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Performance optimization of a gas-steam combined power plant partially fed with syngas derived from pomace

Lorenzo Dambrosio, Bernardo Fortunato, Marco Torresi, Sergio Mario Camporeale, Francesco Fornarelli

[a]*Department of Mechanics, Mathematics and Management (DMMM), Polytechnic University of Bari, Via Orabona 4, Bari 70125, Italy*

Abstract

In this paper a gas-steam combined-cycle, partially fueled by syngas (produced in an embedded downdraft gasifier fed with pomace), is considered. In addition, an auxiliary combustion system is directly fed by ligno-cellulosic biomass. The thermodynamic model of the entire system is developed by means of the Cycle-Tempo software. The gasification process is supposed to occur at ambient pressure and air is used as gasifying agent. An optimization process has been introduced by means of the Design of Experiment (*DoE*) technique. The design variables and their corresponding ranges have been chosen by using a heuristic criterion. The power plant performance is represented by the thermal efficiency, η_I, the exergetic efficiency, η_{II}, the cost of electricity, *COE*, and the net return, R_{net}. The *DoE* technique provided the so-called Pareto barrier, which isolates all the non-dominated solutions.

Keywords: combined power plant; biomass gasification; DoE; optimization;

1. Introduction

Notwithstanding the large amount of biomasses, there are still few plants that use this energy source. This is mainly caused by the problem in managing the gasification process even though experiments and numerical simulations are continuously developed in order to improve the knowledge on this complex phenomenon. Actually, gasification involves many processes with numerous parameters. The granulometry, the ash content, the humidity, are only few of the parameters that have to be considered in the preliminary definition of the biomass. Moreover, the heat transfer, the chemical reactions, the flow behaviour have to be taken into account in order to correctly model the process. The biomasses can be more easily burned in a power plant after having been gasified. The final product of the process consists in a syngas that can be used in energy production systems [1]. Usually, the gasification modelling consists

* Corresponding author. Tel.: +39-080-596-3406 ; fax: +39-080-596-3411.
E-mail address: lorenzo.dambrosio@poliba.it

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in simplified procedures to predict the final composition of the produced syngas in terms of chemical composition [2, 3, 4, 5, 6]. Briefly, the gasification process is a partial oxidation of solid organic material within specific reactors by means of several sub-steps characterized by different operating conditions in term of thermodynamic and chemical transformations. Above $350°C$ the biomass starts to be decomposed into a gaseous fuel and other chemical compounds that includes hydrocarbons, hydrogen, water vapor, carbon dioxide, carbon monoxide and tar; whereas the solid part of the biomass becomes a mix of ash, carbon, sulfurs and hydrocarbons. We can distinguish direct and indirect gasifiers. The first use part of its own fuel products to provide the heat to complete the pyrolysis, the latter has a separate combustion chamber and a heat transfer fluid that introduces more complex technological solutions in the process.
The objective of this study is to carry out an optimization process by means of the Design of Experiment (*DoE*) technique. The design variables (the variables to be tuned in order to optimize the plant performance) and their corresponding ranges have been chosen by using a heuristic criterion: compressor pressure ratio, β, Turbine Inlet Temperature, TIT, $\Delta T_{PinchPoint}$ and $\Delta T_{ApproachPoint}$. On the other hand, the power plant performance (variables to be optimized) are represented by the thermal efficiency, η_I, the exergetic efficiency, η_{II}, the cost of electricity, *COE*, and net return, R_{net}. The *DoE* technique provided the so-called Pareto barrier which isolates all the non-dominated solutions.

2. Model Description

The entire model of the gas-steam combined power plant, considered in this paper, has been developed by means of the CycleTempo software. The detailed description of the gasifier model can be found in [2] and [3]. In order to burn a syngas obtained from a biomass directly in the combustor of a gas turbine, the syngas must be cleaned, cooled and compressed, otherwise the most valuable parts of the gas turbine (e.g. the turbine blades) can be compromised by fouling or corrosion. All these syngas treatment processes have a considerable cost and cause numerous complications in the system. However, the same purity of the syngas is not required if the thermal input is transferred to the operating fluid by means of an external combustor. Hence, the raw syngas is directly conveyed into an external combustor, where it is burned with the air coming from the gas turbine. Actually, after the expansion in the gas turbine (36), the comburent air is first heated up in the biomass combustor fed by lingo-cellulosic biomass (50), then, it is partially cooled down in the Heat Recovery Steam Generator (42-44) of the combined power plant and finally regenerated (35) (see Fig. 1). The main plant characteristics are summarized in Table 1.

Table 1. simulation Data for the combined power plant

	Parameters	
$P_{37} = 1.013 bar$	$P_{52} = P_{55} = 50 bar$	$TIT = T_{46} = 1173K$
$T_{37} = 291K$	$P_{44} = 1.013 bar$	$T_{44} = T_{60}$
$\eta_{is,c} = \eta_{is,t} = 0.87$	$\eta_p = 0.65$	$T_{49} - T_{47} = 50K$
$\eta_{m,c} = \eta_{m,t} = 0.98$	$\Delta T_{app} = 70K$	$LHV_{fur} = 15MJ/kg$
$\eta_{fur} = 0.87$	$\Delta T_{pp} = 5K$	$G_{bio} = 0.15kg/s$
$P_{54} = 0.05 bar$	$T_{44} - T_{43} = 30K$	$T_{water} = 290K$
$\beta = 9$	$T_{comb} = 1300K$	
$\eta_{tot} = 0.3172$	$G_{fur}/G_{bio} = 0.3937$	$P_{tot} = 1082kW$

3. Economic Analysis

The economic issue plays a key role in the power plant design. It affects all the thermodynamic and environmental aspects [2, 7]. The economic profitability can be evaluated in terms of the *Cost of Energy*, *COE* [€/kWh]

$$COE = \frac{C_{CAP}/P_{af}}{h_{eq}} + C_{OM} + \frac{C_{FUEL}}{\eta_g}, \quad (1)$$

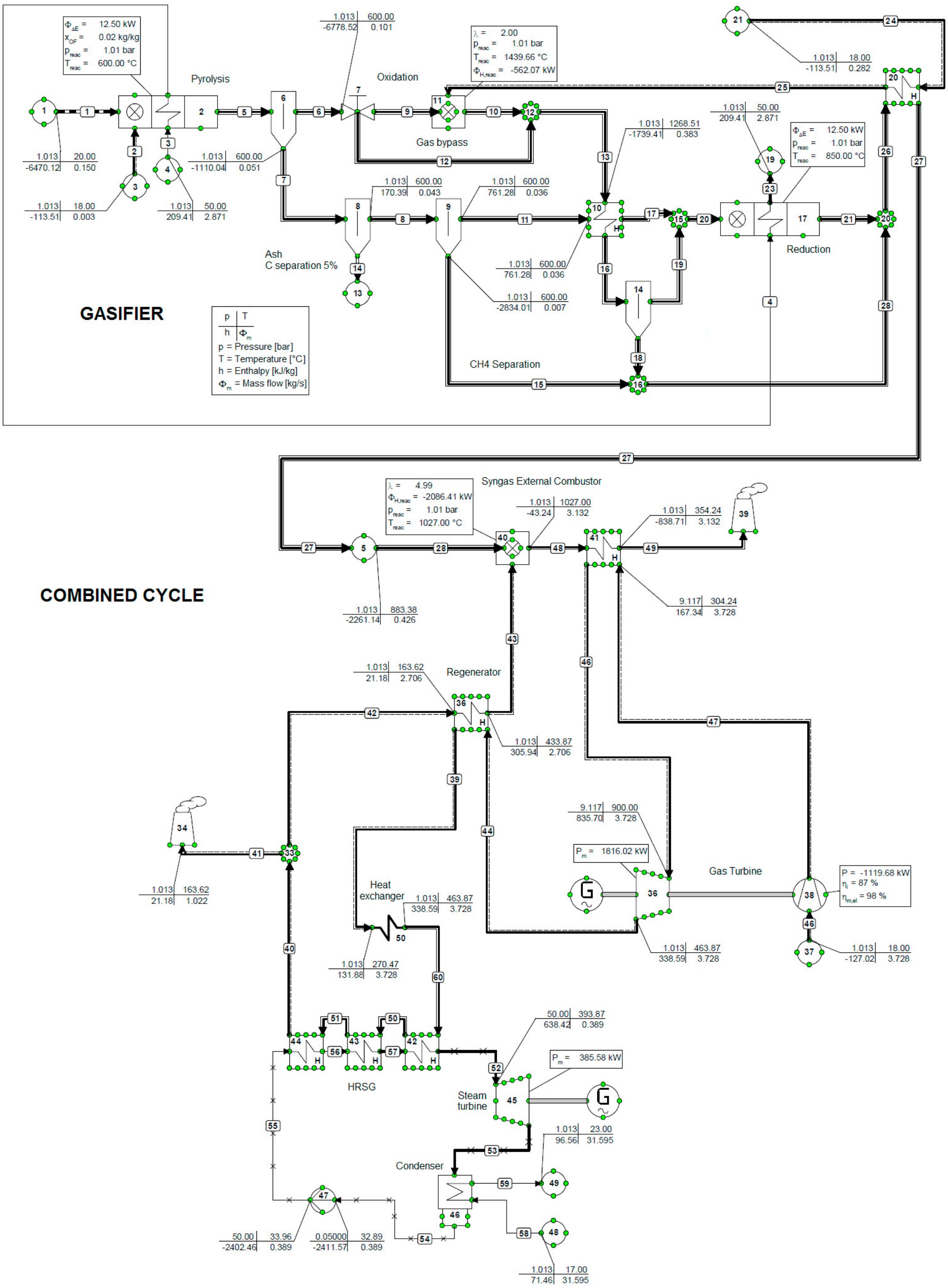

Fig. 1. CycleTempo Layout of the steam-gas combined power plant with embedded downdraft gasifier. Based on data defined in Tab. 1

where C_{CAP} represents the global plant capital cost (carried back to the first operating year), P_{af} takes care of depreciation by annual installments and h_{eq} is the equivalent number of operating hours per year (here 2500h per year) of the plant, working under nominal conditions. On the other hand, C_{OM} indicates the operating and maintenance costs and can be assumed to be 0.005 [€/kWh]. Finally, C_{FUEL} and η_g are the fuel cost and the plant global efficiency, respectively. All the terms in Eq. (1) are expressed in [€/kWh]. The depreciation factor, P_{af}, can be evaluated as:

$$P_{af} = \frac{1}{i}\left(1 - \frac{1}{(1+i)^N}\right), \tag{2}$$

being i the interest rate (here considered equal to 5%) and N the number of years to depreciate over (in this case, $N = 20$).

The plant capital cost, C_{CAP}, can be divided into four contributions: the gasifier cost, $C_{gasifier}$, the combined cycle plant cost, C_{plant}, the burner costs (the external combustor, $C_{ext-comb}$, plus the post combustor, $C_{post-comb}$), and the heat exchangers cost, C_{heat}. As far as the first three costs are concerned, according to Fortunato et al[2] and Lozza [7]. they can be assumed as:

$$\begin{aligned} C_{gasifier} &= 200\,[€/kW], \\ C_{plant} &= 550\,[€/kW], \\ C_{ext-comb} = C_{post-comb} &= 100\,[€/kW]. \end{aligned} \tag{3}$$

Concerning the heat exchangers, from heat transfer law, assuming from [7] the global heat transfer coefficient $U = 150\ [W/m^2K]$, it is possible to determine the heat exchanger total surface A. As a consequence the heat exchangers specific cost reads:

$$C_{heat} = \frac{C_{sup}A}{P_{TOT}}\,[€/kW], \tag{4}$$

where C_{sup} is the specific cost of the heat exchanger per unit area equal to 600 $[€/m^2]$ according to [7]; finally, P_{TOT} represents the total power of the power plant.

In Eq. (1) the term C_{FUEL} is composed by 2 terms: the first one, C_{bio}, takes into account the biomass used in the gasifier, whereas the second one, C_{fur}, considers the cost of the ligno-cellulosic biomass employed in the post combustor. Their usual values are $C_{bio} = 0.0092\ [€/kWh]$ and $C_{fur} = 0.012\ [€/kWh]$

In order to complete the economic analysis, it is necessary to evaluate the revenues deriving from the plant energy production. The first income source is due to the sale of electricity, $R_{electricity}$, defined as:

$$R_{electricity} = q_{electricity}P_{TOT}h_{eq}\,[€]. \tag{5}$$

A value of 0.08 $[€/kWh]$ for the average electricity specific price, $q_{electricity}$, has been assumed. Another income source is represented by the economic incentives, R_{inc}, which assumes a similar expression of Eq. (5)

$$R_{inc} = q_{inc}P_{TOT}h_{eq}\,[€]. \tag{6}$$

From [8] a value of 0.2031 $[€/kWh]$ for the average electricity specific incentive, q_{inc}, has been considered.

Finally the net revenue R_{net} can be evaluated subtracting the COE from the total incomes:

$$R_{net} = R_{electricity} + R_{inc} - COE. \tag{7}$$

4. Design of Experiment

The Design of Experiment (*DoE*) is a quite effective technique to observe the effects of the design variable variations on the system (power plant) outputs (performance). It is a statistic methodology, which operating together with the Pareto dominance relationship, can lead to the detection of the areas in the design variable space offering the best performance (Pareto barrier) [9].

The first step in this method is to identify among the output variables those that have to be optimized, representing, therefore, the power plant performance. On the other hand, it is necessary to choose among all the design variables those who mostly affect the performance. As far as the performance variables are concerned, two main aspects must be taken into account: the energetic efficiency and the economic impact of the power plant energy production. In this perspective, for the energetic efficiency issue, the thermal efficiency, η_I, and the exergetic efficiency, η_{II}, have been considered, whereas the economic impact has been evaluated by means of the cost of energy, COE, and the net revenue R_{net}.

Based on the experience, the design variables that affect the most the plant performance are: the compressor pressure ratio, β, the turbine inlet temperature, TIT, the pinch point, $\Delta T_{PINCH-POINT}$, and the approach point, $\Delta T_{APPROACH-POINT}$, temperature differences. Also the variability ranges of the design variables have been determined based on the experience, trying to exploit those existing solutions in comparable plants. The resulting design variable sets constituting the 72 cases DoE are listed below:

$$\begin{aligned} &\beta && [-] = [5, 7, 9, 11], \\ &\text{TIT} && [^\circ C] = [900, 1000, 1100], \\ &\Delta T_{PINCH-POINT} && [^\circ C] = [5, 10, 20], \\ &\Delta T_{APPROACH-POINT} && [^\circ C] = [50, 60]. \end{aligned} \tag{8}$$

5. Pareto Optimal Solutions

Multi-objective optimization involves more than one objective function to be optimized simultaneously. In the present paper the objective functions are represented by the 4 performance variables defined in paragraph 4. Unlike in the case of a single-objective optimization, where the objective function is optimized by one single value of the design variable vector, multi-objective optimization includes more than one solution (theoretically infinite) obtained for as many values of the design variable vector. In order to clarify this statement, it is convenient to introduce the concept of *non-dominated solution* [10], [11]. Let $\mathbf{X} = [X_1, X_2, ..., X_N]$ and $\mathbf{Y} = [Y_1, Y_2, ..., Y_M]$ be the design variable input and the corresponding performance variable output, respectively. Suppose all the performance variables Y_i, $(i = 1, ..., M)$ have to be minimized (for different optimizations the changes are straightforward). Considering two different performance variables vectors, $\mathbf{Y^1}$ and $\mathbf{Y^2}$, corresponding to the design variable vectors $\mathbf{X^1}$ and $\mathbf{X^2}$, respectively, if

$$\forall i \in [1, ..., M] : Y_i^1 < Y_i^2 \tag{9}$$

then the solution $\mathbf{X^2}$ is referred as *dominated* by solution $\mathbf{X^1}$. Moreover, if

$$\exists i \in [1, ..., M] \ni Y_i^1 > Y_i^2 \tag{10}$$

then the solution $\mathbf{X^2}$ is referred as *non dominated* by solution $\mathbf{X^1}$. Finally, if

$$\exists i, j \in [1, ..., M],\ i \neq j \ni Y_i^1 < Y_i^2,\ Y_j^1 > Y_j^2 \tag{11}$$

then the solutions $\mathbf{X^1}$ and $\mathbf{X^2}$ are referred as *non dominated* each other. Comparing all the possible solutions, according to *non-dominated solution* relation, it is possible to obtain the set of all the *non-dominated* solutions that constitutes the so-called *Pareto barrier*. Of course, it does not make practical sense to compare *all the possible solutions*, therefore only the solutions included in the DoE will be considered to build the *Pareto barrier*. In tables 2 and 3 the resulting *Pareto barrier* is summarized. As concluding remarks, since, among *non-dominated* performance, η_I, η_{II} and COE differ only slightly, it is possible to state that the decisive factor is represented by R_{net} and therefore the solution N. 1 is the most convenient.

Table 2. Non-dominated solutions.

N.solution	β	TIT [$^\circ C$]	$\Delta T_{PINCH-POINT}$ [$^\circ C$]	$\Delta T_{APPROACH-POINT}$ [$^\circ C$]
1	5	1100	5	50
2	5	1100	10	50
3	5	1100	20	50

Table 3. Non-dominated performance.

N.solution	η_I	η_{II}	COE [€/kWh]	R_{net} [€]
1	0.4010	0.3566	0.1024	681891
2	0.4012	0.3568	0.1018	679046
3	0.4015	0.3572	0.1012	671453

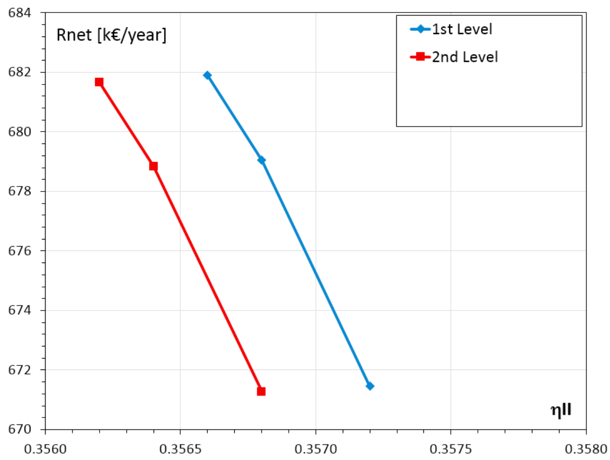

Fig. 2. 1st and 2nd level *Pareto barrier.*

It is noteworthy that, in the present case, the optimization problem can be downscaled without any loss of generality. In fact, from table 2, it is possible to observe that β, TIT and $\Delta T_{APPROACH-POINT}$ do not vary through the entire *Pareto barrier*. However, whilst $\beta = 5$ and $TIT = 1100°C$, as confirmed in the literature [12], represent well-known design values which maximizes η_I and η_{II}, small variations in $\Delta T_{APPROACH-POINT}$ could bring some improvements in the *non-dominated* performance. This aspect reduces the design variables vector to $[\Delta T_{PINCH-POINT}, \Delta T_{APPROACH-POINT}]$. On the other hand, as stated earlier from table 3, among *non-dominated* performance, only R_{net} undergoes appreciable variations. Therefore, the optimization process is applied only to η_{II} (in order to take into account the exergetic aspects of the energy conversion) and R_{net}.

In order to improve the *non-dominated* solutions, it is necessary to move from the *Pareto barrier*, obtained applying the *non-dominated* relation to *DoE* (1st level *Pareto barrier*), to a new *Pareto barrier*. In order to understand how to improve the *Pareto barrier*, the sub-optimal solution should be considered. This can be accomplished removing the *non-dominated* solutions from *DoE* and carrying out the *non-dominated* relation to the residual *DoE*. Fig. 2 illustrates both the 1st level *Pareto barrier* and the sub-optimal *Pareto barrier* (2nd level *Pareto barrier*). The only difference between these two *Pareto barrier* levels concerns the $\Delta T_{APPROACH-POINT}$, $50°C$ for the 1st level and $60°C$ for the 2nd level: thus, one can conclude that reducing the $\Delta T_{APPROACH-POINT}$, the *non-dominated* solutions improve. For this reason, the optimization process considers 25 new design variables points around the 1st level *Pareto barrier*, featured by $\Delta T_{PINCH-POINT} = [5, 8, 10, 15, 20]$ and $\Delta T_{APPROACH-POINT} = [46, 48, 50, 52, 54]$, whose *non-dominated* solutions are specified in Table 4: The corresponding optimized *Pareto barrier* is sketched in Fig. 3a

Again, the best *non-dominated* solutions are obtained when $\Delta T_{APPROACH-POINT}$ assumes the minimum value. Considering $\Delta T_{APPROACH-POINT} = 35°C$, being the lowest value as suggested by [7] and carrying out again the optimization process, the resulting *Pareto barrier* play the role of *limit Pareto barrier* (Fig. 3b). Of course, the differences in term of η_{II} and R_{net} between the *Pareto barriers* are quite small, but nevertheless it is interesting the optimization trend moving in the design variables space.

Table 4. Optimized non-dominated solution.

N.solution	R_{net} [€/*year*]	η_{II}	$\Delta T_{PINCH-POINT}$	$\Delta T_{APPROACH-POINT}$
1	681985	0.3567	5	46
2	680419	0.3568	8	46
3	679130	0.3569	10	46
4	675496	0.3571	15	46
5	671534	0.3573	20	46

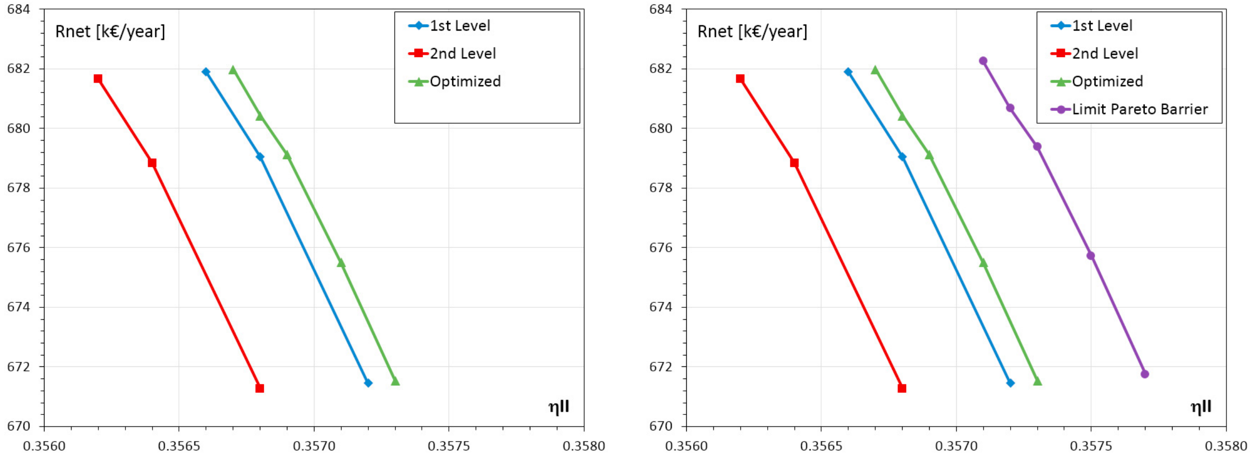

Fig. 3. (a) Optimized *Pareto barrier*; (b) limit *Pareto barrier*.

6. Conclusions

In this paper a thermodynamic model of a fixed bed downdraft gasifier used to turn a solid biomass into a syngas has been outlined; it has been based on the Cycle-Tempo software (*TU Delft*, the Netherlands). The syngas offers a more efficient combustion with respect to the solid biomass direct combustion both in terms of heat and power generation, and it can be much more easily transferred, where needed. The gasification process has been supposed to occur at ambient pressure by means of air as gasifying agent. In the present gasifier model, all of the main gasification processes (i.e. drying, pyrolysis, oxidation and reduction) have been separately implemented. Moreover, an optimization process has been introduced by means of the Design of Experiment (*DoE*) technique. The design variables (to be tuned in order to optimize the plant performance) and their corresponding ranges have been chosen by using a heuristic criterion: compressor pressure ratio β, turbine inlet temperature TIT, $\Delta T_{PINCH-POINT}$ and $\Delta T_{APPROACH-POINT}$. On the other hand, the power plant performance (variables to be optimized) are represented by the thermal efficiency η_I, the exergetic efficiency η_{II}, the cost of electricity COE and net return R_{net}. The *DoE* technique provided the so-called *Pareto barrier*, which isolates all the non-dominated solutions. Finally, an optimization strategy lets *DoE Pareto barrier* to be enhanced until *limit Pareto barrier*.

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