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WHAT FRACTION OF THE ELECTRICAL ENERGY PRODUCED IN A HYBRID SOLAR-FOSSIL POWER PLANT SHOULD QUALIFY AS 'RENEWABLE ELECTRICITY'?

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ABSTRACT

Hybrid power production facilities, based on the integration of renewable resources into conventional fossil-fuel-fired power plants have gained a growing interest during the past decades due to a world-wide continuous increase of shares of the renewable sources into the electricity generation market. In fact, in spite of the variable nature of most of the renewable sources, the hybrid configuration may provide a more economic, sustainable, and reliable use of the renewables in all load-demand conditions compared to renewable single-resource facilities. Nonetheless, the question of what fraction of the electricity produced in such facilities is to be considered as generated from renewables, still remains not fully addressed. This implies that there is space for some arbitrariness in the quantification of the share of the produced electricity to be qualified for the subsidies granted to renewable electricity, as normally prescribed by most of the policies that promote the applications of renewable primary energy resources. To overcome this problem, in this work we first define the classical Single-Resource Separate-Production Reference allocation method (SRSPR) usually considered by the regulators which is based on reference partial primary energy factors that must be chosen by some authority as representative of the performance of the (best available or representative average single-resource) power production technologies that use the same renewable resource and the same fossil fuel as the hybrid facility. Then we propose a Self-Tuned Average-Local-Productions Reference allocation method (STLAPR) whereby the electricity allocation fractions are based on the energy scenario of the local area of interest that includes the hybrid plant itself. We compare the two methods for a case study consisting on the renewable-to-fossil allocation of the power produced in an Solar-Integrated Combined-Cycle System (SICCS) with parabolic trough solar field. It turns out that the differences between the classical SRSPR and the STLAPR method become significant as the hybrid facilities take on a sizable fraction of the production of electricity in the local area.

1 INTRODUCTION

In several industrial and manufacturing sectors, higher production efficiencies are achieved by integrating the production of a mix of different goods and/or using a mix of different resources and/or raw materials. Such facilities are therefore either multi-resource or multi-generation, or both. In Ref. 1 we focused on a single-resource multi-generation facility (such as a gas-fired heat-and-power cogenerator) and addressed the problem of defining a 'fair' method to allocate the consumption of the single resource in the facility among the different cogenerated products (how much of the gas consumption in the cogenerator should be assigned to the production of heat and how much to the production of electric power), in other words, how to determine the primary energy factors of heat and electricity produced in a cogeneration facility. In this paper, we focus on single-product multi-resource facilities, and address the problem of defining a 'fair' method to allocate the product of the facility among the different resources it consumes. An example of particular interest in the energy sector, which motivates the present work and is taken here as our case study, is that of the so-called 'hybrid' power production facilities, which combine and integrate the consumption of renewable energy resources (like wind, solar, hydro, etc.) into fossil-fuel-fired traditional energy systems such as steam cycles, gas-turbine cycles, or combined cycles. Such hybrid energy systems are at the center of active

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development because they may provide a more economic, sustainable, and reliable use of renewable and fossil resources in all load-demand conditions compared to renewable-resource-only facilities. Public awareness of the need to reduce global warming and the significant increase in the prices of conventional energy resources have encouraged many countries to provide new energy policies that promote renewable energy applications and hybrid power plants [2]. Since such policies usually provide subsidies to the production of electricity from renewable resources, the important question arises of how in a hybrid facility one should compute what fraction of the produced electricity is to be considered as produced from renewables and hence qualifies for the subsidies. In other words, we need a 'fair' method to allocate the electricity produced by the facility among its consumptions of renewable energy and fossil fuel. In the present analysis we specifically focus on the electricity allocation in hybrid fossil+solar facilities, as they represent a favourable solution in terms of a reliable use of solar energy, capable to mitigate the drawbacks of its intrinsic high degree of daily and seasonal variability. In the hybrid configuration, the solar energy supply is in fact backed up efficiently by fossil primary energy to compensate short-time deficits of solar input. Different hybrid fossil+solar configurations are possible and have been the object of several studies in recent years, dealing with technological integration issues as well as with the metrics necessary to evaluate the hybrid plant from both the thermodynamic and economic point of view [3]. Three main schemes are currently considered for the hybridization: the solarized gas turbines [4,5] the hybrid combined cycles [6,7] and the solar reforming systems [8]. For the purposes of testing and comparing allocation methods in the present paper, we adopt as our case study the technology of Solar-Integrated Combined-Cycle System (SICCS) with parabolic trough solar field. Presently, this represents one a mature hybridization solution for large-scale application [9] as confirmed by the recent realization of a few pilot plants [10,11]. The allocation problem we consider here is 'dual' to the one we consider in Ref. 1, and our presentation will emphasize where possible the analogies. In Section 2 we formally define the allocation problem and discuss the 'classical' methods usually adopted or under consideration by the regulators, including the Exergy method and the Single-Resource Separate-Production Reference allocation method (SRSPR) which requires that some local authority fixes a set of reference efficiencies and periodically updates them. In Section 3 we introduce and propose an adaptive marginal allocation method (that we call STALPR) which is slightly more elaborate but requires no prescribed reference efficiencies, rather, it is self tuned and context-dependent by replacing the reference efficiencies with the actual average efficiencies of the power plant scenarion in the local area, including the hybrid facility itself. In Section 4 we present and compare the results of the SRSPR and the STALPR methods for our case study.

2 ALLOCATION PROBLEM DEFINITION FOR A HYBRID POWER PLANT

We consider the allocation of a single final product among the different input resources of the hybrid power plant sketched in Figure 1. On a yearly basis it consumes a quantity of renewable primary energy and of fossil primary energy, and delivers of electrical energy. This can be the case of a hybrid natural-gas or coal power plant integrated with a biomass or solar energy input.

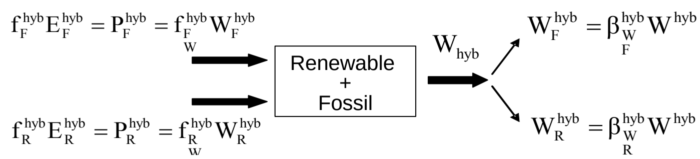

Figure 1: Allocation problem definition for a hybrid power plant.

Since the incentive policies usually provide subsidies to the electricity produced by renewable sources only, a fair criterion is necessary to identify the renewable share of the produced electricity, i.e., how to split the overall produced electrical energy into two terms and representing the renewable and fossil shares. For this purpose we define the electricity allocation fractions β's representing the two unknowns of the resource allocation problem

$$\beta_{W_R}^{hyb} = \frac{W_R^{hyb}}{W_{hyb}} \quad \text{and} \quad \beta_{W_F}^{hyb} = \frac{W_F^{hyb}}{W_{hyb}} \tag{1}$$

where of course

$$\beta_{W_R}^{hyb} + \beta_{W_F}^{hyb} = 1 \tag{2}$$

The electricity allocation fraction $\beta_{W_R}^{hyb}$ represents the fraction of the overall electricity production that is to be considered as obtained from the renewable resource(s) used by the hybrid facility.

Then, for the hybrid facility we define the primary energy factors[1] of the resources it uses

$$f_R^{hyb} = \frac{P_R^{hyb}}{E_R^{hyb}} \quad \text{and} \quad f_F^{hyb} = \frac{P_F^{hyb}}{E_F^{hyb}} \tag{3}$$

where E_F^{hyb} and E_R^{hyb} are the fuel energy (based on lower heating value) of the fossil and renewable resources,

[1] We recall that the "primary energy factor" of a given good is defined as the amount of primary energy that is consumed to produce a unit amount of that good, taking into consideration all processes in its life cycle. In case of a power plant it equals the inverse the conversion efficiency calculated on the basis of the overall primary energy consumption, i.e., not just the direct consumption in the facility itself but also in all processes in its life cycle (for example, for natural gas Ref. 12 suggests to consider the actual consumption incremented by 10% to account for the rest of the extraction and pipelining life cycle).

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respectively, and the partial primary energy factors $f^{hyb}_{\substack{R\\W}}$ and $f^{hyb}_{\substack{F\\W}}$ of the portions of the overall electricity produced which we allocate to either the renewable or the fossil resource

$$f^{hyb}_{\substack{R\\W}} = \frac{P_R^{hyb}}{W_R^{hyb}} \quad \text{and} \quad f^{hyb}_{\substack{F\\W}} = \frac{P_F^{hyb}}{W_F^{hyb}} \tag{4}$$

The above system of equations can be solved for the four unknowns $\beta^{hyb}_{\substack{W\\R}}$, $\beta^{hyb}_{\substack{W\\F}}$, $f^{hyb}_{\substack{R\\W}}$ and $f^{hyb}_{\substack{F\\W}}$ in terms of given values for W_{hyb}, P_R^{hyb}, P_F^{hyb}, f_R^{hyb}, f_F^{hyb} provided we provide an additional reasonable relation between $f^{hyb}_{\substack{R\\W}}$ and $f^{hyb}_{\substack{F\\W}}$. Such relation provides the closure of the problem and characterizes the allocation method.

To be more explicit, it is convenient to recast the above equations in terms of the following new variables

$$\chi_{res}^{hyb} = \frac{f_F^{hyb}}{f_R^{hyb}} \tag{5}$$

$$\sigma_{hyb} = \frac{P_F^{hyb}}{P_R^{hyb}} \tag{6}$$

$$\eta_{hyb} = \frac{W_{hyb}}{E_F^{hyb} + E_R^{hyb}} \tag{7}$$

$$\chi_W^{hyb} = \frac{f^{hyb}_{\substack{F\\W}}}{f^{hyb}_{\substack{R\\W}}} \tag{8}$$

It is noteworthy that the parameter η_{hyb} is the energy conversion efficiency of the hybrid plant. As a result, the average primary energy factor of the mix of resources used by the hybrid plant can be written as follows

$$f_{hyb} = \frac{P_F^{hyb} + P_R^{hyb}}{E_F^{hyb} + E_R^{hyb}} = \frac{f_F^{hyb}E_F^{hyb} + f_R^{hyb}E_R^{hyb}}{E_F^{hyb} + E_R^{hyb}} = \frac{(\sigma_{hyb}+1)\, f_F^{hyb}}{\sigma_{hyb} + \chi_{res}^{hyb}} \tag{9}$$

Moreover, a few substitutions and rearrangements allow us to write the relations between the allocation fractions and the partial primary energy factors in terms of the other parameters of the hybrid facility as follows

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\chi_W^{hyb}}{\sigma_{hyb} + \chi_W^{hyb}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\sigma_{hyb}}{\sigma_{hyb} + \chi_W^{hyb}} \tag{10}$$

$$f^{hyb}_{\substack{R\\W}} = \frac{\left(\sigma_{hyb} + \chi_W^{hyb}\right) f_{hyb}}{\left(\sigma_{hyb}+1\right)\chi_W^{hyb}\eta_{hyb}} \quad \text{and} \quad f^{hyb}_{\substack{F\\W}} = \frac{\left(\sigma_{hyb} + \chi_W^{hyb}\right) f_{hyb}}{\left(\sigma_{hyb}+1\right)\eta_{hyb}} \tag{11}$$

There expressions show that the allocation problem is fully closed once a criterion is given to determine the value of χ_W^{hyb}. Such criterion characterizes the allocation method.

In the remainder of this section we briefly review the main classical allocation methods and show how they apply to the present allocation problem. In Section 3 we introduce the STALPR method we propose.

2.1 Fossil centered allocation method

According to this allocation method, $f^{hyb}_{\substack{F\\W}}$ is fixed to a reference value $f^{ref}_{\substack{F\\W}}$ (normally assigned by some authority for each type of fuel) representative of the inverse of the efficiency with which the same primary fossil-fuel resource is used for power production in a reference technology, for instance the best available technology or a representative average of non-hybrid (i.e., single-resource) technologies based on the same fossil fuel that is used in the hybrid plant under consideration. In other words, this allocation method assumes the closure relation

$$f^{hyb}_{\substack{F\\W}} = f^{ref}_{\substack{F\\W}} \tag{12}$$

From the solution of Eqs. (2) to (4) we obtain

$$\beta^{hyb}_{\substack{W\\F}} = \frac{\dfrac{P_R^{hyb}}{f^{ref}_{\substack{F\\W}}}}{W_{hyb}} = \frac{\sigma_{hyb} f_{hyb}}{\left(\sigma_{hyb}+1\right)\eta_{hyb} f^{ref}_{\substack{F\\W}}} \tag{13}$$

$$\beta^{hyb}_{\substack{W\\R}} = 1 - \beta^{hyb}_{\substack{W\\F}} \tag{14}$$

meaning that the production of electrical energy allocated to the fossil fuel is the amount that would be produced with the reference technology by consuming the same amount of fuel primary energy P_F^{hyb} consumed by the hybrid facility. The remaining portion of electricity is attributed to the renewable resource. From Eqs. (2) to (4) we also obtain the following expressions for χ_W^{hyb} and $f^{ref}_{\substack{R\\W}}$ which are implied by the closure condition (12)

$$\chi_W^{hyb} = \frac{\left(\sigma_{hyb}+1\right)\eta_{hyb} f^{ref}_{\substack{F\\W}}}{f_{hyb}} - \sigma_{hyb} \tag{15}$$

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$$f^{ref}_{\substack{R\\W}} = \frac{f^{ref}_{\substack{F\\W}}}{\chi^{hyb}_{W}} \tag{16}$$

2.2 Single-Resource Separate-Production Reference allocation method (SRSPR)

This allocation method assumes the following closure condition

$$\chi^{hyb}_{W} = \chi^{ref}_{W} \quad \text{with} \quad \chi^{ref}_{W} = \frac{f^{ref}_{\substack{F\\W}}}{f^{ref}_{\substack{R\\W}}} \tag{17}$$

where $f^{ref}_{\substack{R\\W}}$ and $f^{ref}_{\substack{F\\W}}$ are reference partial primary energy factors chosen by some authority as representative of the performance of the (best available or representative average, usually single-resource) power production technologies that use, respectively, the same renewable resource and the same fossil fuel as the hybrid facility.

Combining Eqs. (2) to (4) and (17) we obtain

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\dfrac{P^{hyb}_{R}}{f^{ref}_{\substack{R\\W}}}}{\dfrac{P^{hyb}_{R}}{f^{ref}_{\substack{R\\W}}} + \dfrac{P^{hyb}_{F}}{f^{ref}_{\substack{F\\W}}}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\dfrac{P^{hyb}_{F}}{f^{ref}_{\substack{F\\W}}}}{\dfrac{P^{hyb}_{R}}{f^{ref}_{\substack{R\\W}}} + \dfrac{P^{hyb}_{F}}{f^{ref}_{\substack{F\\W}}}} \tag{18}$$

Notably the ratios at the numerator $P^{hyb}_{R} \big/ f^{ref}_{\substack{R\\W}}$ and $P^{hyb}_{F} \big/ f^{ref}_{\substack{F\\W}}$ represent the amount of electricity that would be produced in reference single-resource (renewable-only and fossil-fuel only) power plants consuming the same amount of fossil and renewable primary energy as the hybrid facility. In other words, the allocation fractions $\beta^{hyb}_{\substack{W\\R}}$ and $\beta^{hyb}_{\substack{W\\F}}$ are based on the relative proportions of the electricity that would be produced with the same primary energy consumptions in non-hybrid facilities operating with the reference partial primary energy factors $f^{ref}_{\substack{R\\W}}$ and $f^{ref}_{\substack{F\\W}}$, respectively.

The relations between the allocation fractions, the partial primary energy factors, and the other parameters of the hybrid facility, according to Eqs. (9) and (10) are as follows

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\chi^{ref}_{W}}{\sigma_{hyb} + \chi^{ref}_{W}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\sigma_{hyb}}{\sigma_{hyb} + \chi^{ref}_{W}} \tag{19}$$

$$f^{hyb}_{\substack{R\\W}} = \frac{\left(\sigma_{hyb} + \chi^{ref}_{W}\right) f_{hyb}}{\left(\sigma_{hyb} + 1\right)\chi^{ref}_{W}\,\eta_{hyb}} \quad \text{and} \quad f^{hyb}_{\substack{F\\W}} = \frac{\left(\sigma_{hyb} + \chi^{ref}_{W}\right) f_{hyb}}{\left(\sigma_{hyb} + 1\right)\eta_{hyb}} \tag{20}$$

2.3 Exergy-based allocation method

According to this method the closure condition is

$$\chi^{hyb}_{W} = \chi^{hyb}_{Ex} \quad \text{with} \quad \chi^{hyb}_{Ex} = \frac{f^{hyb}_{\substack{F\\Ex}}}{f^{hyb}_{\substack{R\\Ex}}} \tag{21}$$

where

$$f^{hyb}_{\substack{F\\Ex}} = \frac{P^{hyb}_{F}}{Ex^{hyb}_{F}} \quad \text{and} \quad f^{hyb}_{\substack{R\\Ex}} = \frac{P^{hyb}_{R}}{Ex^{hyb}_{R}} \tag{22}$$

are the primary-energy-to-exergy ratios[2] of the fossil and the renewable primary resources used in the hybrid facility.

By solving the system of Eqs. (2) to (4) and (21) we obtain

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\dfrac{P^{hyb}_{R}}{f^{hyb}_{\substack{R\\Ex}}}}{\dfrac{P^{hyb}_{R}}{f^{hyb}_{\substack{R\\Ex}}} + \dfrac{P^{hyb}_{F}}{f^{hyb}_{\substack{F\\Ex}}}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\dfrac{P^{hyb}_{F}}{f^{hyb}_{\substack{F\\Ex}}}}{\dfrac{P^{hyb}_{R}}{f^{hyb}_{\substack{R\\Ex}}} + \dfrac{P^{hyb}_{F}}{f^{hyb}_{\substack{F\\Ex}}}} \tag{23}$$

or equivalently

$$\beta^{hyb}_{\substack{W\\R}} = \frac{Ex^{hyb}_{R}}{Ex^{hyb}_{R} + Ex^{hyb}_{F}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{Ex^{hyb}_{F}}{Ex^{hyb}_{R} + Ex^{hyb}_{F}} \tag{24}$$

Thus, the allocation fractions are based on the relative proportions of the exergies of the resources fed to the hybrid plant, i.e., on the relative proportions of the electricity that would be produced from the two resources in a hypothetic reference scenario in which every machinery operates reversibly, i.e., at the highest possible conversion efficiency compatible with thermodynamic limitations. Also here the relations between the allocation fractions, the partial primary energy factors, and the other parameters of the hybrid facility, can be written according to Eqs. (9) and (10) as follows

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\chi^{hyb}_{Ex}}{\sigma_{hyb} + \chi^{hyb}_{Ex}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\sigma_{hyb}}{\sigma_{hyb} + \chi^{hyb}_{Ex}} \tag{25}$$

$$f^{hyb}_{\substack{R\\W}} = \frac{\left(\sigma_{hyb} + \chi^{hyb}_{Ex}\right) f_{hyb}}{\left(\sigma_{hyb} + 1\right)\chi^{hyb}_{Ex}\,\eta_{hyb}} \quad \text{and} \quad f^{hyb}_{\substack{F\\W}} = \frac{\left(\sigma_{hyb} + \chi^{hyb}_{Ex}\right) f_{hyb}}{\left(\sigma_{hyb} + 1\right)\eta_{hyb}} \tag{26}$$

[2] The primary-energy-to-exergy ratio of a given resource is defined as the ratio of the primary energy associated with the unit amount of that resource to the exergy per unit amount.

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3 STALPR ALLOCATION METHOD FOR A HYBRID FOSSIL-AND-SOLAR POWER PLANT

Similarly to what we observed in a previous paper [1], a limitation of the classical allocation methods is that they are based on some prescribed reference partial primary-impact-to-product ratios for the separate single-resource productions (in our example, primary-energy-to-electricity in renewable-only and in fuel-only reference facilities). These reference ratios are to be fixed by some authority and in general differ from the actual average ratios that characterize the local area which constitutes the reference context for the facility. To overcome this problem, we proposed a self-consistent method whereby the allocation is adaptive and self-tuned to the local energy scenario. We call it the Self-Tuned Average-Local-Productions Reference (STALPR) method. The method was initially conceived for the allocation of fuel primary energy [1] and CO_2 [13] emissions in case of cogeneration plants. In this section, we extend it to the case of a fossil/renewable hybrid power plant belonging to a local area where all other electricity power facilities are single-resource, *n* using fossil fuels, and *m* using renewable resources. We assume for simplicity that both the set of *n* fossil plants and the set of *m* renewable plants are conceptually lumped together into single overall units producing respectively the overall amounts of electrical energy $W_R^{sr} = \sum_{i=1}^{n} W_R^{sr,i}$ and $W_F^{sr} = \sum_{i=1}^{m} W_F^{sr,i}$, and characterized by the average renewable and fossil primary energy factor

$$\bar{f}^{sr}_{\substack{R\\W}} = \frac{\sum_{i=1}^{n} f^{sr,i}_{\substack{R\\W}} W_R^{sr,i}}{\sum_{i=1}^{n} W_R^{sr,i}} \quad \text{and} \quad \bar{f}^{sr}_{\substack{F\\W}} = \frac{\sum_{i=1}^{m} f^{sr,i}_{\substack{F\\W}} W_F^{sr,i}}{\sum_{i=1}^{m} W_F^{sr,i}}$$

A sketch of the local-area powerplant scenario is shown in Fig.2.

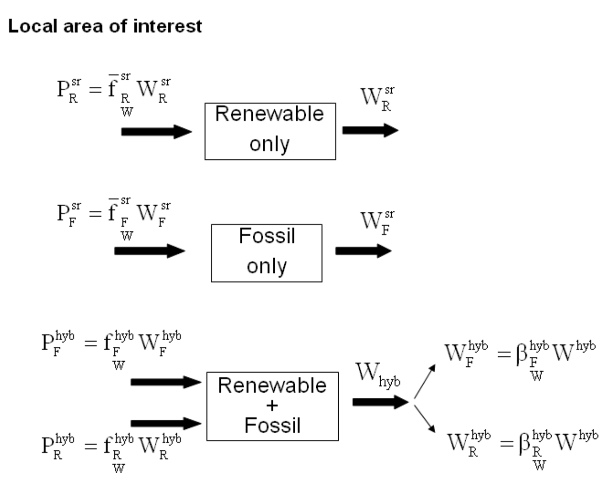

Figure 2: Schematic representation of a local area of interest with a single hybrid plant.

The rationale of the proposed method is that the allocation parameters should not be based on static reference values of primary-impact-to-product ratios for the various different resources, but should be self-determined by the method itself as characteristic average features of the actual energy production scenario and mix of resources used in the local area of interest, including the hybrid facility itself. Therefore, to characterize the local-area scenario we define $f^{loc}_{\substack{R\\W}}$ and $f^{loc}_{\substack{F\\W}}$ as the average primary energy factors for the fossil fuel and renewable resource conversion to electricity in the local area. With reference to Fig. 2 they are calculated as

$$f^{loc}_{\substack{R\\W}} = \frac{\bar{f}^{sr}_{\substack{R\\W}} W_R^{sr} + f^{hyb}_{\substack{R\\W}} W_R^{hyb}}{W_R^{sr} + W_R^{hyb}} \quad \text{and} \quad f^{loc}_{\substack{F\\W}} = \frac{\bar{f}^{sr}_{\substack{F\\W}} W_F^{sr} + f^{hyb}_{\substack{F\\W}} W_F^{hyb}}{W_F^{sr} + W_F^{hyb}} \qquad (27)$$

or equivalently, substituting the definition of the β's given in Eqs.(1)

$$f^{loc}_{\substack{R\\W}} = \frac{\bar{f}^{sr}_{\substack{R\\W}} W_R^{sr} + f^{hyb}_{\substack{R\\W}} \beta^{hyb}_{\substack{W\\R}} W_{hyb}}{W_R^{sr} + \beta^{hyb}_{\substack{W\\R}} W_{hyb}} \quad \text{and} \quad f^{loc}_{\substack{F\\W}} = \frac{\bar{f}^{sr}_{\substack{F\\W}} W_F^{sr} + f^{hyb}_{\substack{F\\W}} \beta^{hyb}_{\substack{W\\F}} W_{hyb}}{W_F^{sr} + \beta^{hyb}_{\substack{W\\F}} W_{hyb}}$$

(28)

Then, following the same logic adopted for the classical SRSPR method, we close the allocation problem by adopting the following rule

$$\chi^{hyb}_W = \chi_{loc} \quad \text{with} \quad \chi_{loc} = \frac{f^{loc}_{\substack{F\\W}}}{f^{loc}_{\substack{R\\W}}} \qquad (29)$$

so that combining Eqs. (2) to (4) and (29) we obtain

$$\beta^{hyb}_{\substack{W\\R}} = \frac{\dfrac{P_R^{hyb}}{f^{loc}_{\substack{R\\W}}}}{\dfrac{P_R^{hyb}}{f^{loc}_{\substack{R\\W}}} + \dfrac{P_F^{hyb}}{f^{loc}_{\substack{F\\W}}}} \quad \text{and} \quad \beta^{hyb}_{\substack{W\\F}} = \frac{\dfrac{P_F^{hyb}}{f^{loc}_{\substack{F\\W}}}}{\dfrac{P_R^{hyb}}{f^{loc}_{\substack{R\\W}}} + \dfrac{P_F^{hyb}}{f^{loc}_{\substack{F\\W}}}} \qquad (30)$$

meaning that the allocation fractions β's are based on the relative proportions of the electrical energies that would be produced in single-resource facilities consuming the same primary resources as the hybrid facility but operating with the average local-area primary energy factors $f^{loc}_{\substack{R\\W}}$ and $f^{loc}_{\substack{F\\W}}$ of the respective resources.

Combining Eqs. (2), (28), (29) and (30) yields a system of six equations in the six unknowns $\beta^{hyb}_{\substack{W\\R}}$, $\beta^{hyb}_{\substack{W\\F}}$, $f^{hyb}_{\substack{R\\W}}$, $f^{hyb}_{\substack{F\\W}}$, $f^{loc}_{\substack{R\\W}}$ and

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$f^{loc}_{F \atop W}$ that can be solved numerically providing the solution of the allocation problem. The problem can also be reduced to the solution of a single second-order equation, therefore yielding an analytical solution. The procedure leading to the second-order-degree equation is extensively reported in Ref. 14. Also the direct duality and analogies with the allocation problem for cogeneration facilities are described in the appendix A of the same paper.

4 CASE STUDY

In order to better focus on the features of the STLAPR approach, in this section we provide an example of its application to the renewable-to-fossil allocation of the power produced in hybrid single-product facilities, and we study the difference between the SRSPR and the STLAPR allocation methods as a function of the degree of penetration of hybrid facilities in a given local area. To this purpose we consider the local area shown in Fig. 2 and we assume that the annual demand of electrical energy is initially supplied according to the following shares:

- 90% by fossil-only (i.e., natural-gas single-resource) power plants operating with $f^{sr}_{F \atop W} = f^{sr}_F / \eta^{sr}_{F \atop W}$, assuming an overall (yearly) average efficiency $\eta^{sr}_{F \atop W}$ = 0.38 and a primary energy factor f^{sr}_F = 1.1 (natural gas). For the sake of comparison, we will consider also how the results would change if we consider $\eta^{sr}_{F \atop W}$ = 0.55 and other values.
- 10% by renewable-only (i.e., single-resource, non-hybrid solar) power plants operating with $f^{sr}_{R \atop W} = f^{sr}_R / \eta^{sr}_{R \atop W}$, assuming an overall (yearly) average efficiency $\eta^{sr}_{R \atop W}$ = 0.153 and a primary energy factor $f^{sr}_R = 1$.

Then we assume that the fossil-only facilities in the local area are progressively replaced by renewable-fossil hybrid plants, until all the single-resource fossil electricity W^{sr}_F is eventually replaced by W_{hyb}, while the single-resource solar electricity W^{sr}_R remains fixed to its initial value.

For simplicity we consider that each renewable-fossil hybrid plant is identical to the others and it is based on the technology of the Solar-Integrated Combined-Cycle System (SICCS) with parabolic trough solar field, as described in Ref. 9. In this solution, the integration is achieved by boiling a fraction of the feed-water in the solar boiler and feeding saturated high-pressure steam into the main steam circuit of the combined cycle at the inlet of the superheater in the HRSG. In this example it is therefore assumed that it is always possible to add a solar field in the area nearby the existing fossil-only facilities so as to convert them into SICCS.

To compute the energy allocation according to the STALPR method it is necessary to determine the global yearly energy balance on the hybrid power plant and to evaluate the parameters P^{hyb}_F / W_{hyb} and P^{hyb}_R / W_{hyb} which characterize the hybrid facility. These are obtained as follows from the data reported in Ref. 9.

- The annual electricity generation W_{hyb} is indicated as 867 GWh.
- P^{hyb}_F is not given explicitly, but can be obtained from the value of annual CO_2 emissions, recalling that (in the hypothesis that the fossil fuel is all CH_4), the combustion of 1 ton of CH_4 yields 2.75 ton of CO_2. Given that in this example 363000 ton of CO_2 are emitted by the SICCS, we can readily obtain a corresponding fuel consumption of 122900 ton of CH_4. Considering LHV_{CH4} = 50 MJ/kg and assuming f^{hyb}_F = 1.1 we find a primary fossil energy consumption P^{hyb}_F = 1878 GWh.
- P^{hyb}_R can be obtained from the design thermal capacity of the solar field which in this case is 90 MW. Assuming a parabolic trough solar field efficiency[3] of 66% and a design Direct Normal Insolation (DNI) of 800 W/m^2 [15], the resulting solar collectors area is 169900 m^2, while the total solar field required land area[4] is 414000 m^2. Assuming an annual insolation of 2500 kWh/year, characteristic of locations with favourable insolation conditions [16], the resulting solar energy falling onto the field is 1035 GWh, but that intercepted by the mirrors is 425 GWh. As typically done when computing efficiencies of solar power plants, we consider the latter to be the primary energy consumption and, therefore, we set P^{hyb}_R = 425 and the primary energy factor f^{hyb}_R = 1.[5]

[3] The efficiency of the solar field is defined as the ratio of the thermal power provided by the solar field to the CC to the insolation on the solar collectors area at design conditions. It is the product of optical, thermal, and piping efficiencies, assumed respectively equal to 74.4%, 90.0%, and 98.9% [15].

[4] The total solar field area includes a minimum distance between each row of parabolic trough collectors (usually in the range of 15 m) to limit shading [15].

[5] Alternatively, we could assume P^{hyb}_R = 1035 GWh and a primary energy factor f^{hyb}_R = 1035/425, i.e., equal to the ratio of the overall solar field area to the overall mirror area. However, in such case we should also set, for consistency, f^{sr}_R = 1035/425, because also the single-resource, non-hybrid solar power plants are assumed to use the same mirror technology as the hybrid

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Table 1 summarizes the above assumptions and the other parameters of the case study.

Table 1: Summary of assumptions made and values of some important parameters for the hybrid solar-and-fossil power plant case study.

Parameters of the local area	
Fraction of the renewable-only electricity in the local area, $\gamma_{W}^{sr,RW}$	0.1
Primary energy factor of solar energy, $f_{R}^{sr,RW}$	1.0
Average efficiency of the renewable-only facilities, $\eta_{\frac{R}{W}}^{sr}$	0.153
Primary energy factor of natural gas (assumed the only fuel used in the local area for fossil-only facilities), $f_{F}^{sr,FW}$	1.1
Average efficiency of the fossil-only facilities, $\eta_{\frac{F}{W}}^{sr}$	0.38 (0.55)
Ratio of primary energy factors of electricity produced in solar-only and fossil-only facilities, Eq. (36), χ_{W}^{sr}	0.4429 (0.3060)
Parameters of the hybrid facilities	
Primary energy factor of solar energy, f_{R}^{hyb}	1.0
Primary energy factor of natural gas (assumed the only fuel used in the local area for hybrid facilities), f_{F}^{hyb}	1.1
Renewable primary energy to electricity ratio, P_{R}^{hyb}/W_{hyb}	425/867
Fossil primary energy to electricity ratio, P_{F}^{hyb}/W_{hyb}	1878/867
Fossil to renewable primary energy ratio, $\sigma_{hyb} = P_{F}^{hyb}/P_{R}^{hyb}$	1878/425
Ratio of primary energy factors of solar energy and fossil fuel, Eq. (5), χ_{res}^{hyb}	1.1
Average primary energy factor of the resources, Eq. (9), f_{hyb}	1.08

The allocation problem as a function of the penetration of hybrid facilities in the local area is best characterized by the following parameters:

$$x = \frac{W_{hyb}}{W_{F}^{sr} + W_{hyb}} \quad (31)$$

which for the local area represents the fraction of the electricity not produced in single-resource solar facilities that is produced in hybrid SICCS plants (for our case study it will range from 0 to 1);

$$y = \beta_{\frac{W}{R}}^{hyb} \quad (32)$$

which is the allocation fraction assigned by the STALPR method to the fraction of the power production in hybrid facility that we should consider as obtained from the renewable resource;

$$g = \gamma_{W}^{sr,R} \quad (33)$$

which is the fraction of the overall electricity produced in the local area that comes form the renewable-only facilities (for our case study $g = 0.1$);

$$h = \frac{f_{\frac{F}{W}}^{sr} W_{hyb} - P_{F}^{hyb}}{f_{\frac{F}{W}}^{sr} W_{hyb}} = 1 - \frac{\sigma_{hyb} f_{hyb}}{(\sigma_{hyb}+1) f_{\frac{F}{W}}^{sr} \eta_{hyb}} \quad (34)$$

which represents the index of fossil fuel savings obtained by hybrid facility with respect to the fossil-only power plants in the area;

$$k = \frac{\dfrac{P_{R}^{hyb}}{f_{\frac{R}{W}}^{sr}}}{\dfrac{P_{R}^{hyb}}{f_{\frac{R}{W}}^{sr}} + \dfrac{P_{F}^{hyb}}{f_{\frac{F}{W}}^{sr}}} = \frac{\chi_{W}^{sr}}{\sigma_{hyb} + \chi_{W}^{sr}} \quad (35)$$

which represents the allocation fraction according to the SRSPR method based on reference values equal to the primary energy factors of the renewable-only and the fossil-only power plants in the area, i.e, as given from Eq. (18) with $f_{\frac{R}{W}}^{ref} = f_{\frac{R}{W}}^{sr}$ and $f_{\frac{F}{W}}^{ref} = f_{\frac{F}{W}}^{sr}$ or equivalently Eq. (19) with $\chi_{W}^{ref} = \chi_{W}^{sr}$ where

$$\chi_{W}^{sr} = \frac{f_{\frac{F}{W}}^{sr}}{f_{\frac{R}{W}}^{sr}} \quad (36)$$

In terms of the above parameters, the equations of the preceding section result in the following second order equation in y

$$f(g,h,k,x,y) = (k-g)xy^2 + [g - hkx(1-(1-g)x)]y - gk(1-hx) = 0 \quad (37)$$

which can be readily solved for the only positive root.

Figures 3 and 4 report the results of this analysis for our case study with two different choices (0.38 and 0.55, respectively)

plant. As a result, this alternate choice would not alter any of the results shown in Figures 3 to 5 (neither for the SRSPR nor for the STALPR method).

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for the value of the average efficiency of the fuel-only power plants in the area.

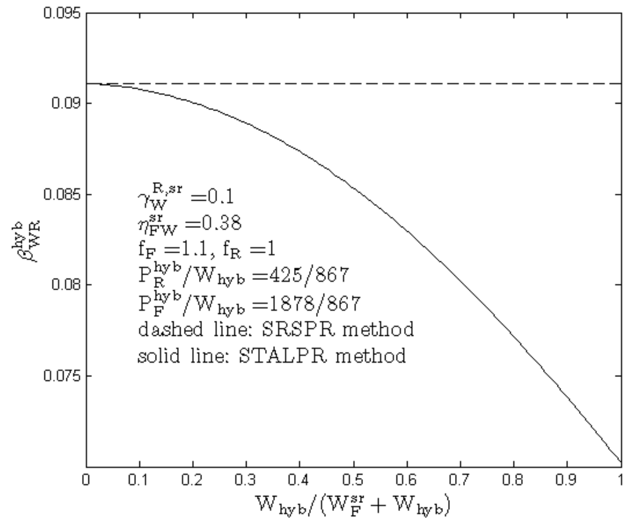

Figure 3: Renewable allocation fraction of the hybrid facility $\beta^{hyb}_{W_R}$, plotted as functions of the hybrid penetration parameter $W_{hyb}/\left(W_F^{sr}+W_{hyb}\right)$ for the parameters listed in Table 1 and $\eta^{sr}_{F_W}$ = 0.38.

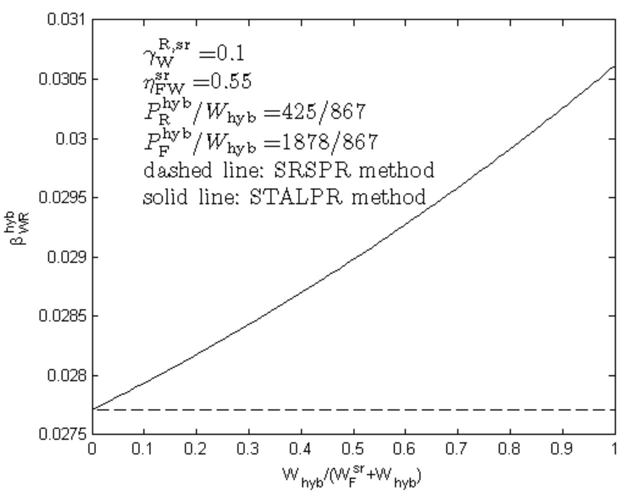

Figure 4: Renewable allocation fraction of the hybrid facility $\beta^{hyb}_{W_R}$, plotted as functions of the hybrid penetration parameter $W_{hyb}/\left(W_F^{sr}+W_{hyb}\right)$ for the parameters listed in Table 1 and $\eta^{sr}_{F_W}$ = 0.55.

Clearly the edge values $x=0$ and $x=1$ represent respectively the condition of no hybrid plant in the local area and the case of complete conversion of all fossil-only electricity into solar-integrated hybrid.

It is noteworthy that at $x=0$ the STALPR method and the SRSPR method coincide provided for the latter we assume as reference values the primary energy factors of the renewable-only and the fossil-only power plants in the local area, i.e., $\chi_W^{ref}=\chi_W^{sr}$. We also note that the slope of the curve changes sign from Figure 3 to Figure 4. Therefore, we show in Figure 5 how the curves change as we vary the value of $\eta^{sr}_{F_W}$. We note that the difference between the SRSPR and the STALPR allocations become significant as the hybrid facilities take on a sizable fraction of the production of electricity in the local area. A comprehensive analysis of this case study and some consideration on the consequent implications on the rationale for incentive policies related to hybrid plants are reported in Ref. 14.

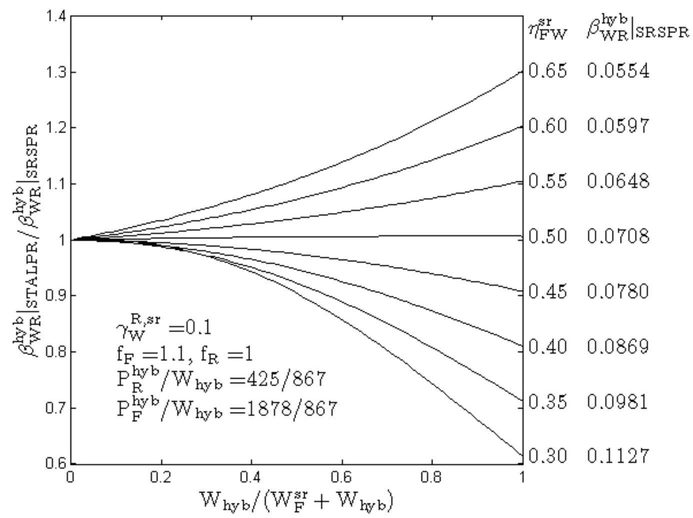

Figure 5: Ratio of the STALPR to the SRSPR values for the renewable allocation fraction of the hybrid facility $\beta^{hyb}_{W_R}$, plotted as functions of the hybrid penetration parameter $W_{hyb}/\left(W_F^{sr}+W_{hyb}\right)$ for the parameters listed in Table 1 and various values of $\eta^{sr}_{F_W}$. The SRSPR values are computed assuming reference values equal to the primary energy factors of the renewable-only and the fossil-only power plants in the area.

5 CONCLUSIONS

In several industrial and manufacturing sectors, higher production efficiencies are achieved by integrating the production of a mix of different goods and/or using a mix of different resources and/or raw materials. Such facilities are therefore either multi-resource or multi-generation, or both. In

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all these cases the key problem is to define a 'fair' method to allocate the consumption of the each resource in the facility among the different multi-generated products. This is for instance the case of multi product systems typically addressed in life cycle analysis problems. Among the possible combinations between resources and products, one case of particular interest for the energy sector is that of cogeneration facilities, where the object of the allocation problem is 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 electrical energy. We addressed this case in a previous paper [1], 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. In Ref. 1, we proposed a self-consistent method that we called STLARP whereby the allocation is adaptive and self tuned to the local energy scenario, with no need for prescribed reference efficiencies.

In this paper, we apply the same logic to define the STLARP method for the allocation problem of the so-called hybrid power production facilities, based on the integration of renewable resources into conventional fossil-fuel-fired power plants. In particular, we focus on the production of electricity in hybrid fossil+solar power plants, because they represent a desirable solution in terms of a reliable use of solar energy, capable to mitigate the drawbacks that derive from its intrinsic high degree of variability. The goal of the allocation problem is to determine what fraction of the produced electricity is to be considered as produced from the solar energy and therefore qualifies for the subsidies typically provided by local legislation to promote the uses of renewable energy.

The results of our analysis are illustrated for a realistic case study, where we consider that Solar-Integrated Combined-Cycle Systems (SICCS) progressively replace the electricity produced by fossil-only facilities in a local area characterized by the presence of both fossil-only and renewable-only power plant. The differences with the classical SRSPR method turns out to become significant as the hybrid facilities take on a sizable fraction of the production of electricity in the local area. For instance, for the base case with $\eta^{sr}_{F \atop W} = 0.38$ (other assumptions as by Table 1), a variation of the hybrid penetration parameter $W_{hyb}/\left(W^{sr}_F + W_{hyb}\right)$ from 0 to 0.5, results in a corresponding change of the renewable electricity allocation fraction $\beta^{hyb}_{W \atop R}$ from 0.091 (coincident with the value obtained from the SRSPR method) to 0.085.

NOMENCLATURE

E	energy
Ex	exergy
f	primary energy factor
$\bar{f}$	average primary energy factor
P	primary energy
W	electricity

SUPERSCRIPTS

Ex	exergy
hyb	hybrid
loc	local area of interest
ref	reference
sr	single resource

SUBSCRIPTS

F	fossil
hyb	hybrid
sr	single resource
R	renewable

GREEK SYMBOLS

β	allocation fraction
γ^{sr}_{RW}	fraction of the overall electricity produced in the local area that comes from the renewable-only facilities
η_{hyb}	efficiency of the hybrid plant defined by Eq. (7)

$\eta^k_{i \atop j}$ and η^k_{ij} partial energy-conversion efficiency of facility k from resource i to product j

σ_{hyb}	nondimensional parameter defined by Eq. (6)
χ^i_j	nondimensional parameter defined by Eqs. (5) and (8)

ACRONYMS

SICCS Solar-Integrated Combined-Cycle System

SRSPR Single-Resource Separate-Production Reference (allocation method)

STALPR Self-Tuned Average-Local-Productions Reference (allocation method)

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