, \text{"other parameters of the local area"}\right) = 0 \quad (3)$$

In the remainder of this section we briefly review the main existing methods and comment on their inadequacies which motivate the development of the new method we propose in the rest of the paper.

2.1 Incremental Electricity-Centered Reference (IECR)

According to this method, we set Eq.(3) as

$$f_{el,chp}^{IECR} = f_{el,sep} \qquad (4)$$

so that by combining Eqs. (1) and (4) we obtain

$$f_{Q,chp}^{IECR} = \frac{f_{F,chp}E_{F,chp} - f_{el,sep}E_{el,chp}}{E_{Q,chp}} \qquad (5)$$

It is clear from Eq. (4) that the primary energy consumption attributed to the production of the cogenerated electricity, $f_{el,chp}^{IECR}E_{el,chp}$, is the primary energy that would be required to produce the same amount of electricity in a separate production facility, $f_{el,sep}E_{el,chp}$, and from Eq. (5) that the primary energy consumption attributed to the production of the cogenerated heat, $f_{Q,chp}^{IECR}E_{Q,chp}$, is the difference between the total primary energy consumption of the facility, $f_{F,chp}E_{F,chp}$, and the primary energy consumed for the separate production of electrical energy, $f_{el,sep}E_{el,chp}$. This electricity-centered method has sometimes been used in the early stages of district heating developments, but it is obsolete and unfair because that it assigns the entire cogeneration savings benefit to the production of heat thus making it appear that the cogenerated heat production has a very little primary energy factor. Let us consider a typical situation of public utilities of a city according to Example A.1 of Annex A of EN 15316-4-5:2007 [2]. The yearly consumption (based on lower heating value) of natural gas is 1000 GWh ($f_{F,chp}$ = 1.1 for natural gas), the net heat production is 350 GWh, the net power production is 347 GWh, and it is assumed that $f_{el,sep}$=2.8. Thus, using Eq. (5) according to the prescription in [2] yields $f^{IECR}_{Q,chp} = 0.37$, an unfairly low value that makes it very hard for all other heat production technologies to compete, and would discourage home owners with access to district heating to invest on energy-saving improvements.

2.2 Incremental Heat-Centered Reference (IHCR)

According to this method, we set Eq. (3) as

$$f^{IHCR}_{Q,chp} = f_{Q,sep} \tag{6}$$

so that by combining Eqs. (1) and (6) we obtain

$$f^{IHCR}_{el,chp} = \frac{f_{F,chp}E_{F,chp} - f_{el,sep}E_{el,chp}}{E_{el,chp}} \tag{7}$$

It is clear from Eq. (6) that the primary energy consumption attributed to the production of the cogenerated heat, $f^{IHCR}_{Q,chp}E_{Q,chp}$, is the primary energy that would be required to produce the same amount of heat in a separate production facility, $f_{Q,sep}E_{Q,chp}$, and from Eq. (7) that the primary energy consumption attributed to the production of the cogenerated electricity, $f^{IHCR}_{el,chp}E_{el,chp}$, is the difference between the total primary energy consumption of the facility, $f_{F,chp}E_{F,chp}$, and the primary energy consumed for the separate production of the same heat, $f_{Q,sep}E_{Q,chp}$. This heat-centered method has sometimes been used in the early stages of industrial cogeneration for waste heat, but it is obsolete and unfair because that it assigns the entire cogeneration savings benefit to the production of electricity. For the same example considered in section 2.1, Eq. (7) yields $f^{IHCR}_{el,chp} = 1.94$, again an unfairly low value.

2.3 Separate-Productions Reference (SPR)

According to this method we set Eq. (3) as

$$\frac{f^{SPR}_{Q,chp}}{f^{SPR}_{el,chp}} = \frac{f_{Q,sep}}{f_{el,sep}} \tag{8}$$

where $f_{el,sep}$ and $f_{Q,sep}$ are reference primary energy factors for the separate productions of electricity and heat, respectively. On account of Eqs. (1) and (2), Eq. (8) is equivalent to setting

$$\alpha^{SPR}_{el,chp} = \frac{f_{el,sep}E_{el,chp}}{f_{Q,sep}E_{Q,chp} + f_{el,sep}E_{el,chp}}$$
$$\alpha^{SPR}_{Q,chp} = \frac{f_{Q,sep}E_{Q,chp}}{f_{Q,sep}E_{Q,chp} + f_{el,sep}E_{el,chp}} \tag{9}$$

meaning that the primary energy consumption of cogenerated electricity and heat are both allocated based on the relative proportions of primary fuel consumption they would require in separate production facilities operating with the reference primary energy factors $f_{el,sep}$ and $f_{Q,sep}$, respectively. Combining Eqs. (2) and (9) yields the explicit expressions for the primary energy factors of the cogenerated electricity and heat, respectively,

$$f^{SPR}_{el,chp} = \frac{f_{F,chp}E_{F,chp}}{f_{Q,sep}E_{Q,chp} + f_{el,sep}E_{el,chp}} f_{el,sep}$$
$$f^{SPR}_{Q,chp} = \frac{f_{F,chp}E_{F,chp}}{f_{Q,sep}E_{Q,chp} + f_{el,sep}E_{el,chp}} f_{Q,sep} \tag{10}$$

This separate-production-centered method is the one currently preferred in most regulatory contexts.

However, as discussed in our previous paper [15], a limitation of the classical allocation criteria is that they are based on some prescribed reference efficiencies for each resource to product conversion. These reference efficiencies are to be assigned by some authority and in general differ from the actual average ratios that characterize the local energy portfolio in which the co-generation under consideration is located. Also the reference values, being fixed by some authority, are not dynamically influenced by the installation of new cogeneration facilities in a given local area, and therefore even the SPR method neglects the effects associated with the modification of the local energy portfolio. This fact may result in distortions of the local energy market, unless the authority continuously updates the reference efficiencies by keeping into constant account the progressive penetration of hybridization within the local area. The need for such a continuously updated set of references constitutes the main motivation of the development of the adaptive and self-consistent approach that we propose in the next section.

The method we propose in Section 3 resolves this problem by keeping a logic similar to the SPR method, but substituting the static and hypothetical ratio $f_{Q,sep}/f_{el,sep}$ in the rhs of Eq. (8) with the dynamic ratio $f_{Q,loc}/f_{el,loc}$ which characterizes the actual local scenario.

3 STALPR ALLOCATION METHOD FOR COGENERATION FACLITIES

In this section we present the proposed method in the particular case of the energy generation scenario shown in

Fig.1 with *n* electricity plants, *m* heat plants, and a single cogeneration facility, pursuing for comparison the same example considered in the previous section, and focusing on determining the primary energy factors of cogenerated electricity and heat. The basic rationale of the proposed method is that the allocation parameters to be used to assign primary energy factors to cogenerated electricity and heat should not be static reference values fixed by some authority and updated from time to time, but should be self-determined by the method itself as characteristic average features of the actual energy production scenario of electricity and heat delivery to the given local area of interest. For this reason we call it the Self-Tuned Average-Local-Productions Reference (STALPR) method.

First we define $f_{el,loc}$ and $f_{Q,loc}$ as the average primary energy factors of electricity and heat produced by the plants that serve the local area of interest defined by

$$f_{el,loc} = \frac{\sum_{i=1}^{n} f_{el,sep,i} E_{el,sep,i} + f_{el,chp} E_{el,chp}}{\sum_{i=1}^{n} E_{el,sep,i} + E_{el,chp}}$$

$$f_{Q,loc} = \frac{\sum_{i=1}^{m} f_{Q,sep,i} E_{Q,sep,i} + f_{Q,chp} E_{Q,chp}}{\sum_{i=1}^{m} E_{Q,sep,i} + E_{Q,chp}} \tag{11}$$

Then, we follow a logic similar to that adopted within the classical SPR method to provide a closure to the system of Eqs. (1) and (3), but instead of Eq. (3) we adopt the following closure rule to determine the primary energy allocation,

$$\frac{f_{Q,chp}}{f_{el,chp}} = \frac{f_{Q,loc}}{f_{el,loc}} \tag{12}$$

or, equivalently,

$$\alpha_{Q,chp}^{SDALPR} = \frac{f_{Q,loc} E_{Q,chp}}{f_{el,loc} E_{el,chp} + f_{Q,loc} E_{Q,chp}}$$

$$\alpha_{el,chp}^{SDALPR} = \frac{f_{el,loc} E_{el,chp}}{f_{el,loc} E_{el,chp} + f_{Q,loc} E_{Q,chp}} \tag{13}$$

meaning that the primary energy consumption of cogenerated electricity and heat are both allocated based on the relative proportions of the actual average primary energy consumption they require in the local area, which includes that of the cogeneration facility itself.

Combining Eqs. (2) and (13) yields the explicit expressions for the primary energy factors of the cogenerated electricity and heat, respectively,

$$f_{el,chp}^{SDALPR} = \frac{f_{F,chp} E_{F,chp}}{f_{Q,loc} E_{Q,chp} + f_{el,loc} E_{el,chp}} f_{el,loc}$$

$$f_{Q,chp}^{SDALPR} = \frac{f_{F,chp} E_{F,chp}}{f_{Q,loc} E_{Q,chp} + f_{el,loc} E_{el,chp}} f_{Q,loc} \tag{14}$$

It is noteworthy that the system of Eqs. (1) , (11) and (12) is nonlinear in the four unknowns $f_{el,loc}$, $f_{Q,loc}$, $f_{el,chp}$, $f_{Q,chp}$. However, we can readily obtain an analytical solution as follows.

By defining the following ratios

$$\sigma_{chp} = \frac{E_{el,chp}}{E_{Q,chp}} \tag{15}$$

$$\eta_{chp} = \frac{E_{el,chp} + E_{Q,chp}}{E_{F,chp}} \tag{16}$$

$$\Phi_{loc} = \frac{f_{Q,loc}}{f_{el,loc}} \tag{17}$$

$$\sigma_{loc} = \frac{\sum_{i=1}^{n} E_{el,sep,i} + E_{el,chp}}{\sum_{i=1}^{n} E_{Q,sep,i} + E_{Q,chp}} \tag{18}$$

the allocation fractions and the primary energy factors given by Eqs. (13) and (14) can be written as follows (we omit the superscript STALPR for simplicity of notation)

$$\alpha_{Q,chp} = \frac{\Phi_{loc}}{\sigma_{chp} + \Phi_{loc}} \quad \text{and} \quad \alpha_{el,chp} = \frac{\sigma_{chp}}{\sigma_{chp} + \Phi_{loc}} \tag{19}$$

$$f_{Q,chp} = \frac{\alpha_{Q,chp} f_{F,chp} E_{F,chp}}{E_{Q,chp}} \quad \text{and} \quad f_{el,chp} = \frac{\alpha_{el,chp} f_{F,chp} E_{F,chp}}{E_{el,chp}} \tag{20}$$

or, equivalently,

$$f_{Q,chp} = \frac{(\sigma_{chp} + 1) f_{F,chp} \Phi_{loc}}{(\sigma_{chp} + \Phi_{loc}) \eta_{chp}}$$

$$f_{el,chp} = \frac{(\sigma_{chp} + 1) f_{F,chp}}{(\sigma_{chp} + \Phi_{loc}) \eta_{chp}} \tag{21}$$

By defining the fractions of cogenerated electricity and heat delivered to the local area and the average primary energy factors of the separate productions, respectively,

$$\gamma_{Q,chp} = 1 - \gamma_{Q,sep} = \frac{E_{Q,chp}}{\sum_{i=1}^{m} E_{Q,sep,i} + E_{Q,chp}}$$

$$\gamma_{el,chp} = 1 - \gamma_{el,sep} = \frac{E_{el,chp}}{\sum_{i=1}^{n} E_{el,sep,i} + E_{el,chp}} = \frac{\sigma_{chp}\gamma_{Q,chp}}{\sigma_{loc}} \tag{22}$$

$$\bar{f}_{Q,sep} = \frac{\sum_{i=1}^{m} f_{Q,sep,i} E_{Q,sep,i}}{\sum_{i=1}^{m} E_{Q,sep,i}}$$

$$\bar{f}_{el,sep} = \frac{\sum_{i=1}^{n} f_{el,sep,i} E_{el,sep,i}}{\sum_{i=1}^{n} E_{el,sep,i}} \tag{23}$$

the average primary energy factors may be written as

$$f_{Q,loc} = (1 - \gamma_{Q,chp})\bar{f}_{Q,sep} + \gamma_{Q,chp} f_{Q,chp}$$

$$f_{el,loc} = (1 - \gamma_{el,chp})\bar{f}_{el,sep} + \gamma_{el,chp} f_{el,chp} \tag{24}$$

Taking the ratio of Eqs. (24) to compute Φ_{loc} according to Eq. (17) and using Eqs. (21) to eliminate $f_{el,chp}$, and $f_{Q,chp}$, we obtain the following relation

$$\Phi_{loc} = \frac{(1-\gamma_{Q,chp})\bar{f}_{Q,sep} + \gamma_{Q,chp}\dfrac{(\sigma_{chp}+1)\, f_{F,chp}\Phi_{loc}}{(\sigma_{chp}+\Phi_{loc})\,\eta_{chp}}}{(1-\gamma_{el,chp})\bar{f}_{el,sep} + \gamma_{el,chp}\dfrac{(\sigma_{chp}+1)\, f_{F,chp}}{(\sigma_{chp}+\Phi_{loc})\,\eta_{chp}}} \tag{25}$$

which clearly defines Φ_{loc} implicitly in terms of the parameters σ_{chp}, η_{chp}, $f_{F,chp}$ of the cogeneration plant and the local parameters $\gamma_{el,chp}$, $\gamma_{Q,chp}$, $\bar{f}_{el,sep}$, and $\bar{f}_{Q,sep}$.

With a few rearrangements and using the last of Eqs. (22), Eq. (25) can be finally cast as follows

$$\begin{aligned}
&(\sigma_{loc} - \gamma_{Q,chp}\sigma_{chp})\eta_{chp}\bar{f}_{el,sep}\Phi_{loc}^{2} \\
&+ [f_{F,chp}\gamma_{Q,chp}(\sigma_{chp} - \sigma_{loc})(\sigma_{chp}+1) \\
&+ (\sigma_{loc} - \gamma_{Q,chp}\sigma_{chp})\sigma_{chp}\eta_{chp}\bar{f}_{el,sep} \\
&- (1-\gamma_{Q,chp})\sigma_{loc}\eta_{chp}\bar{f}_{Q,sep}]\Phi_{loc} \\
&- (1-\gamma_{Q,chp})\sigma_{chp}\sigma_{loc}\eta_{chp}\bar{f}_{Q,sep} = 0
\end{aligned} \tag{26}$$

This second degree equation in Φ_{loc} can be easily solved for the only positive root it admits. Once Φ_{loc} is found, the primary energy factors $f_{el,chp}$ and $f_{Q,chp}$ can be obtained from Eqs. (21) and the values of $f_{el,loc}$ and $f_{Q,loc}$ from Eqs. (24).

A thorough analysis of the dependence of Φ_{loc} on the various parameters of the local area is reported in Ref. 15. In particular, it is important to study the dependence of Φ_{loc} on $\gamma_{Q,chp}$ because it defines how $f_{el,chp}$ and $f_{Q,chp}$ change with the penetration of cogeneration (represented in this particular case by the size of the single chp plant shown in Fig.1). In fact, according to Eqs. (21) an increase in Φ_{loc} always implies an increase in $f_{Q,chp}$ and a corresponding reduction in $f_{el,chp}$, and viceversa[1].

4 COMPARISON OF THE ALLOCATION METHODS

In this section we apply the STALPR approach and compare it to the classical method on the basis of following example. We consider that the local area shown in Figure 1 is representative of a generic mix of industrial, residential and tertiary activities so that the overall yearly thermal energy consumption is twice the consumption of electricity, thus resulting in $\sigma_{loc} = 0.5$. We assume that heat and electricity are initially produced by means of a certain number of separate production plants, considered for simplicity identical to one another and characterized by electricity and heat primary energy factors $f_{el,sep,i} = \bar{f}_{el,sep} = 2.8$ and $f_{Q,sep,i} = \bar{f}_{Q,sep} = 1.22$. Then we consider that the separately produced heat and electricity are progressively replaced by cogeneration plants. To select realistic values for the parameters of the example, we identify two distinct cases on the basis of which the following typical chp technology is implemented:

a) steam cycle with back pressure steam turbine (BPST) operating with average $\eta_{chp} = 85\%$ and $\sigma_{chp} = 0.2$;

b) combined cycle (CC) operating with average $\eta_{chp} = 78\%$ and $\sigma_{chp} = 1.2$.

In either case, each chp plant is assumed identical to the others so that the "*r*" installations can be treated as a single unit of equivalent size, therefore allowing the straightforward solution of Eq. (26) . The degree of penetration of heat cogeneration in the local area, defined by the size of the equivalent chp plant, is then measured by the value of the parameter $\gamma_{Q,chp}$. It is

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[1] The sign of the partial derivatives of Eqs.(21) $\dfrac{\partial f_{Q,chp}}{\partial \Phi_{loc}} = \dfrac{(\sigma_{chp}+1)\, f_{F,chp}\sigma_{chp}}{(\sigma_{chp}+\Phi_{loc})^{2}\eta_{chp}}$ and $\dfrac{\partial f_{el,chp}}{\partial \Phi_{loc}} = -\dfrac{(\sigma_{chp}+1)\, f_{F,chp}}{(\sigma_{chp}+\Phi_{loc})^{2}\eta_{chp}}$ is indeed always positive and negative, respectively.

noteworthy that in case of CC, where $\sigma_{chp} > \sigma_{loc}$, the condition $0 < \gamma_{Q,chp} < \min(1, \frac{\sigma_{chp}}{\sigma_{loc}})$ limits the penetration of heat cogeneration to the maximum value $\gamma_{Q,chp}^{max} = 0.417$ reached when the electricity demand of the local area is saturated. In case of BPST, where $\sigma_{chp} < \sigma_{loc}$, the limiting values is $\gamma_{Q,chp}^{max} = 1$, which refers to the situation when all the heat is produced by cogeneration. Table.1 summarizes the assumptions considered in this example. Figure 2 shows the results of the analysis in terms of primary energy factors and Φ_{loc} profiles, plotted as a function of $\gamma_{Q,chp}$. The corresponding values given by the classical methods are reported in Table 2.

Table 1: Assumptions made in the example.

Parameters of the local area		
σ_{loc}	0.5	
$f_{el,sep,i} = \bar{f}_{el,sep}$	2.8	
$f_{Q,sep,i} = \bar{f}_{Q,sep}$	1.22	
Parameter of the chp plants		
	CC	BPST
$f_{F,chp,i}$	1.1	1.1
σ_{chp}	1.2	0.2
$\eta_{chp,i}$	78%	85%
$\gamma_{Q,chp}$	≤ 1	≤ 0.417

Table 2: Values of the heat and electricity primary energy factors calculated for the present example by means of the classical allocation methods.

	IECR		IHCR		SPR	
	$f_{el,chp}$	$f_{Q,chp}$	$f_{el,chp}$	$f_{Q,chp}$	$f_{el,chp}$	$f_{Q,chp}$
CC	2.8	-0.257	1.569	1.22	1.897	0.826
BPST	2.8	0.993	1.665	1.22	2.443	1.064

It can be noted that according to the classical methods the primary energy factors do not change with $\gamma_{Q,chp}$ (Tab.2) as they refer to the fixed scenario of standard separate productions with $f_{el,sep} = 2.8$ and $f_{Q,sep} = 1.22$. On the contrary, the resulting profiles of f's and Φ_{loc} (Fig.2) provided by the STALPR method are functions of $\gamma_{Q,chp}$. In particular, in case of CC ($\sigma_{chp} > \sigma_{loc}$,) Φ_{loc} increases with $\gamma_{Q,chp}$: as already observed this implies that $f_{Q,chp}$ and $f_{el,chp}$ respectively increase and decrease with $\gamma_{Q,chp}$, meaning that as heat cogeneration further penetrates in the local area, a higher fraction of primary energy of the chp plants is allocated to the production of heat. This is consistent with the fact that the chp plants have in this case a higher proportion of electricity than that required by the local area ($\sigma_{chp} > \sigma_{loc}$) and thus the penetration of heat cogeneration goes together with an even higher penetration of electricity cogeneration, which therefore takes up a higher share of the overall cogeneration benefits. Analogous considerations can be made for the case of BPST (where $\sigma_{chp} < \sigma_{loc}$), resulting in the converse implication on $f_{Q,chp}$ and $f_{el,chp}$.

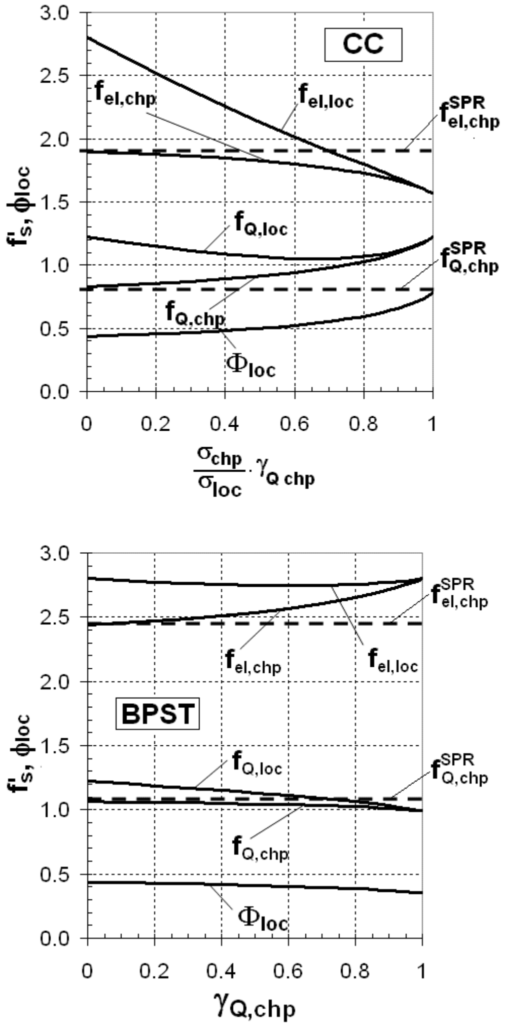

Figure 2: Φ_{loc} and primary energy factors plotted as a function of the parameter $\gamma_{Q,chp}$ for the values listed in Table 1. Top: chp facilities based on combined cycle (CC) technology. Bottom: chp facilities based on steam cycle technology with back pressure steam turbine (BPST). Dashed lines in both figures refer to the primary energy factors calculated with classical SPR method.

Finally, it is worth observing that with the increase of $\gamma_{Q,chp}$ the chp primary energy factors calculated with the STALPR method progressively depart, as expected, from the values obtained with the SPR method. In the cases considered in the example, the maximum difference in $f_{Q,chp}$ between the two methods is 6.7% for the BPST case and 47.6% for the CC case, while the maximum difference $f_{el,chp}$ is 14.6% for the BPST case and 17.3% for the CC case. A sensitivity analysis on the dependence of the local primary energy factors as function of a wide range variation of the parameters that characterize the local area of interest can be found in the Appendix of Ref. 15.

5 EXTENSION OF THE STALPR METHOD TO ALLOCATE CO$_2$ EMISSIONS

Allocation of carbon dioxide emissions can be done by using the same STALPR logic used to allocate primary energy consumption. We present the method for a local-area scenario with multiple energy-intensive products. With the amount $E^{\text{facility k}}_{\text{product j}}$ of product of j-th type delivered by the k-th production facility serving the area of interest, we associate not only the specific primary energy factor $f^{\text{facility k}}_{\text{product j}}$ but also the specific CO$_2$ emission factor $g^{\text{facility k}}_{\text{product j}}$.

Let $G^{\text{facility k}}_{\text{primary}}$ denote the overall CO$_2$ emission of the k-th facility, given by

$$G^{\text{facility k}}_{\text{primary}} = \sum\nolimits_i g^{\text{facility k}}_{\text{resource i}} E^{\text{facility k}}_{\text{resource i}} \tag{27}$$

For example, if resource k is iron ore and we express $E^{\text{facility k}}_{\text{resource i}}$ in ton of iron ore, then $g^{\text{facility k}}_{\text{resource i}}$ is in Gton of CO$_2$ equivalent emission per ton of ore. Again, if resource k is waste heat recuperated from an industrial process and we choose to express $E^{\text{facility k}}_{\text{resource i}}$ as the exergy of the waste heat, then $g^{\text{facility k}}_{\text{resource i}}$ is in Gton of CO$_2$ equivalent emission per GWh of recovered-waste-heat exergy.

Next we define the ratio of the amount of product j in facility k to the overall CO$_2$ emission by facility k

$$\psi^{\text{facility k}}_{\text{product j}} = \frac{E^{\text{facility k}}_{\text{product j}}}{G^{\text{facility k}}_{\text{primary}}} \tag{28}$$

Finally, we denote by $g^{\text{loc.ave.}}_{\text{product j}}$ the average CO$_2$ emission factor for product j. In our STALPR method, allocation fractions are based on these average factors, therefore, the equivalent of Eqs. (19) is

$$\beta^{\text{facility k}}_{\text{product j}} = \frac{g^{\text{loc.ave.}}_{\text{product j}} E^{\text{facility k}}_{\text{product j}}}{\sum\nolimits_m g^{\text{loc.ave.}}_{\text{product m}} E^{\text{facility k}}_{\text{product m}}} = \frac{g^{\text{loc.ave.}}_{\text{product i}} \psi^{\text{facility k}}_{\text{product j}}}{\sum\nolimits_m g^{\text{loc.ave.}}_{\text{product m}} \psi^{\text{facility k}}_{\text{product m}}} \tag{29}$$

the equivalent of Eqs. (20) are

$$g^{\text{facility k}}_{\text{product j}} = \frac{\beta^{\text{facility k}}_{\text{product j}} G^{\text{facility k}}_{\text{primary}}}{E^{\text{facility k}}_{\text{product j}}} = \frac{\beta^{\text{facility k}}_{\text{product j}}}{\psi^{\text{facility k}}_{\text{product j}}} = \frac{g^{\text{loc.ave.}}_{\text{product j}}}{\sum\nolimits_m g^{\text{loc.ave.}}_{\text{product m}} \psi^{\text{facility k}}_{\text{product m}}} \tag{30}$$

and the average primary energy factors of the local area, i.e., the equivalent of Eqs. (11) are given by

$$g^{\text{loc.ave.}}_{\text{product j}} = \frac{\sum\nolimits_k g^{\text{facility k}}_{\text{product j}} E^{\text{facility k}}_{\text{product j}}}{\sum\nolimits_n E^{\text{facility n}}_{\text{product j}}} = \sum\nolimits_k g^{\text{facility k}}_{\text{product j}} \gamma^{\text{facility k}}_{\text{product j}} \tag{31}$$

where we have introduced the local market share of facility k with respect to the production of j

$$\gamma^{\text{facility k}}_{\text{product j}} = \frac{E^{\text{facility k}}_{\text{product j}}}{\sum\nolimits_n E^{\text{facility n}}_{\text{product j}}} \tag{32}$$

Finally, substituting Eq. (30) into (31), we obtain the system of equations

$$1 = \sum\nolimits_k \frac{\gamma^{\text{facility k}}_{\text{product j}}}{\sum\nolimits_m g^{\text{loc.ave.}}_{\text{product m}} \psi^{\text{facility k}}_{\text{product m}}} \tag{33}$$

which for given values of the $\psi^{\text{facility k}}_{\text{product j}}$ and the $\gamma^{\text{facility k}}_{\text{product j}}$ determines the values of the $g^{\text{loc.ave.}}_{\text{product m}}$'s which in turn can be used in the previous equations to find all other factors and fractions.

It is clear that the example considered in Section 4 can be readily recast also in terms of the allocation of emissions, by assuming a properly identified value of $g_{F,chp,i}$ for methane.

In practice, again, we conclude and suggest that a self-consistent cogeneration regulation for CO$_2$ emissions can based on the proposed STALPR fair-allocation method by simply adopting Eqs. (27), (28), (32), and (33).

6 CONCLUSIONS

Cogeneration technologies, i.e., the combined productions in a single facilities of a mix of two or more different energy-intensive goods, are capturing higher and higher fractions of the energy market because they entail important savings in primary energy and avoided emissions. In this framework, one key problem is to define a 'fair' method to determine the amount of fuel consumption in the cogenerator that should be assigned to the production of heat and the amount that should be attributed to the production of electricity. Cogeneration regulations are in fact being developed in order to allocate the benefits associated to cogeneration in a fair way between the different cogenerated goods.

In this paper we focus on such allocation problem, motivated by the need to overcome the limitations of the classical allocation methods which require some prescribed reference primary energy conversion efficiencies defined by some authority. To resolve the issue, we propose a natural extension of the SPR method so as to take in due and fair account the local scenario in which a given cogeneration facility operates. The result, that we call the Self-Determined Average-Local-Productions Reference (STALPR) method, is self-consistent in that the allocation parameters are self-determined in terms of the energy scenario of the given local area of interest.

We illustrate the results of our analysis for a realistic case study, where we consider that either cogeneration steam cycle with back-pressure steam turbine (BPST) or a cogeneration combined cycle (CC) progressively replace the heat and the electricity demand in a local area characterized by the presence of only heat and electricity single-production facilities. We show that the differences between STALPR and SPR allocations are important in local areas with relatively high levels of cogeneration.

Finally, we observe that the same allocation logic used for primary energy can be readily used to allocate carbon dioxide and other emissions among the different products. Therefore we provide the mathematical framework to extend the formulation of STALPR approach to the case of fair allocation of carbon dioxide emissions.

NOMENCLATURE

E	energy
f	primary energy factor
g	specific CO_2 emission factor
G	overall CO_2 emission

SUBSCRIPTS

chp	combined heat and power
el	electricity
loc	local area
F	fuel
Q	heat
sep	separate production

GREEK SYMBOLS

α	primary energy allocation fraction
$\gamma_{i,j}$	fraction of the product i (heat or electricity) delivered by plant j (chp or separate production)
η_{chp}	overall efficiency of the chp plant
σ_{chp}	electric index of the chp plant
σ_{loc}	electricity to heat ratio in the local area of interest
Φ_{loc}	ratio of the electricity and heat primary energy factors in the local area (Eq.17)

ACRONYMS

BPST	Back pressure steam turbine
CC	Combined cycle
IECR	Incremental Electricity-Centered Reference
IHCR	Incremental Heat-Centered Reference
SPR	Separate -Productions Reference
STALPR	Self-Tuned Average-Local-Productions Reference

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