Optimal Indirect Integration of Steam Rankine Cycles in Concentrated Solar Power Coupled with Thermochemical Storage

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Abstract. Storing energy in thermo-chemical form is a promising alternative for renewable energy sources and one of the fields that could exploit its advantages is constituted by Concentrated Solar Power (CSP). High efficiencies, high energy densities, long-term storage and dispatchability in power generation could be tackled with the employment of a Calcium-Looping in a central tower CSP plant. Although Brayton cycles based on sCO_2 and He probably represent the most efficient option, it can be interesting to investigate the integration of Steam Rankine cycles because of the lower costs and the higher stage of development that characterize this technology. The present work has the purposes of studying this kind of integration and analyze the system in both energy and economic terms. To perform a comprehensive investigation, the power block layout and its thermal feeding strategy are included in the analysis and optimized. In addition, a multi-objective optimization is performed to evaluate possible compromises between the two most important aspects related to the entire power plant.

1 Introduction

The application of Thermal Energy Storage (TES) brings significant advantages to Concentrated Solar Power (CSP) [1]. This allows compensating the variation of solar radiation, making possible to have a dispatchable generation [2] and allows to design a plant with components having smaller nominal sizes, fact that helps to reduce the cost of electricity [3]. The central tower layout is a very interesting configuration since it presents high efficiencies and relevant operating conditions [4]. At the same time, the Thermo-Chemical Energy Storage (TCES) operating with Calcium-Looping (CaL) rose a great interest during the recent period [5]. The expected advantages [6] that could be obtained with the adoption of this system are mainly due to high operating temperatures [7] and null thermal losses. The process is based on a reversible reaction: when calcination occurs, the $CaCO_3$ is decomposed in CaO and CO_2 thanks to the absorption of solar radiation, while this energy amount is released by the inverse reaction, named carbonation. The chemical reaction is reported in Eq. 1.

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$$CaCO_{3\,(s)} + HEAT \leftrightarrow CaO_{(s)} + CO_{2\,(g)} \qquad \Delta H_r^0 = \pm 178\ kJ/mol \tag{1}$$

Phenomena influencing the reaction kinetics [8], equilibrium conditions [9] and some aspects that introduce non-idealities [10] have to be considered, if it is intended to execute a consistent analysis. Therefore, operating temperatures and pressures are set coherently to the reaction physics and the term called CaO conversion (X) is introduced to consider the process of deactivation characterizing calcium oxide.

The CaL integration in a central tower CSP plant can be either direct or indirect. In case of direct integration, CO_2 acts both as a chemical reactant (it is inserted in the carbonator) and as a power fluid, since it produces electrical power by expanding when exit the reactor. In case of indirect integration, electricity is produced employing a separate power cycle, thermally fed with a heat transfer during the discharging process.

Many aspects related to this kind of TCES for CSP are investigated in previous studies that can be found in scientific literature. Regarding the analysis of the materials employed in the process, the evaluation of CaO precursors is made in [11,12] and the deactivation phenomena is investigated for the creation of a predictive model in [8,13]. The process synthesis and system design are investigated in [14,15], operating conditions are carefully analyzed and optimized in [16] and the Heat Exchanger Network (HEN) for the discharging plant section is studied in [17] with pinch analysis. A TCES based on CaL is considered for storing energy surplus coming from photovoltaic [18] or hybridized with this technology [19]. A comprehensive outlook of this kind of power system is exposed in [20].

According to the analysis present in scientific literature, the most investigated configuration is the direct integration and a smaller number of works is devoted to the more complex field of indirect integration. In this context, the exploitation of Steam Rankine Cycles (SRC) is an interesting aspect that still requires a deeper investigation. In fact, although lower efficiencies are expected with respect to Brayton cycles (supercritical CO2 or He), the lower investment costs, the higher reliability and development stage characterizing SRCs are important aspects that can represent a non-negligible advantage on the competing technologies. The indirect integration of a Steam Rankine Cycle is optimized in energy terms in [21], while a different layout is proposed in a study related to the carbonator modelling [22].

The purposes of the present analysis are to study the SRCs indirect integration in a central tower CSP plant with TCES based on Calcium-Looping. The investigation is intended to be conducted both in energy and economic terms, taking into account the most significant aspects characterizing this kind of system. A multi-objective optimization is performed to evaluate possible compromises between plant efficiency and costs. The influence of some important parameters is discussed and novel plant configurations are presented.

2 Case study

A schematic of the plant considered in the present analysis is shown in Fig. 1. The process starts when the $CaCO_3$ is taken from the storage, preheated and sent to the calciner, where is converted in CaO and CO_2 absorbing the solar radiation reflected by the heliostat field and the Compound Parabolic Collector (CPC). The two products are therefore cooled and sent to the vessels; concerning the CO_2, the Storage Compressor (SC) allows to store the gaseous compound at high pressure (75 bar) and reduce the vessel volume. The opposite process is conducted extracting the two compounds from their storages (the CO_2 has to be expanded with the Storage Turbine, ST) and preheating them to enter the carbonator operating at ambient pressure. The reactor outflows are therefore cooled down and the $CaCO_3$ is stored, while the carbon dioxide is recirculated in the process thanks to the Blower (B).

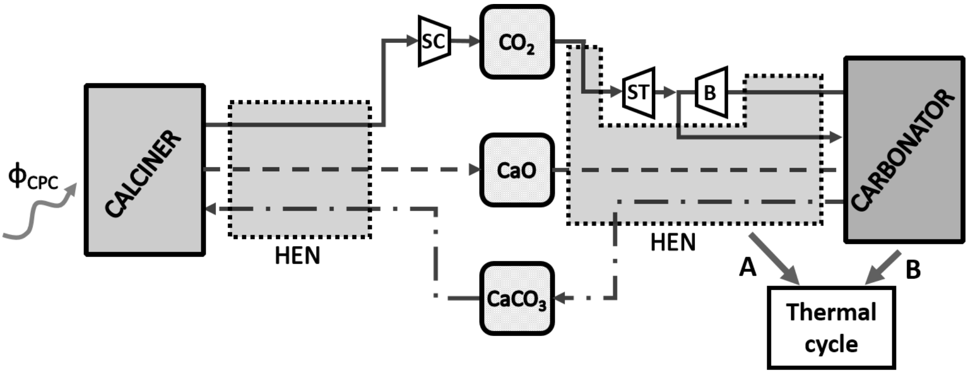

Fig. 1. Simplified representation of the system considered in the present analysis.

Two alternatives for the heat recovery in the power block are included in the present analysis: a Heat Recovery on the Carbonator Products (HRCP, marked with A in Fig. 1) and a Heat Transfer on the Carbonator Wall (HTCW, marked with B in Fig. 1). It is possible to choose only one or both the power block thermal feeding strategies and finding the most suitable configuration is one of the tasks for the optimization.

3 Integration model

The method followed in the present work is selected in order to face the different aspects characterizing the process and to perform a comprehensive analysis. This is made possible by the exploitation of different strategies for the synthesis and design optimization as reported in Fig. 2, where the process structure is shown in form of flow chart. The following subsections are devoted to the discussion of the single steps that compose the process.

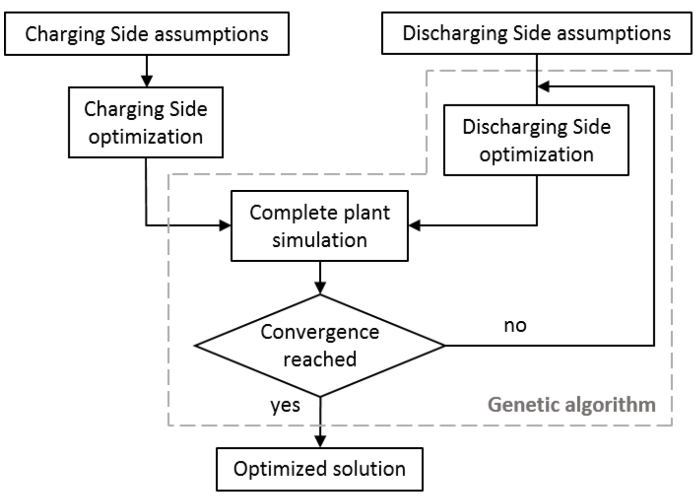

Fig. 2. Optimization process flow chart.

3.1 Discharging process: Thermal cycle

The Power Block (PB) size is set to 2 MWe with the aim of evaluating a pilot plant, coherently with the early stage of development of this technology. The SRC layout is also optimized by adding some independent variables, related to the presence/absence of the components.

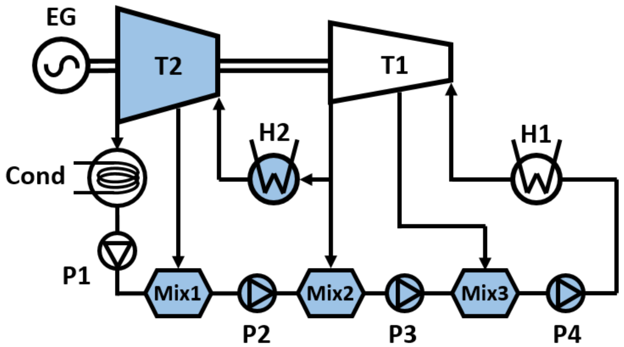

Fig. 3. Complete power block layout.

The most complex configuration that the cycle can reach is presented in Fig. 3; a maximum of two turbines with no more than one bleed for each is set according to the power block size. Then, depending on the values reached by the optimization variables, the components colored in blue can be removed by the algorithm. Open feedwater heaters with saturated outlet conditions are considered for the present study. As a simplifying assumption, the deaerator is not included. The convenience of a specific thermal cycle configuration is therefore evaluated by the algorithm according to both energy and economic criteria.
The independent variables related to the power block are: first turbine inlet pressure (T1IP), turbines inlet temperature (TIT), reheat existence (RehEx), intermediate pressure (p_{int}), bleeding in turbine 1 (bT1), bleeding pressure of turbine 1 (bpT1), intermediate bleeding (bint), bleeding in turbine 2 (bT2), bleeding pressure of turbine 2 (bpT2). The assumptions and the variables ranges are estimated according to [15,21,23,24].

3.2 Discharging process: Carbonator side

The HEN synthesis, the optimization of operating conditions for primary components (Storage Turbine, Blower, carbonator) and the strategy for the heat recovery in the power block are the most important aspects related to the Carbonator Side (CarbS). They are strictly related between them since they have a mutual influence and they are very important for the evaluation of the plant costs and performance. As a result, the HEATSEP method [25,26] is selected to optimize the discharging process. This methodology relies on the contemporary optimization of the two aspects previously cited; in particular, heat transfer is analyzed by using pinch analysis and the other parameters are optimized with a genetic algorithm. It is worth to mention that the constraint of null external heating is addressed to the process in order to exploit only solar radiation as energy source.
To enlarge the analysis extension, the heat recovery in the power block is perfromed in different steps: heat exchange in the economizer, evaporator, superheater and reheater. The possibility to perform a HRCP or HTCW is evaluated for any of these heat transfer stages. Furthermore, the other variables to optimize related to the carbonator side are: carbonator temperature (T_{carb}), CaO temperature at the carbonator inlet ($T_{CaO,in}$), CO2 temperature at the carbonator inlet ($T_{CO2,in}$), storage turbine inlet temperature (STIT), blower inlet temperature (BIT) and economizer/evaporator/superheater/reheater heat transfer on carbonator wall (eco/eva/sup/rehHTCW).

The assumptions and the variable ranges related to the carbonator side are considered according to [8,15,21].

3.3 Charging process

The plant section devoted to the charging process is constituted by the Calciner Side (ClcS) and the Solar Side (SolS). Because of the presence of the three storages, these sections are independent from the rest of the plant; as a result, they can be separately optimized.
The charging side is simulated with a simplified transient approach, with the aim of considering the variable solar radiation reflected by the heliostat field; in this way, the different components are properly dimensioned for the peak (or design) power. The winter solstice is used to set the nominal value in order to guarantee potential for working condition in the entire year. The calciner and solar sides are simulated and optimized as proposed in [27], where the HEN is designed with the pinch analysis while solar calciner and heliostat field are dimensioned through a devoted optimization. The objective function can be either energetic or economic and this double possibility is included in the total optimization process. Once that the charging process is simulated, any information for the evaluation of the entire plant characteristics are collected and it is therefore possible to calculate the total efficiency (η_{tot}) with Eq. 2:

$$\eta_{tot} = \frac{E_{el,tot}}{Q_{sol}} = \frac{\int_{day}\left(\dot{W}_{el,CarbS}(t) + \dot{W}_{el,ClcS}(t)\right)dt}{\int_{day} A_{helio} DNI(t)dt} \tag{2}$$

where $\dot{W}_{el,CarbS/ClcS}$ is the Carbonator/Calciner Side electrical power, A_{helio} is the heliostat field area and DNI stands for Daily Normal Irradiance.
Other benchmarks (such as CaL/CarbS/PB efficiency, defined in [16,28]) are calculated to investigate some aspects related to different portions of the system.

4 Economic evaluation

In order to observe how the investment cost of components is able to influence the system layout, an economic analysis is carried out employing proper cost functions. Thanks to the absence of consumption of external energy sources, the economic analysis is limited to the component prices and other investigations (such as the payback time or the net present value) are excluded since not necessary. Cost functions and other useful assumptions are taken form [27]. In addition, the following hypothesis/considerations are made:

- The price of open feedwater heaters and vessels for the storage of solids (CaO, $CaCO_3$) is not considered since negligible with respect to other components.
- The price of a carbonator with heat transfer on its wall is estimated performing a correction on the reference cost function, in order to consider the different power fluid and operating conditions;
- The carbonator side HEN is predicted by a suitable function developed from preliminary optimization results.

The benchmark assumed for the economic optimization is the specific investment cost (ic_{tot}, computed with Eq. 3). The normalization of the sum of the component costs by the daily electrical production avoids the influence of the plant size variations determined by turbomachinery of calciner and carbonator sides.

$$ic_{tot} = \frac{\sum_i [IC_i]}{E_{el}} \tag{3}$$

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5 Results

The following subsections are devoted to the presentation and discussion of the results obtained with the presented optimization tool. Being independent from the discharging process, the charging plant section reaches the same configuration in any kind of optimization executed: the number of intercooling stages for the carbon dioxide compression is always equal to five (the highest attainable) and the HEN configuration is the simplest as possible, splitting the calcium carbonate and performing the preheat. Therefore, the following paragraphs are more focused on the discharging process and other details related to the solar/calciner sides are not discussed.

5.1 Energy optimization

The energy optimization has the aim of evaluating the layout and operating conditions that allows to achieve the highest plant performance for the design day. With this process, the total system efficiency reaches 16.26%, the Calcium-Looping efficiency is 31.34% and the thermal cycle performance 41.5%. The algorithm converges to the most complex power block layout (reheat and three bleedings). Turbine inlet conditions reach their maximum achievable (540°C and 140 bar) and bleeding pressures are 61.4/23.3/2.4 bar respectively. Thanks to these steam extractions, the water temperature passes from 46.2°C to 277°C.

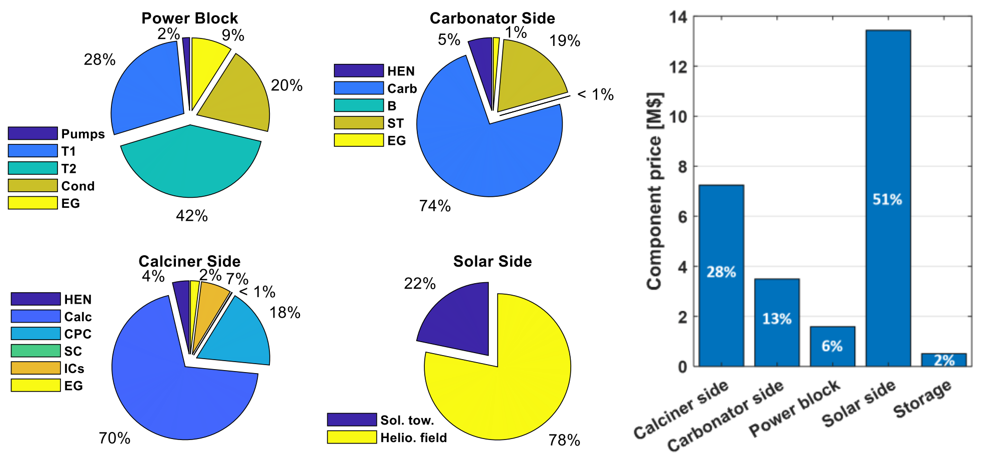

Fig. 4. Energy optimization: percentage of components prices for any plant section (left) and sections cost as a percentage of the total investment (right).

The entire power block thermal feeding is performed on the reactor wall. Consequently, the HEN of the carbonator side has only the aim to preheat the two reactants: CaO enters the reactor at 626°C and CO_2 at 582°C. It is worth to notice that the reactor operating temperature does not reach the maximum set in the optimization but converges to 756°C. In addition, the algorithm finds the following best configuration: CO_2 recirculated in the discharging process becomes null, which means that the carbonation is executed providing the reactants in their stoichiometric proportions (except for the non-reacting CaO due to deactivation). These optimal operating conditions are therefore a direct consequence of the selected layout: the relatively low temperature of the Steam Rankine Cycle influences the carbonator temperature and the fact that the power block thermal feeding is entirely performed in the HTCW configuration makes unnecessary the presence of the gaseous stream at the reactor outlet.

The component costs expressed in percentage for the different plant portions and the section cumulative costs are reported in Fig. 4. As expected, turbines, chemical reactors (31.7 MW for the calciner, 5.7 MW for the carbonator) and heliostat filed (50'398 m^2) are the most expensive elements in their corresponding plant sections. Thanks to the higher number of operating hours and the constant conditions, the carbonator size is smaller with respect to the solar calciner but the presence of heat exchangers at the carbonator wall contribute to rise significantly the price of this component. However, the discharging process operating conditions for SRC the are less demanding with respect to the integration of sCO_2 or He cycles (especially for the difference between carbonation temperature and power fluid conditions) and therefore, for equal sizes, a reactor operating with water is expected to be cheaper with respect to the case of gaseous power fluids.
Observing the cumulative section costs it can be noticed that the plant portion devoted to the charging process constitutes nearly the 80% of the total cost. Therefore, it is possible to say that this section has a great importance in economic terms, but the discharging process remains the most influent part for the plant efficiency. Finally, the specific plant cost reaches a value of 160 $/MJ$_e$.

5.2 Economic optimization

The purpose of the economic optimization is the evaluation of the configuration and operating conditions that minimize the plant specific cost. The system resulting from the economic optimization presents a total efficiency of 15%, a CaL performance equal to 30% and a power block performance that reaches 41.5%; The specific plant cost is equal to 152.4 $/MJ$_e$.

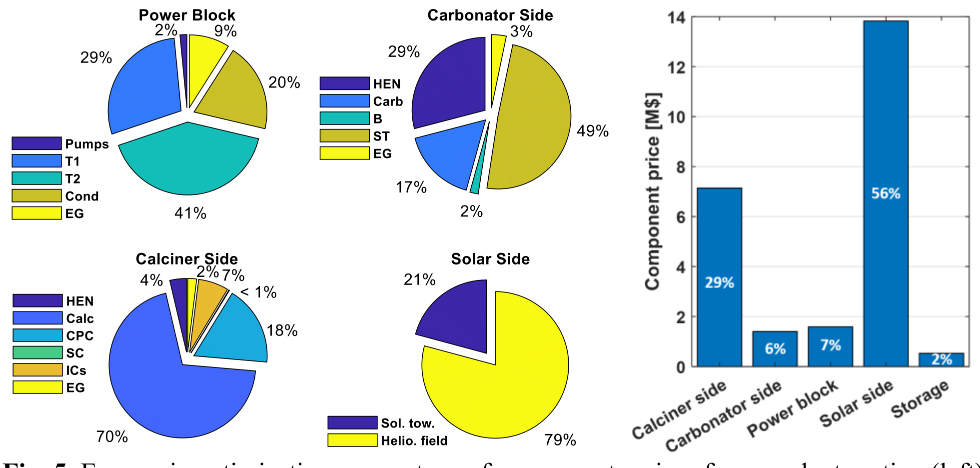

Fig. 5. Economic optimization: percentage of components prices for any plant section (left) and sections cost as a percentage of the total investment (right).

This configuration has both similarities and differences with respect to the case previously analyzed. In fact, the power block layout and operating conditions are nearly identical to the ones found with the energy optimization. This means that a power cycle able to reach the highest performance as possible is convenient even in case of economic optimization. This phenomenon can be explained considering that an efficient discharging process reduces the size (and therefore the prices) of the charging plant section, which represents the most significant contributor to the plant investment cost. A radical difference is instead encountered for the carbonator side and, in particular, for the power block thermal feeding strategy; any stage of the heat transfer is performed in the HRCP configuration.

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Consequently, it can be employed an adiabatic reactor and the management of this component is expected to become easier. However, at the same time, the thermal transfer process occurring in the carbonator side becomes more complex since there are more fluids and higher heat fluxes exchanged during the discharging process. To reach this configuration is necessary a CO_2 flowrate entering the carbonator equal to 3.3 times the stoichiometric amount; in this way it is possible for the two composite curves to get closer and increase the heat transfer efficiency. However, this strategy for the heat recovery in the power block is less efficient than the other alternative and therefore the discharging process is characterized by lower performance.

Regarding the remaining part of the plant, the solar calciner has a size of 31 MW while the total reflective area of the heliostat field is equal to 53’417 m^2.

In Fig. 5 are reported some results obtained from the economic optimization concerning the plant investment costs. Because of the employment of an adiabatic reactor, the carbonator side has a lower impact on the total capital investment, while the charging plant section has a higher size to satisfy the slightly higher daily demand of CaO required by the discharging process,. It is interesting to notice that, despite a less efficient discharging process determines an increase of the solar side investment cost, which is the most expensive plant section, this increase is exceeded by the cost decrease occurring in the carbonator side. The economic convenience is therefore ensured.

5.3 Multi-objective optimization

As seen in the two previous subsections, the energy and economic optimizations lead to two different results. This means that, at least in a portion of the total variable domain, the objective functions are in contrast between them. Therefore, it can be interesting to analyze this aspect with a multi-objective optimization and observe how the different configurations or operating parameters affect the system in terms of performance and investment cost.

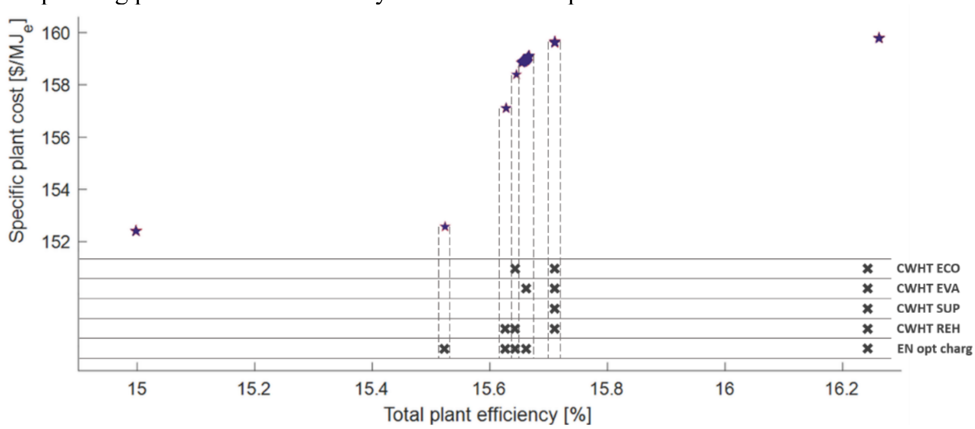

Fig. 6. Pareto curve for the multi-objective optimization.

In Fig. 6 is shown the Pareto curve obtained from the optimization process. The reason why it appears with consistent discontinuities is due to the changes occurring in the system configuration, which are mostly managed by binary variables. As already explained, the parameters related to the power block do not appreciably change in this optimization; therefore, the remaining variables that can cause changes in the plant performance/costs are the ones related to the carbonator side. Concerning these last parameters, the influence of carbonator side temperatures on the objective functions is lower with respect to the one determined by the thermal recovery configurations, which are considered thanks to binary

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parameters. For this reason, binary parameters are the only variables concretely capable to find new elements for the Pareto curve, but, because of their dual nature, the resulting regions of the Pareto front are constituted by single points, and, to make it more understandable, the layout changes are highlighted in Fig. 6 with the addition of a table.
The progressive change from a HRCP to a HTCW setup determines an increase in the system efficiency and plan investment costs. For first, it results to be more convenient to move the reheating stage from the thermal feeding with sensible heat to the thermal transfer with heat of reaction; then it is added the economizer. The evaporation stage is relatively critical in the HRCP configuration because it constitutes an isothermal process involving a significant heat transfer. For this reason, a further improvement is obtained when the thermal transfer is performed on the reactor wall. Finally, as already seen, the highest benefit in efficiency terms is obtained when the entire power block is thermally fed by the heat of reaction.
Concerning the charging side optimization, the difference between a section dimensioned according to energy (EN opt. charg.) or economic (EC opt. charg.) criteria is noticeable in terms of plant efficiency but practically negligible in economic terms. As a consequence, for most of the configurations found by the Pareto curve, the charging section is energy-optimized.

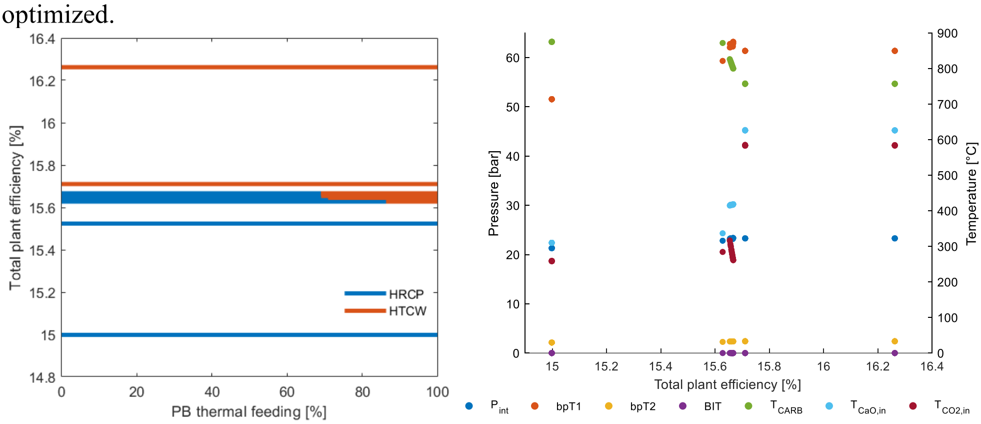

Fig. 7. Power block thermal feeding partition in percentage (left, a) and variation of the most important parameters (right, b), both along the Pareto curve.

Further results obtained by the multi-objective optimization are reported in Fig. 7. These data are referred to the Pareto curve and presented as a function of one of the objective functions: the plant efficiency. In Fig. 7a is shown the way in which the heat for the power block is recovered (expressed in percentage). It is interesting to notice that the passage from one setup (HRCP) to the second (HTCW) happens monotonously. Concerning Fig. 7b, the variation of the most interesting parameters related to operating conditions (pressures and temperatures) is reported. The Blower Inlet Temperature and the bleeding pressure in the second turbine (bpT2) do not significant change while the carbonator operating temperature decreases when the system efficiency increases; an opposite trend is reported by the other parameters (temperature of the reactants entering the carbonator, power block intermediate pressure and bleeding pressure of first turbine). These variations are appreciable in the central region of the Pareto curve because it is where are found different configurations for the discharging section layout, while the two extremes are only determined by different optimization strategies for the charging section, which do not cause actually a change in the plant setup.
Finally, the parameters that always reach their achievable maximum value in the multi-objective optimizations are: power block turbine inlet pressure and temperature, storage turbine inlet temperature and intercoolings number for the calciner side compression.

6 Conclusions

The exploitation of a Calcium-Looping for Thermo-Chemical Energy Storage in a central tower CSP plant is studied in the present analysis. The indirect integration of a Steam Rankine Cycle is assumed for the energy production. The entire system in simulated with the aim of conduct a comprehensive analysis; operating conditions and component sizes are determined through optimization processes. To extend the study, multiple power block layouts and thermal feeding options can be selected during the optimization process, such that the choice of the most convenient configuration is left to the algorithm. The strategy adopted for the system optimization allows managing both the operating conditions of primary components (handled by a genetic algorithm) and the thermal transfer processes (treated by the pinch analysis). Overall daily efficiency and specific investment cost are the two objective functions adopted for the present investigation. A multi-objective optimization is carried out with the aim of evaluating the possible compromises between these two main aspects.
The obtained results show that the optimal power block configuration does not change for the different optimization criteria (energy and economic): a performing power cycle results therefore to be convenient in both energy and economic terms for the entire system operation. The system efficiency rises by the 8% (in relative terms) when the optimization criteria passes from economic to energetic, while +5% is the variation encountered in the specific plant cost for the same passage. Power block thermal feeding is demonstrated to have a significant influence on plant performance, costs and Heat Exchanger Network layout. In particular, performing a Heat Transfer on the Carbonator Wall makes possible to achieve the highest performances (16.3%) and a relatively simple layout (thanks to the lower number of streams participating to the thermal transfer in the carbonator side HEN). Finally, the influence exercised by the variables on the objective functions is assessed with a multi-objective analysis and other plant configurations are highlighted in the Pareto curve.
The comprehensive investigation performed in the present work makes possible to establish the characteristics affecting this novel technology and, in particular, the features related to this kind of integration. Various information are provided with the aim of comparing the power block integration with other alternatives already studied in scientific literature and recognize the strengths and weaknesses that can influence the choice of a Calcium-Looping integration.

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