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Abstract

In this work, an exergoeconomic analysis is applied to the power cycle of a concentrated solar plant for its design improvement. A supercritical CO2 cycle connected with the exothermic reactor of a thermochemical storage unit is considered. The analysis is conducted with the goal of highlighting the advantages of exergoeconomic analysis while suggesting changes to both the design parameters and the system configuration. Starting from the plant configuration which guarantees the maximum efficiency, the exergoeconomic analysis is iteratively applied with the goal of reducing the unit cost of electricity. The analysis is conducted in a way that cost functions of the components can be substituted with the cost analysis of specific designs. This is a big advantage of this procedure, which is suitable for applications in which economic analysis requires a detailed knowledge of the system characteristics. The procedure is then validated comparing the results with those obtained through mathematical optimization.

Keywords: Exergoeconomics; Thermoeconomic analysis; Energy system optimization; Design improvement; Supercritical CO_2 cycles; Thermochemical storage.

1. Introduction

Various approaches to the optimal design and design improvement have been proposed in the literature in the past years. Very effective are the approaches based on the integration of exergy analysis and economic analysis since these allow to take into account both the investment costs for the components and the actual performances of the component, including the irreversibility generation. The present paper is focused on the exergoeconomic approach proposed by Tsatsaronis and co-workers in the nineties [1]. This is a design improvement approach, not an optimization approach. This means that the final result of the design is not an optimum, but an improvement of the initial design.

In the authors' opinion, this method presents various advantages:

1) it is easy to apply once the analyst acquires a background on exergy and thermoeconomic analysis;
2) it can be used also in the case of discontinuous cost functions, in which case conventional optimization approaches would fail;
3) it can be applied to synthesis problems, i.e. when the system configuration is modified during the design process (in this case, optimization can be adopted to optimize a configuration different than the initial one and thus expand the optimization field).

The method presents a potential disadvantage, related with the fact that the design improvement phase is not automatic, unless combined with approaches such as artificial intelligence or fuzzy logic [2]. But this also means that the designer has full control of the procedure.

The improvement can be applied within an iterative procedure, in order to approach an optimum (which might be a local optimum) as much as possible.

Some applications of the method have been proposed in the literature. In [3], authors show the performance improvement that can be obtained for a test case, known in the literature as the "CGAM" (the name comes from the name initials of the proponents; Christos Frangopoulos, George Tsatsaronis, Antonio Valero and Michael von Spakovsky). This is a gas turbine with air preheating, able to generate electricity and heat. In [4], authors analyze a coal fired power plant, highlighting that by increasing the exergetic efficiency of some components the unit cost of electricity produced by the plant is decreased. In [5], a cogeneration plant based on diesel engine is analyzed, considering its operating conditions. Other applications are presented in [6] and [7]. In a recent paper [8], the exergoeconomic analysis is applied to various configurations of a supercritical CO2 cycle, with the goal of selecting the best one.

Despite various papers have been presented in the literature focused on this utilization of thermoeconomics, authors believe that this approach is a milestone in the thermal engineering history and is probably utilized under its capabilities.

In this paper, an indirect integration of the supercritical Brayton power cycle using CO_2 as the working fluid is considered. Some possible plant configurations are discussed in Section 2; these are considered both as the initial configuration for the design improvement as well as terms of comparison to the final results. The exergoeconomic methodology is iteratively applied to the optimal design condition of each configuration obtained from an improvement step, with the goal of showing how the methodology can drive to the optimization of the system even in cases in which the conventional optimization techniques cannot be applied. The methodology is deeply discussed in Section 3.

2. Reference plants for CaL integration in CSP

The motivation for this work resides in the activities developed within the European project SOCRATCES. This project aims at proposing a prototype of a thermochemical storage unit based on Calcium Looping (CaL) for application to Concentrated Solar Plants (CSP). A schematic of the CSP system integrated with CaL thermochemical storage is shown in Figure 1. Thermal storage is based on a reversible chemical reaction, the calcination-carbonation reaction. The charging phase (i.e the thermal storage) is obtained through a calcination reaction:

$$CaCO_3+\Phi \rightarrow CaO+CO_2 \tag{1}$$

This reaction requires 178 kJ/mol, which are provided by a heliostat field. The calciner is designed in order to allow reaching a temperature over 900 °C. The reverse reaction is used to retrieve the stored energy:

$$CaO+CO_2 \rightarrow CaCO_3+\Phi \tag{2}$$

This occurs in a carbonator reactor, which operating temperature is about 850 °C. The heat released from this reaction is used to feed a power cycle. Integration of the power cycle might be direct or indirect. In the case of direct integration, the working fluid is CO_2. The CO_2 flow rate must be in excess with respect to that requested for the carbonation. The excess fluid is thus heated up by the exothermic reaction and it is then ready for the use in the power cycle. In the case of indirect integration, a heat exchanger should be installed in the reactor in order to extract the heat released from the reaction. This introduces a thermodynamic irreversibility in the process, but increases the flexibility in terms of power cycles that can be integrated.

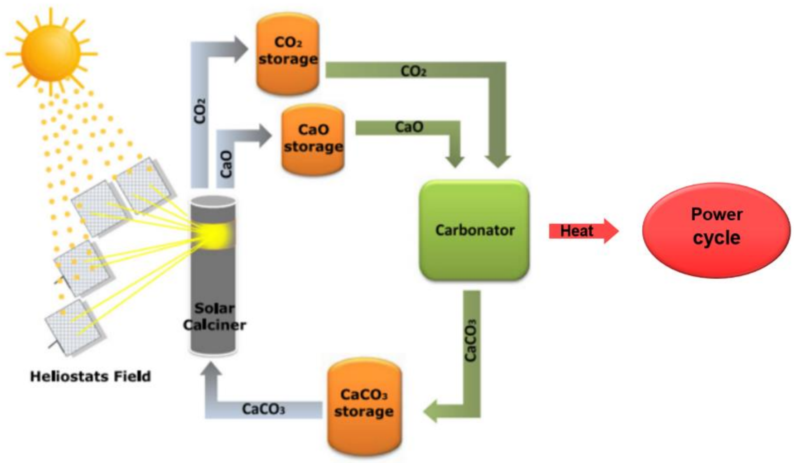

Fig. 1. Schematic of the CaL integration in a CSP plant

Various options of indirect integration are: Rankine cycles, Brayton cycles, Organic Rankine cycles, Stirling cycles. Among these options, supercritical CO2 Brayton cycle is particularly interesting for the promising high efficiency that can be obtained. Multiple plant configurations have been proposed in the literature for various applications ranging from concentrated solar power [9] to nuclear plants [10] to fossil fuel thermal power plants [11-13]. Some of these configurations are:

a. Brayton supercritical cycle (Base)
b. Brayton cycle with recirculation (Rec)
c. Brayton cycle with recirculation and re-heating (Rec-RH)
d. Brayton cycle with recirculation, re-heating and intercooling (Rec-RH-Int)

The cycles are shown in Fig. 3. In the cycle A, the CO2 at 40 °C and 78 bar (point 1) enters the compressor (CP1) and is compressed to the maximum pressure (which is a design variable), pre-heated in the regenerator (HE1) by the CO2 stream exiting the turbine (T1) and then heated in the heater (H) to the maximum temperature. This heater extracts heat from the carbonator shown in Figure 2. The maximum temperature in point 4 is then constrained by the carbonator temperature. The CO2 then expands in the turbine, which supplies mechanical power to the compressor and to the inverter. The regenerator is designed so that a minimum temperature difference is guaranteed between the hot and cold streams. The CO2 exiting the regenerator (point 6) is then cooled by means of environment air, which is considered at 20 °C. In cycle B, part of the CO2 exiting the regenerator is extracted before entering the cooler and directly compressed. A second difference with respect to cycle A is that the regenerator is divided in two sections (HE1 and HE2). On the hot side the stream is the complete CO2 flow rate exiting the turbine while, on the cold side, the bypass flow (point 4) is mixed with the main flow (point 3) after the first section. In cycle C, the expansion is divided in two sections (T1 and T2) in series. A second heater connected with the carbonator is installed between the two turbine sections. In cycle D, the compression of the main flow is performed by means of two compression sections (CP1 and CP2) with an inter-refrigeration located in between.
These plants and the other configurations presented in this paper are modeled considering the typical black box design models of components. Compressors and turbines are modeled using the hypothesis of adiabatic component and through assumption of their isentropic efficiencies. Heat exchangers are modeled imposing a minimum temperature difference between the two fluids which exchange heat

and calculating the heat transfer area using the approach of mean logarithmic temperature difference. The model considered here is implemented in a Matlab code in order to easily perform optimizations. CO2 properties are calculated using Fluidprop [14].

Table 1 shows the enthalpies and entropies for the fluid entering and exiting the various components in their optimal design condition. This is obtained considering the plant efficiency as the objective function to be maximized. Efficiencies in these four configurations increases with the system complexity, being 0.418, 0.461, 0.478 and 0.497, respectively. When economics is considered, the figure significantly changes. For this reason, it is worth investigating these systems with the goal of reducing the economic cost of electricity. This is performed starting from the fourth configuration and then applying the exergoeconomic approach for design improvement discussed in the next section.

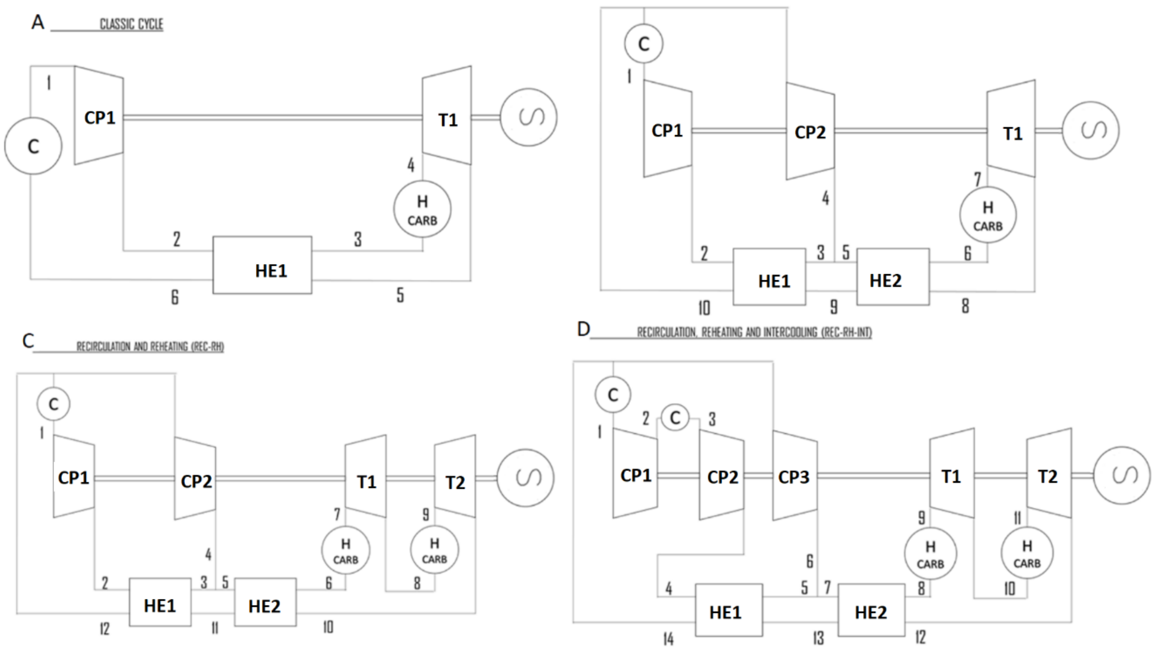

Fig. 2. Supercritical CO_2 cycles

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
hA (J/kg)	-98084	-47731	412609	714879	531514	71174								
hB (J/kg)	-98084	-47802	177388	177388	177430	469844	714888	531709	239253	71057				
hC (J/kg)	-98084	-47741	177730	177730	177703	561814	714880	617614	718936	623914	239831	71174		
hD (J/kg)	-98084	-94158	-148030	-114006	127087	127087	127152	555213	714882	615328	719024	626307	198180	33183
sA (J/kgK)	-1060	-1045	-189	168	187	-583								
sB (J/kgK)	-1060	-1045	-559	-559	-559	-113	168	188	-239	-583				
sC (J/kgK)	-1060	-1045	-559	-559	-559	0	168	177	286	295	-238	-583		
sD (J/kgK)	-1060	-1059	-1229	-1218	-655	-655	-655	-8	168	177	289	298	-314	-677

Table 1. Entalpies and entropies of the working fluid (CO_2) in the four plants

3. Design improvement by exergoeconomic analysis

The exergoeconomic analysis is iteratively applied to the components of the plant, as shown in Figure 3. Each step is conducted without the need to know the cost functions, in order to emulate the case in which costs are discrete. The procedure consists of the following steps:

1) First the optimization of a configuration is conducted considering the plant efficiency as the objective function to maximize. The free variables in the optimization are the typical design variables encountered in power plants. In the case of configuration D shown in Figure 2, these are: the pressure ratio in compressors 1 and 2, the pressure ratio in turbine 1, the mass flow rate fraction to compressor 3, the inlet temperature in turbines 1 and 2, the outlet temperature in coolers 1 and 2, the minimum temperature difference at the outlet of heat exchangers 1 and 2.
   Despite the isentropic efficiencies can be also considered as design variables, these are set to typical values that are considered in the literature: 0.88 for the compressors and 0.92 for the turbine (see for example [15]). Similarly, an electrical efficiency of 0.95 has been considered for the generator. At this stage, the exergy flows associated with all the energy flows exchanged between the various components are calculated.
2) The total cost of investment of the various components are calculated. This step is here performed using cost functions; this option allows one to compare the results of the design improvement with those obtained with mathematical optimization. In fact, mathematical optimization needs the use of cost functions when an economic objective function is adopted. Instead, design improvement needs, at each iteration of the procedure, knowledge of the costs associated with a specific plant design. This means that cost functions are actually not necessary. The costs of components could be calculated based on a detailed design performed on the basis of the results obtained at the first step and considering the required amount of materials, the production and assembling processes, etc.
   The cost functions adopted for calculations are taken from [16]. The general form of these functions are:

$$C_i = F_{M,i} \cdot 10^{(K1 + K2 \log 10\ (X_i) + K3[\log 10(X_i)]^2)} \quad (3)$$

   where C_i is the investment cost of the i-th component, $F_{M,i}$ is a factor associated with the material that is used, X_i is a characteristic parameter associated with the size of component (the heat transfer surface for the heat exchangers and the mechanical power for the turbines and the compressors) and K_1, K_2 and K_3 three coefficients which value is shown in Table 2. The X quantities are directly obtained from the system model. In the case of heat exchangers, the mean logarithmic temperature difference method has been adopted in order to relate the heat transfer surface to the heat flux.

Component	K_1	K_2	K_3	F_M
Compressor	2.2897	1.3604	-0.1027	3.8
Turbine	2.7051	1.4398	-0.1776	5.9
Heat exchanger	4.6656	-0.1557	0.1547	2.4

Table 2. Parameters adopted in the cost functions

3) A thermoeconomic analysis at a component level is performed for the optimal design. In the literature there are various methods to perform this step. Here the approach proposed by Lozano and Valero is adopted [17].

- The cost balance of each component is written as

$$\sum_{j=1}^{n} \Psi_j \cdot c_j + Z_i = 0 \qquad \text{(i=1,2,...m)} \qquad (4)$$

where subscript i refers to the various (m) components, Ψ_j indicates the general exergy flow entering (+) or exiting (-) the component, c_j is the unit cost of the j-th exergy flow (in €/kJ) and Z_i is the investment cost rate associated with the i-th component. Exergy flows are calculated as:

$$\Psi_j = m_j \cdot \left(h_j - h_0 - T_0 \cdot (s_j - s_0)\right) \qquad \text{for fluid streams} \qquad (5)$$

$$\Psi_j = W_j \qquad \text{for mechanical/electric power} \qquad (6)$$

$$\Psi_j = \Phi_j \cdot \left(1 - \frac{T_0}{T_j}\right) \qquad \text{for heat fluxes} \qquad (7)$$

where m is the mass flow rate, W is the power, Φ is the heat flux and subscript 0 refers to the environment conditions.

The role each component plays in the system is expressed by defining the products that are obtained from the thermodynamic process occurring in its control volume and the resources that are used. Possible losses, i.e. physical streams that are released in the environment, can be also identified. Products, resources and losses are defined using all the exergy flows that are exchanged between the various components and with the environment. This representation of the system is usually called the productive structure. Once this is available, the cost of each exergy flow is obtained by applying the following common assessment rules:

- The unit cost associated with exergy flows entering the system from the environment is assumed equal to their price, unless a better evaluation is possible.
- The unit cost associated with losses is assumed equal to 0, unless a different evaluation is more appropriate (e.g. waste streams that require post-treatment in a different plant).
- In the case the resource of a component is defined as the difference between two (or more) flows, the unit cost of these flows is the same.
- In the case the product of a component is defined as the summation of two (or more) flows, the unit cost of these flows is the same.

With these rules a number of linearly independent equations equal to the number of flows is obtained, therefore the unit cost of the various flows can be calculated. Starting from these values it is possible to calculate the unit cost of the productive flows, namely resources and products. Table 3 shows the way this calculation can be performed.

Type of productive flow	Definition	Unit cost of the productive flow
Resource	$\Psi_a - \Psi_b$	$c_F = c_a = c_b$
Resource	$\Psi_a + \Psi_b$	$c_F = \frac{c_a \cdot \Psi_a + c_b \cdot \Psi_b}{\Psi_a + \Psi_b}$
Product	$\Psi_a - \Psi_b$	$c_P = \frac{c_a \cdot \Psi_a - c_b \cdot \Psi_b}{\Psi_a - \Psi_b}$
Product	$\Psi_a + \Psi_b$	$c_P = c_a = c_b$

Table 3. Calculation of the unit cost of productive flows

4) The exergoeconomic analysis is then applied to the optimal plant and the critical points are analyzed. This step is performed relying on three indicators calculated for each component: the total cost rate, the relative cost difference and the exergoeconomic factor.

<u>Total cost rate of the component</u>. The total cost rate of the component is evaluated taking into account both the contribution of the initial investment cost rate Z and the cost of the irreversibilities in the process occurring in the component. The latter is obtained by multiplying the exergy destruction rate Y_i resulting from the exergy analysis performed at step 1 times the unit cost of the resource for the component c_F (see Table3).

$$C_{TOT} = Z + Yi \cdot c_F \quad (8)$$

The total cost represents the importance, from an economical viewpoint, of a component within a system. A comparison of the total costs for all the components allows one to evaluate the most relevant components to be improved. In fact, the total cost rate accounts for the impact of possible changes in the design of a component: the higher the total cost rate, the higher the impact of a change on the overall plant.

<u>Relative cost difference</u>. This parameter is calculated as the difference between the unit cost of the product of a component cP and the unit cost of its resource c_F and it is then normalized with respect to the unit cost of the resource:

$$r = \frac{c_P - c_F}{c_F} \quad (9)$$

When the difference between the cost of the product and the cost of the resource is high, it means that the component acts in an expensive manner, therefore the product results as very expensive with respect to the resource that is processed. Large values of the parameter r are thus associated to components that are not suitable for the system. Such behavior can be due to a) a too large investment cost for that component in the considered system or b) a too large irreversibilities generated during the operations.

<u>Exergoeconomic factor</u>. The exergoeconomic factor is defined as the ratio between the investment cost Z and the total cost C_{TOT} resulting from Eq. 2. This quantity thus results as:

$$f = \frac{Z}{Z + Yi \cdot c_F} \quad (10)$$

The value of f can vary between 0 and 1. When its value is closer to 1, it means that the investment cost plays a crucial role in the total cost of the component, C_{TOT}. In such cases, the improvement strategies should be focused on the reduction of the investment cost. On the other hand, when the exergoeconomic factor is closer to 0, it means that the investment cost is much smaller than the cost of irreversibilities, therefore the suggested improvement strategy should be oriented towards an increase in the component efficiency.

Through knowledge of the three parameters C_{TOT}, *r* and *f*, it is possible to define a strategy to improve system. At first, the total cost can be used to identify the component where an improvement is expected to cause a high impact. For this reason, components should be ranked in decreasing order of the total cost rate C_{TOT}, so that changes with large impact are preferred. Then it is important to observe the components with high values of C_{TOT} that also present a high value of r. This allows identifying the components which are more relevantly affected by criticalities. The parameter f is then used to analyze which is the reason for the criticality in the selected component. This allows deciding possible improvement directions, namely to reduce the investment costs and accept consequent reductions in the efficiency or to increase the efficiency and thus accept consequent increases in the investment costs. The actions that are performed might involve a variation in the plant configuration, e.g. the elimination of the selected component or the separation of the process performed in that component in two stages, or the variation of one or more design variables affecting the process performed by the selected component.

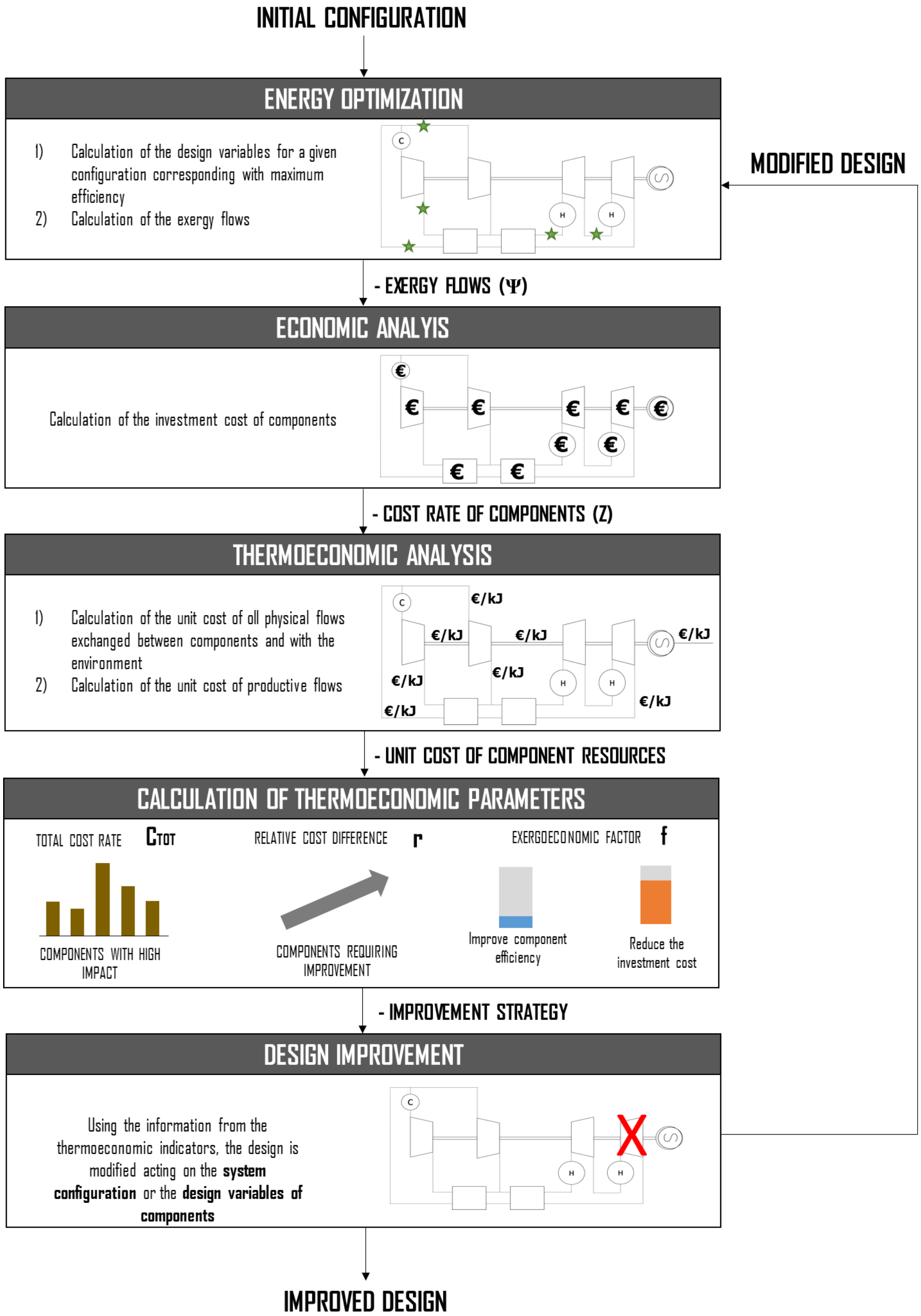

Fig. 3. Schematic of the iterative exergoeconomic method

4. Iterative design improvement

The analysis starts with the Brayton cycle with recirculation, re-heating and intercooling (configuration D) because the configurations A-C can be obtained from it by properly removing some of the components. In addition, this is the configuration able to obtain the largest efficiency. The values of the design variables corresponding with the optimal thermodynamic design are selected.

The exergetic, economic and thermoeconomic analysis for the initial configuration is performed. As already discussed in the previous section, the economic analysis is conducted without need of cost functions (even if these are here adopted in order to compare the results with those obtained with mathematical optimization), thus mimicking the need for a detailed design to obtain the cost of components. The unit cost of electricity for this case is 0.0899 €/kWh.

In the case of complex systems it is recommended to start the analysis by grouping the components by functions. This allows one avoiding the potential issue that might occur when a thermodynamic transformation is shared by various smaller components instead of being concentrated in a single one. In this latter case, the extensive indicator (the total cost rate) is reduced by the smaller size of the components. At this first stage, only the main components are considered: compressors, coolers, recovery heat exchangers, heaters and turbines.

The results of exergoeconomic analysis are presented in figure 4, where the three indicators are shown. The figure shows that the turbines and the recovery heat exchangers are the components with the largest total cost rate, respectively more than 2.4 times and 1.8 times with respect to that of the coolers and compressors. The relative cost difference of the turbines is double than that of the heat exchangers, therefore the turbines should be further analyzed to improve the system configuration. Before analyzing this group of components, it is worth mentioning the case of the coolers. Despite their total cost rate is not so large, their relative cost difference is. This is due to the fact that these are dissipative components and the exergy of their products is very small (it would be zero in the case the heat were directly discharged in the environment). The large thermodynamic irreversibility associated with thermal dissipation is the reason why the unit cost of their product and, correspondingly, the relative cost difference is very large (the exact value would be 6.65, but in the figure the maximum value has been limited to 1.2 in order to allow better visualization of the results of the various components). In the selected productive structure, the product of the coolers has been considered as an additional resource to the compressors they are connected to. In fact, the goal of the coolers is to reduce the temperature of the gas before its compression. The fact that, despite this assumption, the indicators associated with the compressors are not particularly large compared with that of the other components indicates that the decision on the components to be improved at this first stage is robust.

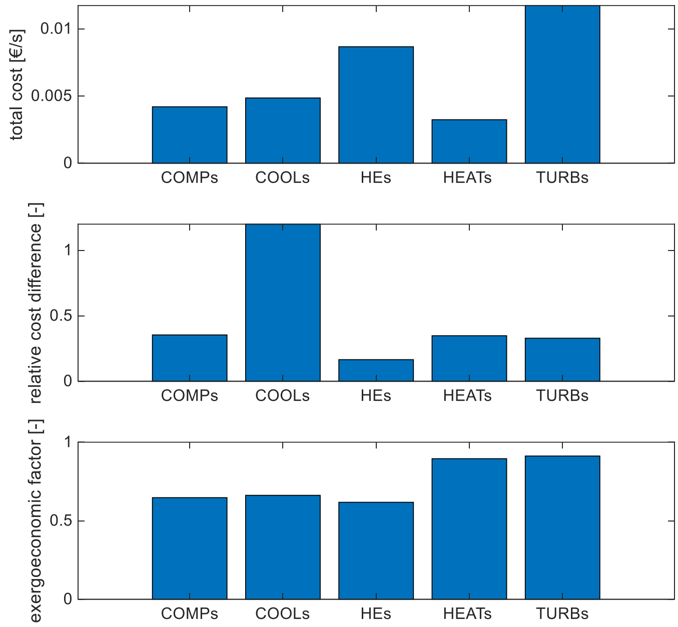

Fig. 4. Exergoeconomic analysis at a component-group level of configuration D

The analysis can be then performed at a component level. Results are shown in figure 5. The two turbine sections present similar values of the exergoeconomic indicators, therefore the action that should be taken is expected to involve both of them. The exergoeconomic factor is about 0.91, which means that the investment cost should be reduced. To achieve this result, the expansion should be performed in a single section instead of two. This also means that the also the second heater should be eliminated.

This configuration (configuration E) is not part of the initial set shown in Figure 1, thus revealing one of the advantages of the exergoeconomic method: it allows exploring configurations that might be outside the design domain. This would not be possible for instance in the case of a synthesis problem based on the assumption of an initial superstructure of the system.

When this configuration is optimized considering the maximum efficiency as the objective function (coherently with the assumption of not using cost functions in the optimization), an efficiency of 0.481 is obtained (3.1% less than the initial configuration) while the corresponding unit cost of electricity is 0.0826 €/kWh (8.1% less than the initial configuration).

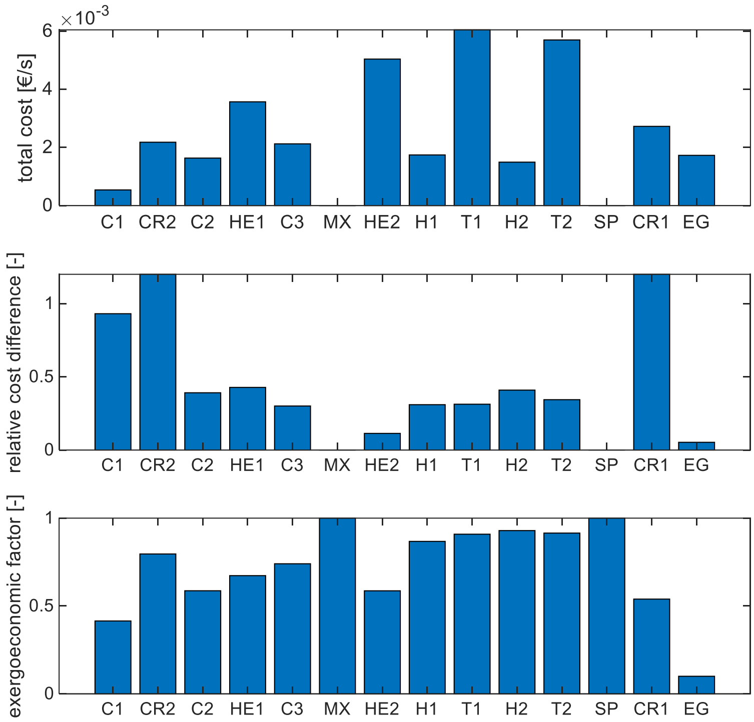

Fig. 5. Exergoeconomic analysis at a component level of configuration D

Results of the exergoeconomic analysis performed for this configuration are shown in Figure 6, where the groups of components are shown. A comparison of these results with those shown in Figure 4 shows that the total cost of the turbines has significantly decreased, thanks to the expansion in a single step instead of two steps. This reduction is mainly due to the investment cost rate, which is decreased of 20.1% (from 0.0116 €/s to 0.0093 €/s). The group of components to be considered for further design improvement is that of the heat exchangers, which presents the second largest total cost rate, just slightly less than the turbines. The relative cost difference is comparable with that of the other groups of components. In all cases, the exergoeconomic factor is larger than 0.5, therefore the action to be performed for design improvement should be focused on the reduction of the investment cost. In this case, it is possible to join the two heat exchangers in a single one. This modification also involves the elimination of the by-pass flow of CO_2 (flow 6 in figure 3D) and the corresponding compressor. This component is also the compressor with the largest total cost rate (about 50% of its group of components, as shown in figure 6), therefore the design change is expected to reduce the investment cost significantly.

Also the new configuration (configuration F) is not included in the initial set. Its optimized design has an efficiency of 0.420 (15.4% less than the initial configuration) and a unit cost of electricity of 0.0756 €/kWh (15.8% less than the initial configuration). The investment cost rate for the heat exchangers and compressors reduces of 40.3% (from 0.0089 €/s to 0.0053 €/s). In particular, a reduction of 51.4% is obtained in the heat exchangers thanks to the larger mean logarithmic temperature difference (which causes a significant reduction in the plant efficiency). In contrast, reduction in the investment cost rate for the compressors is only 19.8%, due to the fact that the remaining compressors have to process a larger mass flow rate.

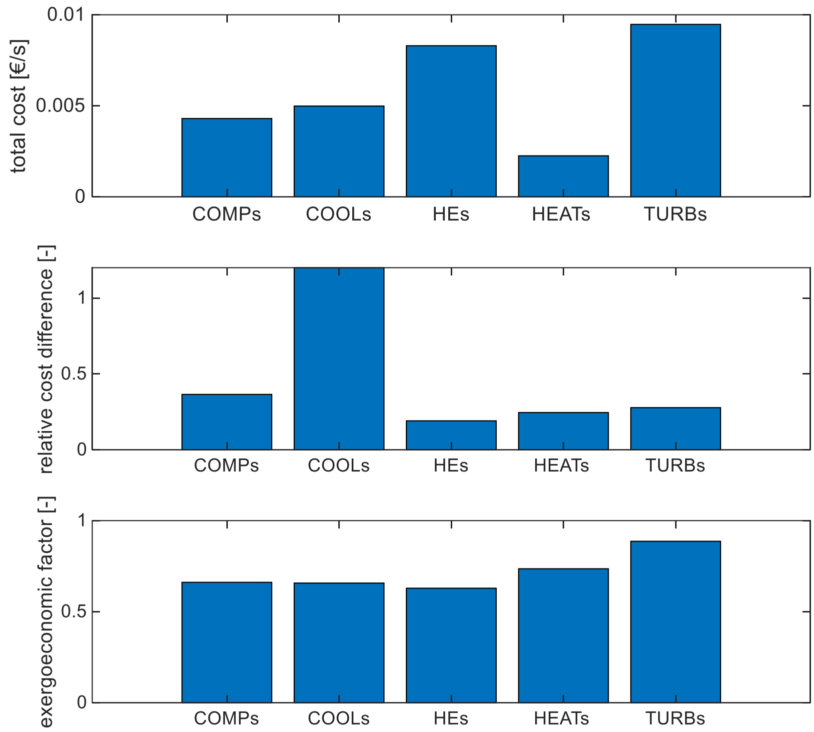

Fig. 6. Exergoeconomic analysis at a component-group level of configuration E

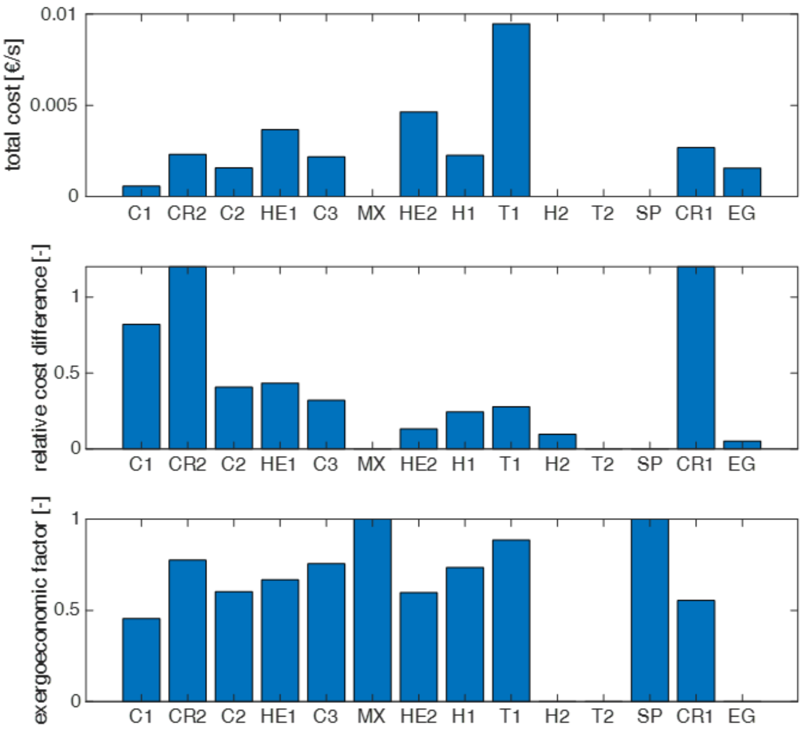

Fig. 7. Exergoeconomic analysis at a component level of configuration E

Further improvements in the design can be obtained by applying the exergoeconomic method. In this case, it is interesting to show the results of the analysis at a component level for configuration F. These are shown in figure 8. The analysis can be now focused on the compressors, since this group of components is ranked third in terms of total cost rate (considering that the coolers are actually directly associated with the compressors) and their relative cost difference is the second one. Figure 8 shows that there is a significant difference between the total cost rate of the two compressors (C1 and C2). A possible improvement can be then obtained by reducing this difference.

The expected results of this improvement are discussed in the next section, where the procedure is compared with mathematical optimization.

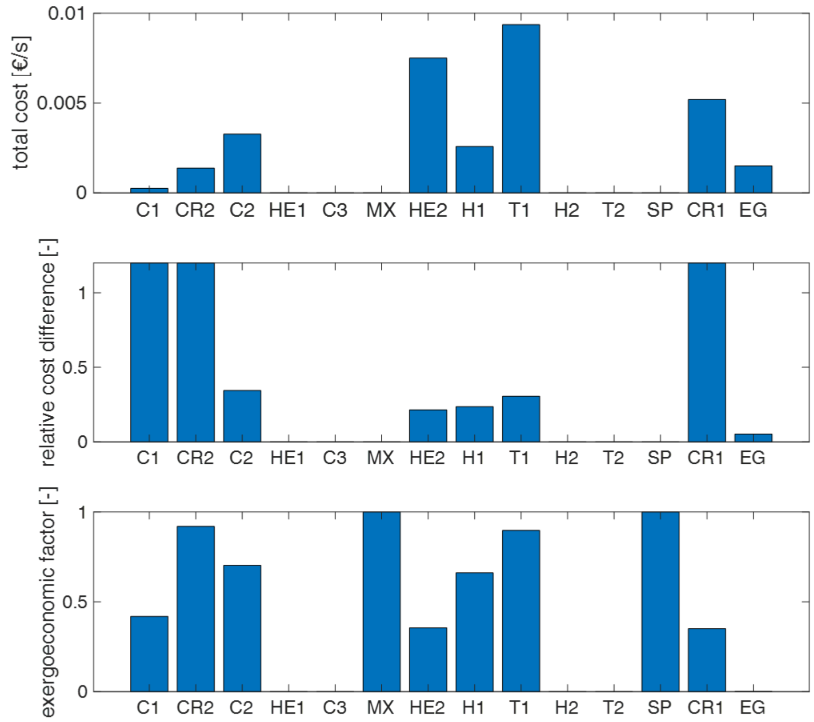

Fig. 8. Exergoeconomic analysis at a component level of configuration F

5. Design improvement vs. optimization

In this section, cost functions are used to perform a mathematical optimization of the system, considering the unit cost of electricity as the objective function to minimize. Optimization is applied to all configurations A-F and results are presented in figure 9, where points marked with "–e" are the results of the economic optimization. The results obtained by applying the design improvement procedure are also presented. It is interesting to observe that configuration F obtained from the design improvement presents performance indicators higher than the economic optimization of configurations B-E. Concerning the configuration F-e, this presents an efficiency 2.8% smaller than configuration F and a unit cost of electricity 3.1% smaller. It is interesting to analyze the differences between these two designs of the same configuration. The main point is related with the pressure ratio in the two compressors: in configuration F, the first pressure ratio is 2.8 times smaller than the second one, while in the second case the difference is reduced to 2.1 times. In the first case the effect of the fluid properties on the compression efficiency is preferred, while in the second case the lower investment cost is preferred. The results in terms of exergoeconomic indicators are presented in figure 10, which shows that the total cost rate of the two compressors is closer than in the case of configuration F.

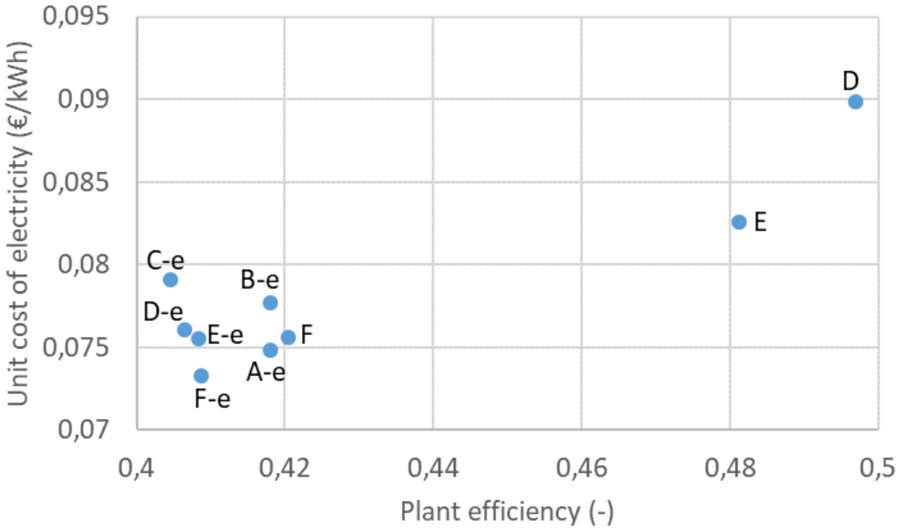

Fig. 9. Efficiency and unit cost of electricity of the examined configurations

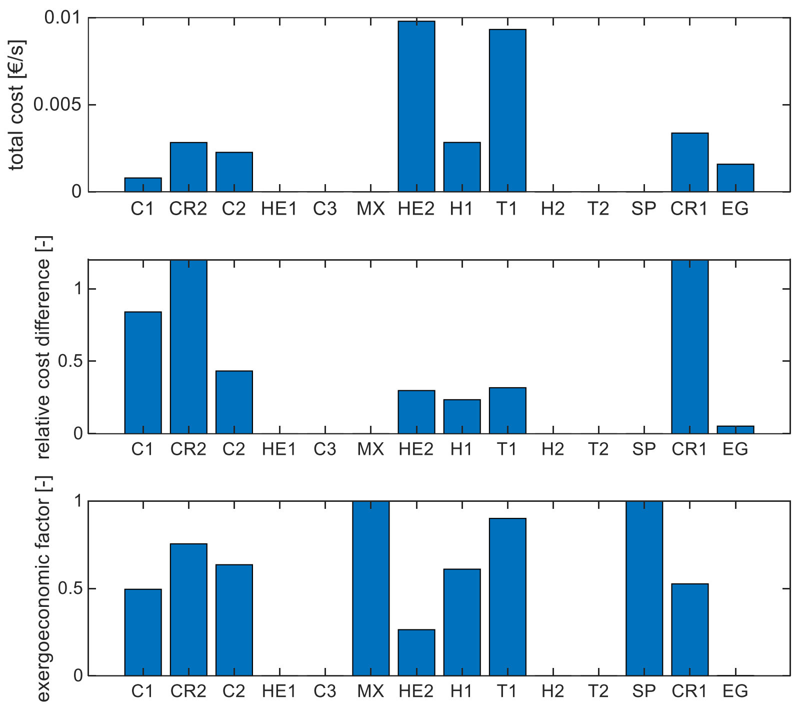

Fig. 10. Exergoeconomic analysis at a component level of configuration F-e

6. Conclusions

In this paper, the design improvement of a Brayton power cycle with supercritical CO2 to be integrated with the discharging section of a thermochemical storage unit is proposed. The analysis is conducted using the exergoeconomic approach, with the goal of investigating possible improvements in the system that can be obtained acting on both the system configuration and the design of components. Some of the advantages of this method are the flexibility while analyzing plant configurations and the possibility to perform the analysis even in the case cost functions are not available. This means that the analysis can rely on precise evaluation of costs (when available) instead of estimations from approximate cost functions. Starting from the initial configuration, which is characterized by the highest efficiency between the examined designs, the method highlights the components which mostly affect the unit cost of electricity, suggesting a simplification of the plant configuration. This simplification is iteratively conducted. At last, the exergoeconomic indicators suggest a re-design acting on the design parameters of the system, without further modifications on the configuration.

Results show that the iterative application of the method allows one reaching performance close to those obtainable with mathematical optimization. This allows demonstrating that the exergoeconomic design improvement is a powerful tool that can be effectively used to investigate novel technologies or novel applications of energy systems.

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Annex 1

The following tables show the thermodynamic conditions for the optimal configurations obtained during the design improvement procedure and the main thermoeconomic variables associated with the various components.

Point	T (°C)	p (bar)	h (kJ/kg)	s (kJ/kgK)	m (kg/s)
1	40.0	78	-98.1	-1.060	7.26
2	53.7	94.5	-91.3	-1.058	7.26
3	40.0	94.5	-182.5	-1.344	7.26
4	70.5	216.6	-160.9	-1.336	7.26
5	191.5	216.6	73.7	-0.742	7.26
6	191.5	216.6	73.7	-0.742	11.74
7	191.5	216.6	73.7	-0.742	4.48
8	578.2	216.6	562.4	0.027	11.74
9	700.0	216.6	715.9	0.196	11.74
10	628.0	129.4	629.5	0.204	11.74
11	700.0	129.4	719.3	0.300	11.74
12	630.1	78	635.4	0.308	11.74
13	211.6	78	146.7	-0.415	11.74
14	90.5	78	1.7	-0.761	11.74
15	90.5	78	1.7	-0.761	7.26
16	90.5	78	1.7	-0.761	4.48

Table A1. Thermodynamic variables for configuration D (optimal design)

Component	Type	Irr (kW)	Z (€/s)	cF (€/kWh)	cP (€/kWh)
1	Compr. 1	5.6	0.0003	0.21	0.37
2	Cool. 2	31.3	0.0018	0.06	0.47
3	Compr. 2	16.0	0.0008	0.13	0.19
4	HE1	73.7	0.0024	0.06	0.09
5	Compr. 3	24.6	0.0016	0.09	0.11
6	Mix.	0.0	0.0000	0.08	0.08
7	HE2	158.1	0.0032	0.06	0.07
8	Heat. 1	47.8	0.0016	0.02	0.02
9	Turb. 1	29.3	0.0054	0.07	0.09
10	Heat. 2	18.7	0.0014	0.02	0.03
11	Turb. 2	28.3	0.0053	0.06	0.08
12	Split	0.0	0.0000	0.06	0.06
13	Cool. 1	63.4	0.0015	0.06	0.46
14	Inverter	73.5	0.0000	0.09	0.09

Table A2. Thermoeconomic variables of the various components in configuration D (optimal design)

Point	T (°C)	p (bar)	h (kJ/kg)	s (kJ/kgK)	m (kg/s)
1	40.0	78.0	-98.1	-1.060	7.03
2	53.4	94.2	-91.4	-1.058	7.03
3	40.0	94.2	-181.3	-1.340	7.03
4	76.6	248.0	-154.3	-1.330	7.03
5	213.7	248.0	96.4	-0.717	7.03
6	213.7	248.0	96.4	-0.717	10.91
7	213.7	248.0	96.4	-0.717	3.88
8	495.0	248.0	456.4	-0.131	10.91
9	700.0	248.0	714.9	0.168	10.91
10	544.5	78.0	531.5	0.187	10.91
11	544.5	78.0	531.6	0.187	10.91
12	544.5	78.0	531.6	0.187	10.91
13	233.7	78.0	171.6	-0.365	10.91
14	96.6	78.0	10.1	-0.738	10.91
15	96.6	78.0	10.1	-0.738	7.03
16	96.6	78.0	10.1	-0.738	3.88

Table A3. Thermodynamic variables for configuration E (optimal design)

Component	Type	Irr (kW)	Z (€/s)	cF (€/kWh)	cP (€/kWh)
1	Compr. 1	5.4	0.0003	0.21	0.38
2	Cool. 2	29.6	0.0018	0.06	0.48
3	Compr. 2	19.3	0.0010	0.12	0.17
4	HE1	71.1	0.0024	0.06	0.09
5	Compr. 3	24.3	0.0016	0.08	0.10
6	Mix.	0.0	0.0000	0.08	0.08

7	HE2	108.2	0.0028	0.06	0.07
8	Heat. 1	121.0	0.0017	0.02	0.02
9	Turb. 1	63.1	0.0084	0.06	0.08
10	Heat. 2	0.0	0.0000	0.02	0.02
11	Turb. 2	0.0	0.0000	0.06	0.00
12	Split	0.0	0.0000	0.06	0.06
13	Cool. 1	71.2	0.0015	0.06	0.45
14	Inverter	71.4	0.0000	0.08	0.08

Table A4. Thermoeconomic variables of the various components in configuration E (optimal design)

1	40.0	78.0	-98.1	-1.060	10.91
2	43.3	81.9	-96.4	-1.060	10.91
3	40.0	81.9	-114.5	-1.117	10.91
4	114.4	248.0	-70.9	-1.104	10.91
5	114.4	248.0	-70.9	-1.104	10.91
6	114.4	248.0	-70.9	-1.104	10.91
7	114.4	248.0	-70.9	-1.104	0.00
8	452.2	248.0	403.1	-0.202	10.91
9	700.0	248.0	714.9	0.168	10.91
10	544.5	78.0	531.5	0.187	10.91
11	544.5	78.0	531.6	0.187	10.91
12	544.5	78.0	531.6	0.187	10.91
13	134.4	78.0	57.6	-0.616	10.91
14	134.4	78.0	57.6	-0.616	10.91
15	134.4	78.0	57.6	-0.616	10.91
16	134.4	78.0	57.6	-0.616	0.00

Table A5. Thermodynamic variables for configuration F (optimal design)

Component	Type	Irr (kW)	Z (€/s)	cF (€/kWh)	cP (€/kWh)
1	Compr. 1	1.7	0.0001	0.31	1.38
2	Cool. 2	7.3	0.0013	0.05	0.84
3	Compr. 2	42.5	0.0023	0.08	0.11
4	HE1	0.0	0.0000	0.00	0.00
5	Compr. 3	0.0	0.0000	0.00	0.00
6	Mix.	0.0	0.0000	0.07	0.07
7	HE2	317.1	0.0027	0.05	0.07
8	Heat. 1	177.6	0.0017	0.02	0.02
9	Turb. 1	63.1	0.0084	0.05	0.07
10	Heat. 2	0.0	0.0000	0.02	0.02
11	Turb. 2	0.0	0.0000	0.05	0.00
12	Split	0.0	0.0000	0.05	0.05
13	Cool. 1	220.1	0.0018	0.05	0.39
14	Inverter	75.3	0.0000	0.07	0.08

Table A6. Thermoeconomic variables of the various components in configuration F (optimal design)

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