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Exergy loss based allocation method for hybrid renewable-fossil power plants applied to an integrated solar combined cycle

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ABSTRACT

This paper presents a novel Exergy Loss based (EL) allocation method for the electricity produced in hybrid renewable-fossil power plants. The rationale behind this approach is that the electricity allocated to the fossil and renewable resources are obtained by subtracting from the respective source input exergies, the corresponding exergy losses, that are identified by dividing the plant into three parts; namely: the renewable, fossil and hybrid sections. The advantage of this approach is that the allocation is based only on the performance of the power plant given by its internal exergy balances, and hence the results are independent from any external arbitrary assumptions on the reference conversion efficiencies of the two resources, as it is typical of classical methods. We show that the allocations obtained using the proposed EL approach, applied to an existing integrated solar combined cycle, are consistent and comparable with the allocations obtained using the Separate Production Reference (SPR) method, as long as reasonable efficiency values of the reference scenario are selected.

1. Introduction

Hybrid power production facilities combine and integrate renewable energy resources, like solar radiation, geothermal heat or biomass combustion with fossil fuel resources used in conventional energy systems such as steam cycle, gas-turbine cycle or combined cycle power plants [1–4]. Interest in these applications is rapidly raising. Because of the intermittent nature of most renewable resources, the hybrid configuration may provide more economic, sustainable, and reliable power under all load-demand conditions as compared to renewable only facilities [5,6]. In particular, hybrid fossil-solar configurations have been the subject of several studies recently, dealing with technology integration challenges as well as with the metrics necessary to evaluate the hybrid plant performance, thermodynamically and economically [7–12].

The question of what fraction of the electricity produced in such facilities can be considered as generated from the renewable resource still remains not fully addressed, leaving room for some arbitrariness in evaluating the share and the fraction of the power that qualifies for subsidies granted to renewable electricity, as normally prescribed by most of the policies that promote the applications of renewable primary energy resources.

As far as the allocation of the original energy source to the electricity output is concerned, the typical approach considers the amount of fossil fuel and renewable energy input, expressed either in terms of energy or exergy, irrespective of the conversion processes occurring within the power plant. Thus, generally speaking, the hybrid power plant is represented by the simplified scheme depicted in Fig. 1 where the net electricity W obtained through the conversion of the fossil fuel energy/exergy and renewable energy/exergy input P_F and P_R, is split into the renewable and fossil component W_F and W_R, by means of the allocation fractions β_R and β_F which represent the two unknowns of the allocation problem. It is worth noting that allocation can be made in terms of either short term (hours or days) or longer term (typically one year) energy balances (or equivalently in terms of short or longer term average power) obtained by integrating the power profile representative of the actual variable operating conditions of the hybrid system, over a certain time interval. The latter case is certainly better suited for quantifying the subsidies to be granted to the renewable electricity as it accounts for the actual energy produced by the renewable source.

According to the so-called proportional methods, the allocation

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Notation

AC	Air compressor
CEP	Condensate extraction pump
DOP	Diathermic oil pump
ECO	Economizer
EL	Exergy Loss (allocation method)
En	Energy
EnP	Energy proportional (allocation method)
EVA	Evaporator
Ex	Exergy
ExP	Exergy proportional (allocation method)
FC	Fossil centred (allocation method)
FP	Feeding pump
FS	Fossil-only section
GT	Gas turbine
HP	High pressure
HS	Hybrid section
ISCC	Integrated Solar Combined Cycle
LHV	Lower Heating Value
LP	Low pressure
P	Generic input source
RS	Renewable-only section
SH	Super heater
SPR	Separate Production Reference (allocation method)
S-EVA	Solar evaporator
ST	Steam turbine
STLARP	Self Tuned Average Local Productions Reference (allocation method)
W	Electricity
x	Exergy losses allocation coefficient

Superscripts

av	Available
in	Inlet
loss	Loss

Subscripts

AC	Air compressor
CEP	Condensate extraction pump
DOP	Diathermic oil pump
Ex	Exergy
F	Fossil
FP	Feeding pump
GT	Gas turbine
FS	Fossil-only section
HS	Hybrid section
HRSG	Heat recovery steam generator
R	Renewable
RS	Renewable-only section
S	Solar
ref	Reference production scenario

Greek symbols

β	Allocation fraction
η	Conversion efficiency

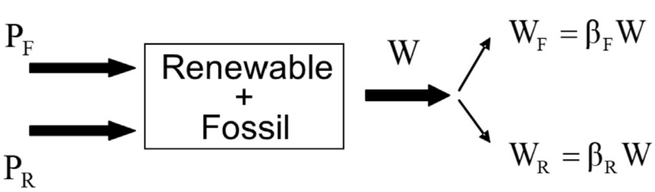

Fig. 1. Allocation problem definition in case of a generic fossil-renewable hybrid power plant.

fractions are given by

$$\beta_R = \frac{P_R}{P_R + P_F} \quad \beta_F = \frac{P_F}{P_R + P_F} \tag{1}$$

where P_R and P_F can be referred to the energy or exergy content of the renewable and fossil fuel input sources, thus defining respectively to the Energy Proportional (EnP) and the Exergy Proportional (ExP) method. One unrealistic implication of the application of this approach is that the fossil energy and renewable energy conversion efficiencies are equal as shown by the following expressions:

$$\begin{aligned} \eta_R &= \frac{\beta_R W}{P_R} = \frac{\frac{P_R}{P_R + P_F} W}{P_R} = \frac{W}{P_R + P_F} \\ \eta_F &= \frac{\beta_F W}{P_F} = \frac{\frac{P_F}{P_R + P_F} W}{P_F} = \frac{W}{P_R + P_F} \end{aligned} \tag{2}$$

Alternatively, the allocation can be determined according to a specific scenario, characterized by the inherent values or formulations of the conversion efficiency of each resource into electricity. These values are normally assigned by some local authority, typically with reference to an average or best available technology.

Using the Fossil Centred (FC) allocation method, the fossil conversion efficiency is fixed to a reference value $\eta_{F,ref}$ representative of the efficiency with which the primary fossil-fuel resource P_F is used for power production in a reference technology. Thus, the share of the fossil and renewable electricity, respectively, are $W_F = P_F\eta_{F,ref}$ and $W_S = W - P_F\eta_{F,ref}$, so that according to Fig. 1, the allocation fractions are given by

$$\beta_F = \frac{P_F \eta_F}{W} \quad \beta_R = \frac{W - P_F \eta_F}{W} \tag{3}$$

In the Separate Production Reference (SPR) allocation method, both the fossil fuel energy and renewable energy conversion efficiencies, η_F and η_R, are fixed to reference values, so that the allocation fractions of the renewable and fossil resources are proportional to the corresponding production of electricity that would be obtained from the consumption of the same resource with the corresponding conversion efficiencies. Accordingly, the expressions of the allocation fractions are

$$\beta_R = \frac{P_R \eta_R}{P_R \eta_R + P_F \eta_F} \quad \beta_F = \frac{P_F \eta_F}{P_R \eta_R + P_F \eta_F} \tag{4}$$

where $P_R\eta_R$ and $P_F\eta_R$ clearly represent the electricity produced from the conversion of the input source P_R and P_F in the assumed reference scenario. Notably in both FC and SPR methods, an inconsistency may arise whenever the hybrid power plant has different features and performance characteristics different from the technologies assumed as reference. To better clarify this point let us consider the case of a hybrid power plant that can be powered either by coal (fossil) or biomass (renewable) primary energy, maintaining the same fuel to electricity conversion efficiency, as can be the case of an external combustion steam power plant. If we assume that on a yearly basis the plant consumes the same amount of fossil and renewable primary energy, it is reasonable to allocate the produced electricity while maintaining the same proportion i.e. $\beta_R = \beta_F = 0.5$. The same result would indeed be obtained by applying the proportional method, whose allocation fractions are defined by Eq. (1). Conversely, the allocation methods based on the reference scenarios would result in somewhat distorted figures as long as the assumed reference efficiency differs from the intrinsic performance of the hybrid plant. For instance, adopting typical values of coal and biomass electricity conversion $\eta_F = 38\%$ and $\eta_R = 20\%$, in case of the SPR method we obtain from Eq. (4) $\beta_R = 0.34$ and $\beta_F = 0.66$.

Several examples on the application of both the SPR and FC methods can be found in the published scientific literature, particularly focusing on energy and emissions allocation for cogeneration and trigeneration units [13–22]. In general, a common limit of all the classic allocation methods, although certainly straightforward to apply, is that the impact of the actual conversion efficiency process of the two resources within the power plant is not considered. The negative implications of this condition can be better emphasized by considering the following second example. Let us consider two solar-fossil hybrid plants and assume that the first one consumes on yearly basis P_{R1} and P_{F1} of primary energy to produce W_1 of electricity, while the second consumes twice the solar energy, maintaining the same values of the other energy balance terms, i.e. $P_{R2} = 2P_{R1}$, $P_{F2}=P_{F1}$ and $W_2=W_1$. If we compute the allocation using the classical methods we invariably find that $\beta_{R2} > \beta_{R1}$ in case of the proportional and SPR methods (Eq. (1) and Eq. (4)) and $\beta_{R2} = \beta_{R1}$ in case of the FC method (Eq. (3)). This clearly leads to the inconsistent conclusion that second plant yields a higher fraction of renewable electricity (with potentially higher advantages in terms granted incentives), in spite of its lower conversion efficiency, given that it consumes twice the primary renewable source to produce the same electricity output.

In some previous papers, we discussed and critiqued classical allocation methods, and introduced a novel 'fair' approach that we called Self-Tuned-Average-Local-Productions-Reference (STLARP) method where the electricity allocation to the different primary energy sources is based on the average conversion efficiencies of the actual energy portfolio of the local area that includes the hybrid plant itself [23–26]. Compared to the SPR method, we obtain a more consistent definition of the reference efficiencies, since the hybrid plant contributes to determining the characteristic of the local area production scenario. However, influence of the hybrid plant becomes appreciable only when the technology produces a sizable fraction of the power portfolio of the local area.

Starting from these considerations, in this paper we introduce a new approach that we call Exergy Loss based (EL) allocation method. This method takes into account the efficiency of the processes with which the fossil and renewable input sources are converted within the power plant itself, providing a more consistent and fair allocation of the two resources into the produced electricity, and overcoming most of the contradictions observed in the classical methods. We use an example to demonstrate the application of the new method. It should be mentioned that the proposed method captures the dependence of the efficiency on the plant design and how the integration of the fossil energy and renewable energy impacts its operation.

The paper is organized as follows. In Section 2 we justify the rationale of the proposed Exergy Loss based allocation method. In Section 3 we introduce and analyse the ISCC plant chosen as our case study. In Section 4 we discuss the results of the allocation obtained using the new method and compare them with the classical approaches. In Section 5 we draw our conclusions.

2. Rationale of the Exergy Loss based allocation method

The rationale of this method is based on the following consideration. From a global second law balance, the electricity produced by the power plant can be computed by subtracting from the fuel and renewable source input exergies, the exergy losses in each component.

Thus, with reference to the generic hybrid plant shown in Fig. 2, we write the global exergy balance as follows

$$W = W_R + W_F = Ex_R^{in} + Ex_F^{in} - \left(Ex_R^{loss} + Ex_F^{loss}\right) \tag{5}$$

where the total plant exergy losses Ex^{loss} can be conceptually allocated to the fossil and renewable shares Ex_F^{loss} and Ex_R^{loss}.

Thus, Eq. (5) is the sum of two partial exergy balances, relevant to the two primary energy sources that feed the power plant

$$\begin{aligned} W_R &= Ex_R^{in} - Ex_R^{loss} \\ W_F &= Ex_F^{in} - Ex_F^{loss} \end{aligned} \tag{6}$$

The terms W_R and W_F (i.e. the renewable and fossil share of the produced electricity) can therefore be obtained from the above equations once the value of Ex_R^{loss} and Ex_F^{loss} are determined. In other words, we need a criterion to split the overall plant exergy loss Ex^{loss}, known from the exergy balance of the hybrid plant, into the two terms Ex_R^{loss} and Ex_F^{loss}.

To define the problem in a more general form, we refer to the schematic layout shown in Fig. 3, as representative of a generic hybrid plant.

We divide the power plant into three sections: Renewable-only section (RS), Fossil-only section (FS) and Hybrid section (HS).

The Renewable-only section includes the plant components specifically devoted to the conversion of the exergy of the renewable source. Related to this part of the plant, we identify the following exergy fluxes: the input exergy of the renewable source Ex_R^{in}, the overall exergy losses Ex_{RS}^{loss} that includes all the exergy losses of the components in the section, the net power produced W_{RS} (negative if consumed), and the net available exergy Ex_{RS}^{av}. The latter can be further converted into power within the hybrid section. The value of Ex_{RS}^{av} can be readily obtained from the exergy balance over the Renewable-only section.

$$Ex_{RS}^{av} = Ex_R^{in} - W_{RS} - Ex_{RS}^{loss} \tag{7}$$

Similarly, for the fossil-only section we have

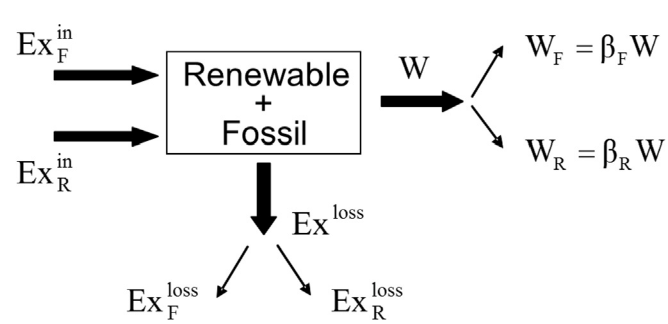

Fig. 2. Schematic exergy balance on the hybrid plant.

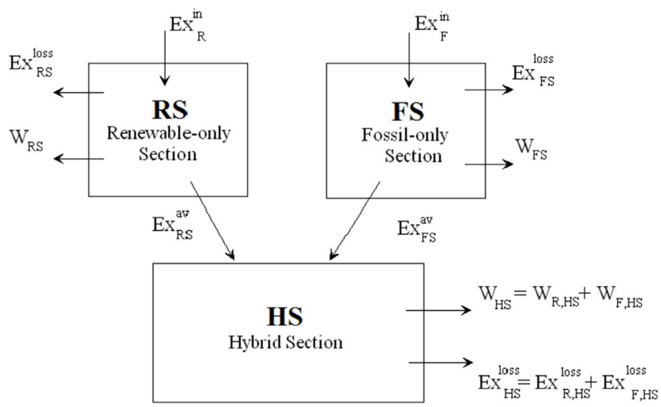

Fig. 3. Conceptual layout of a hybrid plant considered in the Exergy Loss based allocation method.

$$Ex^{av}_{FS} = Ex^{in}_{F} - W_{FS} - Ex^{loss}_{FS} \tag{8}$$

Finally in the Hybrid section, the exergy fluxes Ex^{av}_{RS} and Ex^{av}_{RS} are converted into the electricity W_{HS} which in turn can be divided into fossil and renewable components $W_{R,HS}$ and $W_{F,HS}$. Similarly, the exergy losses of the hybrid sectionEx^{loss}_{HS}, are divided in the two terms $Ex^{loss}_{R,HS}$and $Ex^{loss}_{F,HS}$.

In view of the layout represented in Fig. 3, Eq. (6) can be rewritten as:

$$\begin{aligned} W_R &= W_{RS} + W_{R,HS} = Ex^{in}_{RS} - Ex^{loss}_{RS} - Ex^{loss}_{R,HS} \\ W_F &= W_{FS} + W_{F,HS} = Ex^{in}_{FS} - Ex^{loss}_{FS} - Ex^{loss}_{F,HS} \end{aligned} \tag{9}$$

Notably, to obtain the value of W_R and W_F it is necessary to determine$Ex^{loss}_{R,HS}$ and $Ex^{loss}_{F,HS}$, i.e. to split the exergy loss of the hybrid section Ex^{loss}_{HS} into the two terms relevant to the renewable and fossil sources.

For this purpose, we introduce the following exergy losses allocation coefficients

$$\begin{aligned} x_{R,HS} &= \frac{Ex^{av}_{RS}}{Ex^{av}_{RS} + Ex^{av}_{FS}} \\ x_{F,HS} &= \frac{Ex^{av}_{FS}}{Ex^{av}_{RS} + Ex^{av}_{FS}} = 1 - x_{R,HS} \end{aligned} \tag{10}$$

showing that the exergy losses in the hybrid section are allocated among the renewable energy and fossil fuel in proportion to the respective available exergies from the renewable and fossil parts. Thus, we can determine

$$\begin{aligned} Ex^{loss}_{R,HS} &= x_{R,HS} Ex^{loss}_{HS} \\ Ex^{loss}_{F,HS} &= x_{F,HS} Ex^{loss}_{HS} \end{aligned} \tag{11}$$

We note that the expression of the allocation coefficients of the hybrid sections in Eq. (10), represents the only arbitrary assumption of this method, and are defined according to the Exergy proportional method. Although other formulations are conceptually possible, we believe that this is the most appropriate approach as it yields the same conversion efficiency of both the fossil and renewable exergies. This is consistent with the fact the two exergies are processed by the same components in the hybrid section, where by definition, it is not possible to further distinguish between the exergy flows of the two sources. For instance, if the SPR approach were followed, the renewable exergy would be arbitrarily and unfairly penalized in the hybrid section as consequence of the typical lower reference efficiency of the renewable sources in comparison to the fossil ones.

By substituting Eqs. (10) and (11) into Eq. (9) we obtain

$$\begin{aligned} W_R &= Ex^{in}_{R} - Ex^{loss}_{RS} - \frac{Ex^{av}_{RS}}{Ex^{av}_{RS} + Ex^{av}_{FS}} Ex^{loss}_{HS} \\ W_F &= Ex^{in}_{F} - Ex^{loss}_{FS} - \frac{Ex^{av}_{FS}}{Ex^{av}_{RS} + Ex^{av}_{FS}} Ex^{loss}_{HS} \end{aligned} \tag{12}$$

Finally, the fossil and renewable allocation fractions and the exergy efficiencies are expressed by

$$\beta_R = \frac{W_R}{W_R + W_F} \quad \beta_F = \frac{W_F}{W_R + W_F} \tag{13}$$

$$\eta_{Ex,R} = \frac{W_R}{Ex^{in}_{R}} \quad \eta_{Ex,F} = \frac{W_F}{Ex^{in}_{F}} \tag{14}$$

It is worthwhile to remark that this method reduces the degree of arbitrariness that characterizes the classical approaches, resulting in a fairer allocation of the electricity generated in hybrid systems. In fact, different from FC and SPR methods it is independent from external assumptions regarding the conversion efficiency of the two resources, as the allocation fraction depends only on the exergy flows of the power plant.

The EL method provides also an improvement of the classic ExP approach toward a better and fairer allocation. In fact, the classical ExP method is applied here only to allocate exergy losses in the hybrid section (as already evidenced, this represents the unique aspect of arbitrariness) while the exergy losses of the components identified within the fossil and renewable sections are specifically subtracted from the exergies of two input sources. On the other side, the EL method requires a detailed exergy analysis of the hybrid system in order to compute the exergy balances of the various sections necessary for the allocation. This computational effort, typically carried out through thermodynamic simulations of the power plant is generally not required in case of the classical methods since they are based only on global input and output data.

3. Case study

As explained earlier, the proposed EL method takes into account the efficiency of the processes with which the fossil and renewable energy input resources are converted within the power plant, evidencing how the integration of the two resources impacts its operation. This is obtained through a detailed exergy analysis of the plant, in contrast to the black-box based approach of the classical allocation methods.

While the classical methods can be adequate and even preferable for their simplicity in a number of situations, the EL method shows its superior features whenever the power plant contains sections or components characterized by substandard performances (i.e. turbomachinery with low efficiencies or the case of not optimized heat exchangers design). If it turns out that the relevant exergy losses associated to such components can be specifically attributed to one of the input sources, then the EL method generally provides a fairer solution to the energy allocation problem than classical methods.

The case study chosen to demonstrate the application of this approach, fits the purpose of the present analysis in that it can evidence the advantages of the proposed method in contrast to some possible contradictions of the classical ones. Nonetheless, the relevance and consistency of the EL method is general, as it can be applied whenever two or more input sources are combined and integrated in a power plant. This can be the case of the rather common hybrid-fossil power plants addressed in this work, as well as other hybrid categories such as the emerging all-renewable hybrids, like solar-biomass and solar-geothermal plants [11].

The chosen case study is the Integrated Solar Combined Cycle System located in Yazd (Iran), described in Ref. [27]. This plant, whose operating data are available as part of design analysis, consists of two 125 MW gas turbines powered by natural gas, coupled with two HRSGs, operated with two steam pressure levels. The steam cycle is based on a single 150 MW turbine, fed by the steam generated within the HSRGs. At full input solar power, the steam turbine provides extra 17 MW of electric power, obtained by expanding 28.2 kg/s of additional steam at the conditions of the high pressure evaporator of the HRSGs, generated exploiting 115 MW of thermal power collected in the solar field. The plant layout is shown schematically in Fig. 4. Since the two gas turbines and the corresponding HSRGs are identical and operate in parallel, for simplicity we consider them as single components with twice the original size.

In Table 1, temperature, pressure and mass flow rate data are given according to their state numbers specified in Fig. 4. For each point listed in the table, exergy rates are also calculated and provided in the last column. Data reported in Table 1 are taken from Ref. [27] where the authors carried out an overall energy and exergy analysis at the design conditions, by developing a thermodynamic model of the ISCC system. These data have also been assumed as reference in subsequent exergo-economic and thermoeconomic analyses [28–30].

In Fig. 4 the partition of the plant into the three sections necessary for the application of the EL allocation method, is also shown. The fossil section includes all the components of the gas turbine; the solar section comprises the solar field and the diathermic oil circulation pump, while the hybrid section includes all the remaining plant components. The exergy flow available from the fossil and solar section, ultimately processed and converted into electricity in the hybrid section, are provided respectively by the exergy content of the gas turbine exhaust (Ex_4) and by the exergy available from the hot stream of the solar evaporator (Ex_{12} - Ex_{13}).

Based on the exergy flows reported in Table 1, it is possible to compute the exergy balances on the overall plant and within each section. Details of this analysis are provided in Table 2. It should be noted that in the fossil section a net power of 252.6 MW is obtained from an exergy input of 859.8 MW, with a resulting electrical exergy efficiency of 29.4%. Moreover, additional 299 MW are available for further electricity conversion in the hybrid section. The

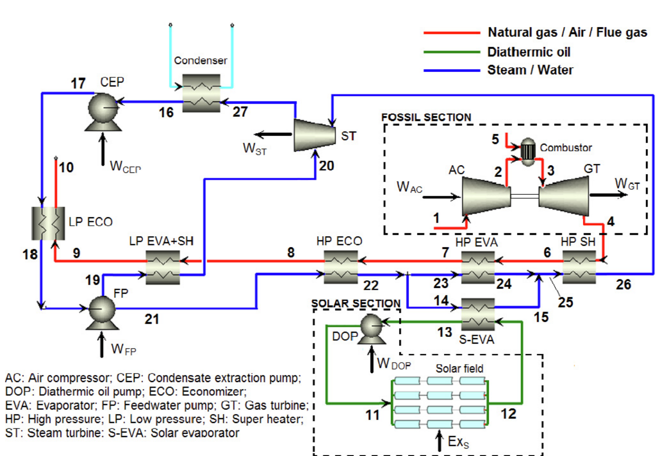

Fig. 4. Layout of the power plant considered in the allocation analysis.

Table 1
Thermodynamic points and exergy flow data of the integrated solar combined cycle shown in Fig. 4 [27–29].

	m, kg/s	T, °C	p, bar	Exergy, MW
1	843.6	19	1.10	0.0
2	843.6	358	11.14	270.40
3	861.0	1132	1.58	873.60
4	861.0	616	1.07	299.00
5	17.3	19	20.00	859.80
6	861.0	520	1.05	231.40
7	861.0	304	1.04	99.82
8	861.0	240	1.04	68.28
9	861.0	167	1.02	36.90
10	861.0	113	1.10	19.66
11	222.5	299	26.00	36.90
12	222.5	393	16.00	62.48
13	222.5	298	11.00	36.66
14	28.2	215	118.00	5.96
15	28.2	313	92.77	31.26
16	172.0	48	0.11	1.40
17	172.0	48	25.50	1.85
18	172.0	117	1.80	10.18
19	28.0	117	9.30	1.68
20	28.0	232	9.10	25.04
21	144.0	119	119.00	10.44
22	144.0	215	118.00	30.52
23	115.8	215	118.00	24.56
24	115.8	306	92.77	126.20
25	144.0	306	92.77	156.84
26	144.0	506	84.80	209.20
27	172.0	48	0.11	34.28
W_{AC}	-	-	-	295.40
W_{CEP}	-	-	-	0.55
W_{DOP}	-	-	-	0.51
W_{FP}	-	-	-	2.26
W_{GT}	-	-	-	548.00
W_{ST}	-	-	-	173.50
Ex_S	-	-	-	91.07

exergy balance in this section is closed by 308.2 MW exergy losses that represent about 36% of the input exergy. In comparison, the solar section is far less efficient, with the overall exergy losses accounting for about 77.2% of the solar input exergy. In the hybrid section a total input exergy of 324.8 MW (sum of the exergies available from the solar and fossil section) are converted into 170.7 MW net power, with a resulting exergy efficiency of 55.3%. Overall, the ISCC produces 422.8 MW from an exergy input of 950.8 MW, with a resulting exergy efficiency of 44.5%.

As a final remark, it must be emphasized that data available for the power plant considered in this example, refer to operation at nominal conditions with full input from the solar field. Although this simplifying assumption provides a straightforward way to compute results for the EL method and compare it with the classical ones, the allocation, for practical purposes, should instead be based on annual balances, or equivalently on averaged power values. In case of the EL approach, this would require a time-dependent plant exergy analysis, integrated over the year, necessary to take into account the variable plant operating conditions caused by the intermittency of the solar source. The latter is generally not necessary for the classical methods as they are based on values of overall annual input sources and electricity produced, which are normally available in the records of a power plant.

Yet, it is possible to conceive a simplified application of the EL method whenever only design data of the hybrid system are available. For instance, the introduction of an intermittency factor, representative of the average availability of the renewable source, which, in the present case, would reduce the peak solar power to an average value, according to insolation data of the site. Thus, the corresponding thermodynamic data in Table 1 necessary to

Table 2
Exergy balances of the various sections of the integrated solar combined cycle shown in Fig. 4.

Exergy flow in Fig. 3	Corresponding streams or components in Fig. 4	Exergy, MW
Fossil section		
Fossil fuel input exergy, Ex_F^{in}	Ex_5	859.80
Net power, W_{FS}	W_{TG} - W_{AC}	252.60
Exergy to hybrid section, Ex_{FS}^{av}	Ex_4	299.00
Exergy losses, Ex_{FS}^{loss}	Ex_5 - (W_{TG} - W_{AC}) - Ex_4	308.20
Solar section		
Solar input exergy, Ex_R^{in}	Ex_S	91.07
Net power, W_{RS}	W_{DOP}	−0.51
Exergy to hybrid section, Ex_{RS}^{av}	Ex_{12}- Ex_{13}	25.82
Exergy losses, Ex_{RS}^{loss}	Ex_S - W_{DOP} − (Ex_{12}- Ex_{13})	65.76
Hybrid section		
Input exergy from fossil section, Ex_{FS}^{av}	Ex_4	299.00
Input exergy from solar section, Ex_{RS}^{av}	Ex_{12}- Ex_{13}	25.82
Net power, W_{HS}	W_{ST} - W_{CEP}- W_{FP}	170.69
Exergy losses, Ex_{HS}^{loss}	Ex_4 - (Ex_{12}- Ex_{13}) - (W_{ST} - W_{CEP} - W_{FP})	154.13
Overall plant		
Fossil fuel input exergy, Ex_F^{in}	Ex_5	859.80
Solar input exergy, Ex_R^{in}	Ex_S	91.07
Total input exergy, $Ex_F^{in} + Ex_R^{in}$	Ex_5+ Ex_S	950.87
Net power, $W_{FS} + W_{RS} + W_{HS}$	($W_{TG} + W_{ST}$) − ($W_{AC} + W_{DOP} + W_{CEP} + W_{FP}$)	422.78
Exergy losses, $Ex_{FS}^{loss} + Ex_{RS}^{loss} + Ex_{HS}^{loss}$	(Ex_5+ Ex_S) -[($W_{TG} + W_{ST}$) - ($W_{AC} + W_{DOP} + W_{CEP} + W_{FP}$)]	528.09

perform the exergy analysis could be obtained through a thermodynamic simulations of the hybrid power plant operating in such average conditions. Alternatively, the EL method can provide the reference efficiencies η_R and η_F calculated at the known design conditions and then apply these values to the more straightforward classical SPR method (Eq. (4)). This may represent a significant improvement of the SPR method given that the efficiencies of the reference scenario would be obtained from the exergy analysis of the plant itself, instead of being arbitrarily specified by an external authority.

4. Comparison among the various methods

In this section, we apply the Exergy Loss based method to the hybrid power plant described in Section 3, providing comparison with the classical allocation approaches. The results of this analysis are summarized in Table 3. The last column reports the main results of the allocations carried out using EL method, obtained by substituting the relevant exergy flows of the hybrid power plant into Eq.(10)–(14). According to this method, about 97% of the produced electricity is allocated to the fossil resource. The resulting exergy conversion efficiency of the fossil and renewable resource are 47.7% and 14.3%. It is worth noting that these results are independent of external assumptions regarding the conversion efficiency of the two resources, as they are based only on the exergy flows of the power plant.

As far as the SPR method is concerned, to be consistent with our previous analysis [24], we adopt $\eta_{R,ref} = 15.3\%$ and two different values of the reference fossil conversion efficiency, namely $\eta_{F,ref} = 38\%$ and $\eta_{F,ref} = 50\%$. It can be seen that with $\eta_{F,ref} = 50\%$, the results of the allocation are similar to those of the EL method. This can be explained, considering that the efficiencies of the selected reference scenario are close to the resulting renewable and fossil efficiency obtained with the EL method. On the other hand, the reduction of the reference fossil efficiency to 38% raises the share of the renewable electricity, which in turns yields a corresponding appreciable increase of the renewable exergy conversion efficiency from 14.6% to 19.0%. In general, with the SPR method, the results of the allocation depend on the efficiencies of the selected reference scenario, as it can be seen from the sensitivity analysis shown in Fig. 5. In particular it should be noted that in both cases reported in Fig. 5, $\eta_{Ex,R}$ experiences a significant variation as function of $\eta_{R,ref}$ (figure on the left) and $\eta_{F,ref}$ (figure on the right), while values of $\eta_{Ex,F}$ remain closer to those obtained with the EL method (dotted lines). The results of the allocation with SPR coincide with those of the EL method in case of $\eta_{R,ref} = 11.2\%$ and $\eta_{F,ref} = 38.0\%$ (figure on the left) and $\eta_{R,ref} = 15.3$ and $\eta_{F,ref} = 51.8\%$ (figure on the right).

The application of the FC method provides inconsistent results.

Table 3
Comparison of the various methods on the electricity allocation of the hybrid power plant shown in Fig. 4. Results of the classical methods (ExP, FC and SPR) are based on the input exergies of the fossil and renewable sources.

Allocation method	Exergy Proportional ExP	Fossil Centred FC		Separate Production Reference SPR		Exergy Loss EL
$\eta_{F,ref}$, %	-	38	50	38	50	-
$\eta_{R,ref}$, %	-	-	-	15.3	15.3	-
$x_{F,HS}$	-	-	-	-	-	0.92
$x_{R,HS}$	-	-	-	-	-	0.08
W_F, MW	382.3	326.7	429.9	405.5	409.5	409.7
W_R, MW	40.5	96.1	−7.12	17.3	13.3	13.1
β_F	0.90	0.77	1.02	0.96	0.97	0.97
β_R	0.10	0.23	−0.02	0.04	0.03	0.03
$\eta_{Ex,F}$, %	44.5	38.0	50.0	47.1	47.6	47.7
$\eta_{Ex,R}$, %	44.5	105.5	−7.8	19.0	14.6	14.3

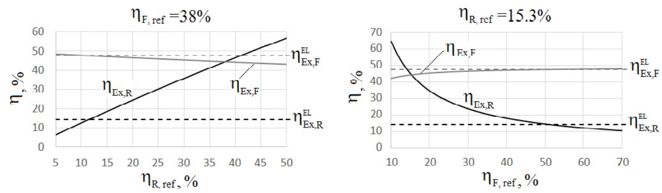

Fig. 5. Sensitivity analysis of the fossil and renewable exergy conversion efficiencies ($\eta_{Ex,F}$ and $\eta_{Ex,R}$) as function of the fossil and renewable efficiencies of the reference scenario ($\eta_{F,ref}$ and $\eta_{R,ref}$) adopted by the SPR method. Dotted lines correspond to the fossil and renewable exergy conversion efficiencies obtained with the proposed EL method ($\eta^{EL}_{Ex,F}$ and $\eta^{EL}_{Ex,R}$).

With $\eta_{F,ref} = 50\%$, the electricity allocated to the fossil resource turns out to be higher than the overall electricity produced by the power plant, resulting in negative values of both β_R and $\eta_{Ex,R}$. On the contrary, choosing $\eta_{F,ref} = 38\%$ leads an excessively high share of the renewable electricity which results greater than the input renewable exergy, leading to 105.5% for the renewable exergy conversion efficiency. In Fig. 6, we plot the renewable exergy conversion efficiency $\eta_{Ex,R}$ as function of the fossil efficiency of the reference scenario $\eta_{F,ref}$ adopted by the FC method, considering the interval where the resulting values of $\eta_{Ex,R}$ are consistent. Again it can be seen that the application of the FC method becomes questionable in this context, given the high sensitivity of $\eta_{Ex,R}$ in response to variations of the efficiency of the reference scenario. For instance, a change of $\eta_{F,ref}$ from 45% to 48% implies a variation of $\eta_{Ex,R}$ from 39% to 11%. Finally, with the exergy proportional method, a too high fraction of the electricity is allocated to the renewable source which corresponds to the unrealistic $\eta_{Ex,R} = 44.5\%$.

We note here that the solar efficiency obtained using the EL method ($\eta_{Ex,R} = 14.3\%$) turns out to be fairly low when compared to the thermodynamic efficiency of the state of the art solar power plants. Indeed, according to the exergy balances shown in Table 2, only 26 MW of the 91 MW input solar exergy are available in the hybrid section, resulting in solar section exergy efficiency of only 28%. This is a consequence of the poor performances of the solar section of the case considered in this study. In fact, input data taken from Ref. [27], provide a combined energy efficiency of the collector-receiver system of only 45.4% which is appreciably lower than 60–70% that one might expect in an up-to-date parabolic trough solar field [31]. While considering a hybrid plant with such low solar field performances, only the EL method correctly accounts of this fact, providing a correspondingly lower value of solar efficiency (14.3%), as compared with the misleading figures provided by the classical methods that excessively reward the solar production ($\eta_{Ex,R}$ is 44% for the ExP method, 105% for the FC and up to 19% for the SPR). Moreover, an increase of the solar input Ex^{in}_{R}, due for instance to the adoption of a larger collectors field, in all the classical methods would yield a higher fraction of renewable electricity (Eqs. (1)–(4)) with potentially higher advantages in terms granted incentives, neglecting the effect of the proportional increase of the exergy losses in the solar section. The EL approach is the only one that takes into account the actual poor efficiency of the solar field, attributing solar centric exergy losses to that source. The Sankey diagrams for the fossil and renewable sources resulting from the application of the EL method are shown in Fig. 7. The poor performance of the solar field is evident by the considerable exergy losses in the solar section which, proportionately, results in significantly higher losses than those shown in the fossil diagram.

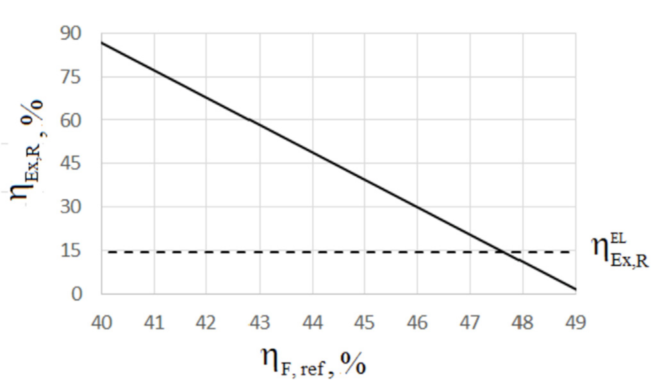

Fig. 6. Renewable exergy conversion efficiency $\eta_{Ex,R}$ plotted as function of the fossil efficiency of the reference scenario $\eta_{F,ref}$ adopted by the FC method. Dotted line corresponds to renewable exergy conversion efficiency $\eta^{EL}_{Ex,R}$ obtained with the proposed EL method.

As a final remark, it is worth noting that, as discussed in the Introduction, classical methods can also be applied considering the generic input sources P (Eqs. (1)–(4)) expressed in terms of their energy rather than exergy, as it was assumed here for a more consistent comparison with the proposed Exergy Loss based method. To complete this analysis, in Table 4 we report the results of the allocation based on the fossil and renewable input energies, namely $\eta^{in}_{En,F} = 795.8$ MW and $\eta^{in}_{En,R} = 97.8$ MW (to be compared to the corresponding input exergies of 859.8 MW and 91.1 MW). These are determined assuming LHV = 49.997 MJ/kg for the input natural gas according to Ref. [29], and $Ex_R = 0.93En_R$ for solar radiation [24].

It should be noted that the results of the classical energy-based method (EnP, FC nd SPR in Table 4) approximately correspond to those of the exergy-based method (ExP, FC and SPR in Table 3) as should be expected for the case at hand, representative of hybrid power production from hydrocarbon fuels and solar radiation, where values of the input energy and exergy of the two sources are comparable. Notably, the FC method with $\eta_{F,ref} = 50\%$ give a conceptually acceptable value of $\eta_{En,R} = 24.5\%$, instead of the inconsistent value of $\eta_{Ex,R} = -7.8\%$ obtained with the corresponding exergy-based FC method (Table 3). Nonetheless, again this result still represents an unfair outcome, as it gives too much advantage to the renewable electricity share, considering the poor performances of the solar field.

5. Discussion

One key issue related to hybrid fossil-renewable power plants, is determining what fraction of the produced electricity should be attributed to the renewable resource and therefore qualified for the subsidies normally prescribed by policies that promote the applications of renewable sources. Presently none of the proposed allocation methods can be considered satisfactory, since they all include some arbitrary assumptions.

Using the novel Exergy Loss based (EL) allocation method that

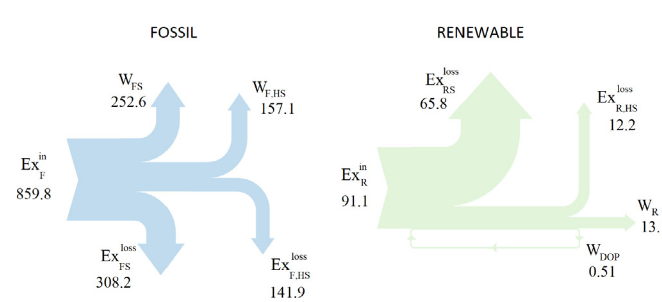

Fig. 7. Sankey diagrams for fossil and renewable sources resulting from the application of the EL method in case of the hybrid power plant shown in Fig. 4. Exergy and electricity flows are expressed in MW and refer to design data of the hybrid system.

Table 4
Results of the classical methods (EnP, FC and SPR) based on the input energies of the fossil and renewable sources, applied to the electricity allocation of the hybrid power plant shown in Fig. 4.

Allocation method	Energy Proportional EnP	Fossil Centred FC		Separate Production Reference SPR	
$\eta_{F,ref}$, %	-	38	50	38	50
$\eta_{R,ref}$, %	-	-	-	15.3	15.3
W_F, MW	376.4	302.4	397.9	402.8	407.4
W_R, MW	46.3	120.4	24.9	20.0	15.3
β_F	0.89	0.72	0.94	0.95	0.96
β_R	0.11	0.28	0.06	0.05	0.04
η_{EnF}, %	47.3	38	50.0	50.6	51.2
$\eta_{En,R}$, %	47.3	122.9	25.4	20.4	15.7

we introduce in this paper, we attempt to reduce the degree of arbitrariness that characterizes the classical approaches, moving in the direction of a more accurate and fair allocation of the electricity generated in hybrid systems. According to this method, the hybrid power plant is divided into three parts, namely Renewable-only, Fossil-only and Hybrid section. Next, starting from the exergy balances computed in each section, the electricity allocated to each resource is obtained by subtracting the relevant exergy losses from the primary input exergies, meaning that in the renewable and fossil sections all the exergy losses are attributed to renewable and fossil resource respectively, while in the hybrid section they are proportionally distributed among the two. It should be noted that the proposed EL method applies the classical Exergy proportional method only to the hybrid section, while the exergy losses of the components identified within the fossil and renewable sections are subtracted from the exergies of two input sources. Thus, we may consider the EL method an improvement of the classic Exergy approach toward a better and fair allocation.

The results of the EL allocation method applied to an integrated solar combined cycle chosen as our case study are comparable with those obtained with the SPR method as long as reasonable efficiency values of the reference scenario are selected. Conversely, the allocation obtained with the other classical methods, such as the Fossil centred and the Exergy proportional, turns out to be inconsistent or misleading. Notably, the Exergy Loss method is independent of external assumptions on the conversion efficiency of the two resources, as it is based only on the performances of the power plant itself. Here, the only arbitrary assumption is the allocation of the exergy losses in the hybrid section that we assume proportional to the corresponding available exergy flows from the fossil and hybrid sections according to the parameters defined in Eq. (10). We noted that one limit of the proposed approach is that the data of the power plant considered in the case study are available only at nominal operating conditions with full input from the solar field, while the allocation should instead be based on annual balances or equivalently on the average annual power. In the EL method, this in theory would imply that a time-dependent plant exergy analysis, integrated over the year, is necessary in order to compute the average annual values required for the allocation. In this regard, we suggest two simplified approaches for the application of the EL method, that can be more easily introduced into a regulation, whenever only design data are available. One can be the use of an intermittency factor that, in the case of hybrid solar systems, accounts for the variable solar radiation of the site. This will reduce the peak solar power to an average value at which the thermodynamic analysis of the plant should be carried out to determine the exergy balances necessary for the application of the EL method. Alternatively, it is possible to consider using a combination of the EL and SPR methods, where the former is employed to determine, at the known plant design conditions, the reference efficiencies required by the latter method. Although somewhat approximate, this solution may represent a significant improvement of the SPR approach given that the efficiencies of the reference scenario will be obtained from the exergy analysis of the plant itself, instead of being arbitrarily specified by an external authority. To assess this options, further analysis and comparisons with other case studies will be carried out in the future.

Finally, it is important to emphasize that a proper selection of the boundaries of the three sections is necessary for a correct allocation of exergy losses of the power plant components and ultimately for the effective application of the method. Although this was rather straightforward in the case analysed in the study, in other more complex plant configurations this procedure may leave space to some arbitrariness. To this purpose, in future works the EL method will be extensively applied to prove its general validity in the different solutions presently proposed for hybrid power plants.

6. Conclusions

This paper proposes a new method for allocating the electricity produced in a hybrid power plants among the fossil (F) and renewable (R) energy input resources it consumes. In contrast to the classical allocation methods, that are based on a black-box approach and require reasonable assumptions for the efficiencies of single-resource reference production methods, the method proposed here bases the allocation on a reasoned analysis of the plant layout details and an exergy analysis of the main subprocesses. In particular, the Exergy Loss based (EL) allocation method subdivides the plant layout into three sections: a renewable-only (R) section, a fossil-only (F) section, and a hybrid (H) section, for each of which we compute the exergy balance. Exergy losses in the R section are fully attributed to the R resource and, similarly, those in the F section are fully attributed to the F resource. Only the exergy losses in the H section are allocated among the F and R resources. This allocation is done in proportion to the net exergy flows that the H section receives from the F and R sections, respectively.

Compared with the separate production reference (SPR) allocation method, the EL method has the advantage that it requires no arbitrary specification of reference efficiencies by some external authority. Therefore, the EL method can be used to determine the nominal efficiencies η_R and η_F of the given hybrid power plant from the analysis of its known design conditions and then these efficiencies can be used as self-determined references for the more straightforward classical SPR allocation method.

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