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Optimization of solar integration in biomass fuelled steam plants

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Abstract

This paper is focused on solar-biomass integration and presents a thermodynamic analysis of solar power utilization replacing the steam bleeds of a regenerative Hirn cycle plant, biomass fuelled, in feedwater pre heating process. In solar-biomass integrated configuration an energy conversion efficiency of solar energy has been evaluated in order to compare the use of solar energy in solo and hybrid configurations. Such efficiency has been adopted as optimization parameter for the best hybrid plant configuration, varying steam pressure and regeneration parameters.

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Keywords: solar energy; biomass; thermodynamic optimization;

1. Introduction

Solar energy is widely the most abundant among renewable sources but some crucial limits are related to its exploitation, especially for electric power production. First of all it's a low density source so it needs to be concentrated in order to reach high temperatures of fluids involved in thermodynamic cycles. High concentration allows high temperatures of fluids and so high cycle efficiencies. However the higher is concentration, the higher are thermal losses of solar collectors, plant complexity and costs.

The second fundamental limit of solar source is its discontinuity, due to night-day alternation and weather condition.

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Energy storage facilities allows to generate electricity from sun continuously, but this involves additional cost. For all these reasons electricity production costs by solar plants are still high and not competitive with other source options, if not with specific incentives.

One of the ways to reduce solar energy costs, also avoiding storage systems, is the solar integration in plants fed by other sources available with continuity(i.e. biomass). A particular approach of solar-biomass integration has been presented, evaluated and discussed in this paper.

Hybridization of solar plants is not a new concept. About thirty years ago Mc Donald (1986) [1] investigated hybrid plants combining CSP (concentrated solar power) with biomass, using dish systems. In this case no plants were built due to high costs and technological constrains.

Another approach of solar integration, proposed by Ying et al.[2] , is the use of solar energy to replace the extracted steam from turbine bleeds, to heat the feed water in regenerative Rankine plants. He evaluated the integration by an exergy merit index, in different cases.

In several cases of solar-biomass hybridization, there is rather a biomass integration in a solar plant: a biomass fired steam boiler is integrated into a CSP plant water-steam cycle or a biomass fired heater is integrated in the thermal oil or molten salt cycle, substituting sun when it’s not available[3][4][5][6].

Fresnel systems have been investigated too for solar-biomass integration [7][8][9][10], but no reference plants are yet available for this CSP option, although it has the advantage to reach high fluid temperature, up to 500 °C and so high conversion efficiencies.

Nomenclature

h	specific enthalpy [kJ/kg]
m	total mass flow rate [kg/s]
P	power delivered by the plant [kW]
Q	thermal power [kW]
T	temperature [°C, K]

Greek symbols

Δ	variation
ε	heat exchanger efficiency
η	efficiency

Subscripts

1bl	with only the first bleed
2bl	with only the second bleed
coll	collectors
g	global
IN	inlet
l	limit
max	maximum value
m	mechanical
nobl	without bleeds
oil	diathermic oil
ORC	organic Rankine Cycle
OUT	outlet
r	real
st	steam
SC	solar conversion
tot	total
w	water

2. The biomass-solar hybrid plant

The basic idea of this paper is the exploitation of the solar energy by plant hybridization instead of using it in exclusively solar plants. In particular the solar integration has been investigated within regenerative steam plants.

The analysis has been focused on a steam plant, burning solid biomass, as reported in fig.1. Two regenerative heat exchangers have been considered, receiving heat from two bleeds. The heat exchangers are arranged in a double mode operation: feed water coming from condenser can be preheated both by turbine bleeds and by thermal oil alternatively.

Thermal oil is heated in two parabolic through collectors circuits, working at different temperature levels.

Thereby, when solar energy is available, the regenerative heat exchangers 8 and 10 take heat form solar circuits 11 and 12, the first working at lower temperature than the second; in this operation mode no steam is drawn from high and medium pressure turbine bleeds and plants provides the maximum electric power. During night and sunless periods, exchangers 8 and 10 are heated by turbine bleeds. In such plant setting, electric power decreases and global efficiency reaches its highest value.

With this plant layout the solar section gives its contribution in terms of heat and allows the turbine to produce more work: the ratio between this incremental work and the solar energy collected by solar section can be considered as an energy conversion efficiency and can be compared with efficiency of plants fed exclusively by solar energy.

The chosen plant size is of 2 MW, delivered when bleeds are avoided, since biomass has a Lower Heating Value less than that of the traditional fuels. For this reason, great power as hundreds of MW have not been taken in account, otherwise enormous fuel mass flow rates would be needed. Then these kind of plants are thought to be exploited in the distributed power generation, which is a new philosophy of intending power generation using more plants of restrained size, instead of few power plants of large size.

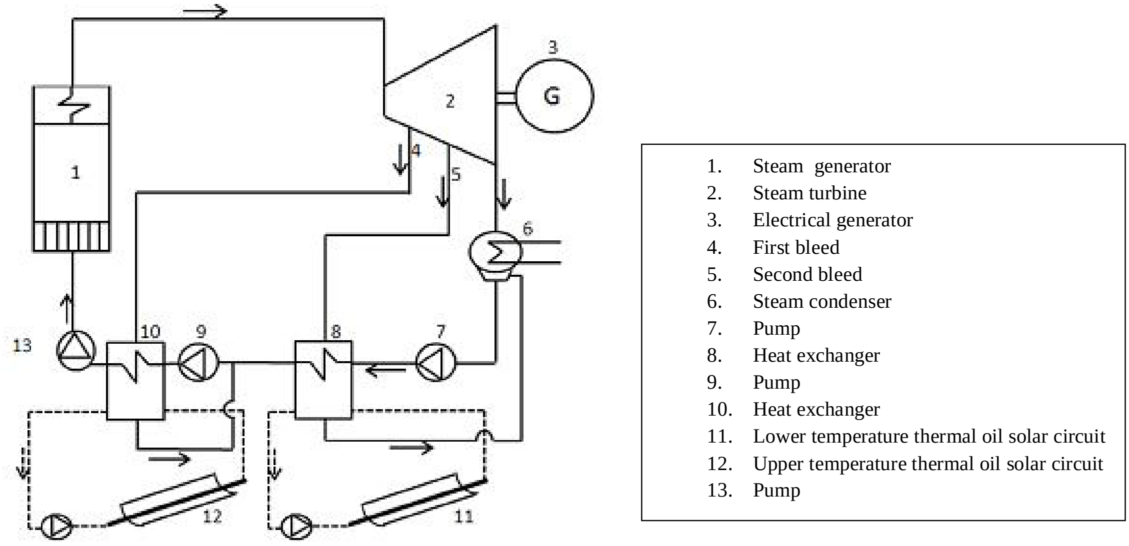

Fig.1: hybrid biomass-solar plant scheme.

3. The thermodynamic analysis

Different plants able to provide 2 MW in the absence of steam extractions were simulated, with $p_{max,st}$ gradually growing: 40, 60, 80, 100 and 120 bar have been exploited as maximum pressures; T_{max} and the pressure at the condenser are respectively equal to 500°C and 0,05 bar for each p_{max} of the cycle.

Isentropic efficiencies of 0,9 have been taken in account for pumps and turbines, in each plant case.

The starting case is the steam plant with a p_{max} of 40 bar. From the equation (1) of the power delivered by the plant without bleeds, known the Δh in steam turbine, and fixing at 0,9 the mechanical efficiency, the involute mass flow rate has been calculated.

$$P = m * \Delta h * \eta_m \tag{1}$$

Reference cases are those with two bleeds, which deliver a lesser power than the 2 MW used for the calculation of the mass flow evolving in the plants; for all these plants were evaluated the optimal conditions in which it’s possible to optimize solar contribution – if instead of one or both of the bleeds.

The simulation starts with the optimization of the extracted fractions and pressures under which make steam extractions for each cycle p_{max}, using Matlab©, when there’s insufficient solar radiation to preheat water; pressures and fractions that allow to obtain the maximum plant efficiency have been evaluated. Optimized pressures and fractions, for each p_{max}, are reported in table 1.

Table 1: Optimized pressures and fractions

Maximum pressure of the cycle [bar]	First extracted fraction [kg/s]	Second extracted fraction [kg/s]	First bleed pressure [bar]	Second bleed pressure [bar]
40	0,230	0,235	15,0	5,0
60	0,250	0,250	22,5	7,5
80	0,250	0,250	30,0	10,0
100	0,280	0,280	37,5	12,5
120	0,300	0,300	45,0	15,0

The amount of heat that must be provided by solar source, in case of the absence of both bleeds is defined as in the equation (2), while when one of the bleeds is missing, it’s defined as in the equations (3) and (4):

$$\Delta Q = m_{tot}*(h_5-h_4)+m_{tot}*(h_3-h_2) \tag{2}$$

$$\Delta Q_{1bl}=(m_{tot}-_{m1bl})*(h_3-h_2) \tag{3}$$

$$\Delta Q_{2bl} = m_{tot}*(h_5-h_4) \tag{4}$$

In order to assess effectively the use of solar energy, efficiency ε of the heat exchanger in the plant, used to transfer heat from the thermal oil circulating in the solar circuit, to the water, and efficiency of parabolic trough solar receivers must be considered. The latter is a function of the temperature of the fluid; a new script has been implemented on Matlab©, where a polynomial function has been built, using polyval e polyfit functions and studies by Forristal [11], to evaluate η_{coll} with temperature.

It is fixed then ε equal to 0.9, and the water hourly thermal capacity was considered as the minimum one. Knowing $T_{w,OUT}$ and $T_{w,IN}$ at the exchanger, the only unknown factor in the expression (5) is just the diathermic oil temperature exchanger at the inlet.

$$\varepsilon = \frac{T_{wOUT}-T_{wIN}}{T_{oilIN}-T_{wIN}} \tag{5}$$

Evaluated this temperature, using the polynomial function built on Matlab©, η_{coll} was calculated at that T_{oil}.

A new parameter, $\eta_{SC,l}$ presents in the numerator the difference between the power obtained by exploiting a single bleed and the power obtained with two bleeds, while in the denominator there's the heat provided by solar source when one of the bleeds is avoided. It is therefore equal to (6) in the solution with single bleed at the higher pressure and solar source exploited at the lower one, and equal to (7) in case of single bleed at the lower pressure, with solar source exploited at the higher pressure. With no bleeds, $\eta_{SC,l}$ is defined from the (8).

$$\eta_{SC,l}\text{-}_{1bl}=(P_{1bl}-P)/\Delta Q_{1bl} \tag{6}$$

$$\eta_{SC,l}\text{-}_{2bl}=(P_{2bl}-P)/\Delta Q_{2bl} \tag{7}$$

$$\eta_{SC,l}\text{-}_{nobl}=(2000-P)/\Delta Q \tag{8}$$

A new parameter, called $\eta_{SC,r}$ is defined as in equation (9).

$$\eta_{SC,r}= \eta_{SC,l}{}^{*}\ \eta_{coll}{}^{*}\varepsilon \tag{9}$$

The collectors efficiencies, η_r of the cycle (wich already considers machines mechanical efficiencies and unitary combustion yield), $\eta_{SC,l}$ and $\eta_{SC,r}$ are shown in tables 2, 3, 4, 5, 6.

Table 2: Characteristic parameters in the different plant configurations, with a cycle p_{max} of 40 bar

CASE	η_r	$\eta_{SC,l}$	η_{coll}	$\eta_{SC,r}$
Two bleeds	0,3408	\	\	\
Without bleeds	0,3135	0,2123	0,7277	0,1390
Single bleed at 15 bar	0,3259	0,2115	0,7374	0,1404
Single bleed at 5 bar	0,3319	0,2678	0,7291	0,1757

Table 3: Characteristic parameters in the different plant configurations, with a cycle p_{max} of 60 bar

CASE	η_r	$\eta_{SC,l}$	η_{coll}	$\eta_{SC,r}$
Two bleeds	0,3545	\	\	\
Without bleeds	0,3256	0,2315	0,7246	0,1510
Single bleed at 22,5 bar	0,3382	0,2272	0,7364	0,1506
Single bleed at 7,5 bar	0,3444	0,2825	0,7264	0,1841

Table 4: Characteristic parameters in the different plant configurations, with a cycle p_{max} of 80 bar

CASE	η_r	$\eta_{SC,l}$	η_{coll}	$\eta_{SC,r}$
Two bleeds	0,3620	\	\	\
Without bleeds	0,3336	0,2434	0,7242	0,1586
Single bleed at 30 bar	0,3457	0,2381	0,7362	0,1578
Single bleed at 10 bar	0,3520	0,2909	0,7260	0,1901

Table 5: Characteristic parameters in the different plant configurations, with a cycle p_{max} of 100 bar

CASE	η_r	$\eta_{SC,l}$	η_{coll}	$\eta_{SC,r}$
Two bleeds	0,3708	\	\	\
Without bleeds	0,3394	0,2551	0,7194	0,1652
Single bleed at 37,5 bar	0,3520	0,2465	0,7345	0,1629
Single bleed at 12,5 bar	0,3589	0,2979	0,7218	0,1935

Table 6: Characteristic parameters in the different plant configurations, with a cycle p_{max} of 120 bar

CASE	η_r	$\eta_{SC,l}$	η_{coll}	$\eta_{SC,r}$
Two bleeds	0,3769	\	\	\
Without bleeds	0,3439	0,2640	0,7159	0,1701
Single bleed at 45 bar	0,3564	0,2532	0,7333	0,1671
Single bleed at 15 bar	0,3638	0,3033	0,7188	0,1962

4. Results discussion

4.1. Comparison of the parameters of the plants with different maximum pressure in various configurations

From the reading of the previous tables, for each plant p_{max}, and for each plant solution adopted, it follows that:

- η_{real} is greater using two bleeds, whatever the p_{max} in the cycle. This situation is shown in figure 2;
- $\eta_{SC,l}$ shows the higher values for the steam plant configuration with the single bleed at the lower pressure and with solar source exploited at the higher pressure, whatever the p_{max} in the cycle. This situation is shown in figure 3;
- $\eta_{SC,r}$ also takes into account the efficiency of the collectors in the various cases and the efficiency of the heat exchanger; it's noted that the drop of η_{coll} related at the increase of operating temperature, using solar energy at higher pressure, weighs less than the difference between the $\eta_{SC,l}$ parameters at different pressures. Then $\eta_{SC,r}$ is always greater for the case with solar at higher pressure and bleed at a lower pressure. This situation is shown in figure 4.

$\eta_{SC,l}$ and $\eta_{SC,r}$ are always greater in the configuration with single bleed at the lower pressure and with solar source exploited at the higher pressure, since there's a greater involute mass flow into turbine for a greater skip of enthalpy. Furthermore, use solar energy at an higher temperature, consists in having heat of a better quality, from which is possible to obtain a greater work - increased exergetic availability. The fact that the increase of T_{oil} lowers the η_{coll}, weighs less than gain in terms of work for the bleed avoided and variation of the heat surplus to provide by solar source.

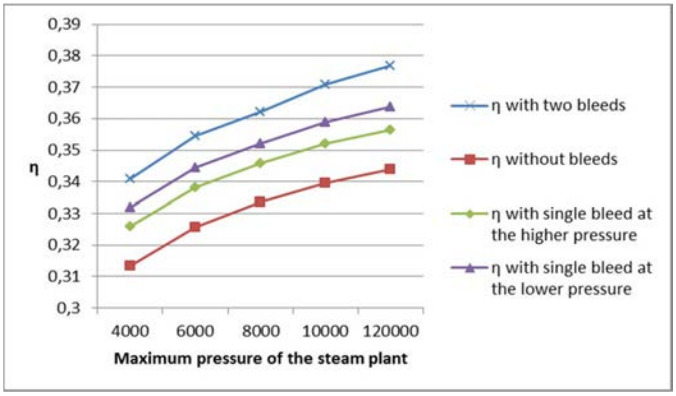

Fig. 2: Evolution of the cycle efficiency versus the $p_{max,st}$.

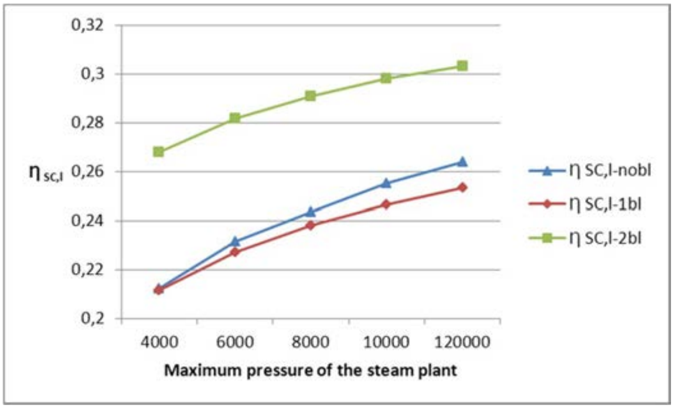

Fig. 3: Evolution of $\eta_{SC,l}$ *versus the* $p_{max,st}$.

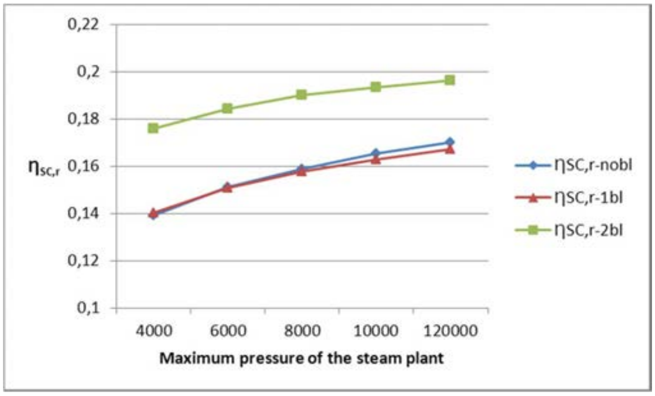

Fig. 4: Evolution of $\eta_{SC,r}$ *versus the* $p_{max,st}$.

4.2. Comparison between steam plants and ORC plants with acetone

Once known that the optimal configuration to take advantage of solar energy is that with a single bleed at the lower pressure and solar source exploited at the higher pressure, the heat to provide in such optimum cases through solar source has been tapped to perform fully the heat adduction phase in an organic Rankine cycle with acetone; diathermic oil enters the heat exchanger with the maximum temperature and the flow rate calculated in the case of steam plant with which the comparison is done.

Evolving mass flows of acetone in each different case of ORC plant were calculated from the expression (1) of the power supplied, placing the difference between 2 MW and the work obtained by the steam plant with which the comparison is done as power output for each ORC plant, and keeping in account a η_m of 0,9.

Once calculated the T_{oil} and the mass flow of the diathermic oil in each steam plant with single bleed at lower pressure, and with solar source exploited at the higher pressure, these two values are fixed also for the ORC plants, which shall have appropriate p_{max}, evaluated with Refprop©, to obtain superheated fluid at the turbine inlet. Using a ΔT of approach point (temperature difference between the hot fluid at the entrance and the cold fluid at the outlet of the exchanger) equal to 20°C, it's possible to calculate the T_{max} of the ORC plants. At the condenser, a temperature of 40°C is considered, while the pressure corresponds to the acetone saturation pressure at 40°C. Also a slight regeneration is present in the various cases, using the heat still disposable from the fluid at the turbine outlet to preheat the acetone at the exit of the pump.

With these parameters, η_r which already considers machines mechanical efficiencies and unitary combustion yield is calculated, and by using efficiency ε of the exchanger (equal to 0,9) and η_{coll}, plant global efficiency is then calculated.

Comparisons have been done between the following plants settings:

- $p_{max,st}$ = 40 bar and $p_{max,ORC}$ = 20 bar;
- $p_{max,st}$ = 60 bar and $p_{max,ORC}$ = 25 bar;
- $p_{max,st}$ = 80 bar and $p_{max,ORC}$ = 28 bar; in this case there's no regeneration, since the acetone at the exit of the pump is hotter than the fluid at the turbine outlet, and efficiencies were lowered compared to previous case.
- $p_{max,st}$ = 100 bar and $p_{max,ORC}$ = 35 bar;
- $p_{max,st}$ = 120 bar and $p_{max,ORC}$ = 40 bar;

The characteristic parameters of the ORC plants, for each maximum pressure, are shown in table 7.

Table 7: Characteristic parameters in the ORC plants

Maximum pressure of the ORC plant [bar]	P_{ORC} [kW]	η_{coll}	η_r	$\eta_{g,ORC}$
20	100	0,7291	0,1978	0,1298
25	123	0,7264	0,2088	0,1365
28	132	0,7260	0,2071	0,1353
35	160	0,7218	0,2212	0,1437
40	180	0,7188	0,2296	0,1485

Comparison between $\eta_{SC,r,st}$ parameter and $\eta_{g,ORC}$ is shown in figure 5, for each $p_{max,st}$.

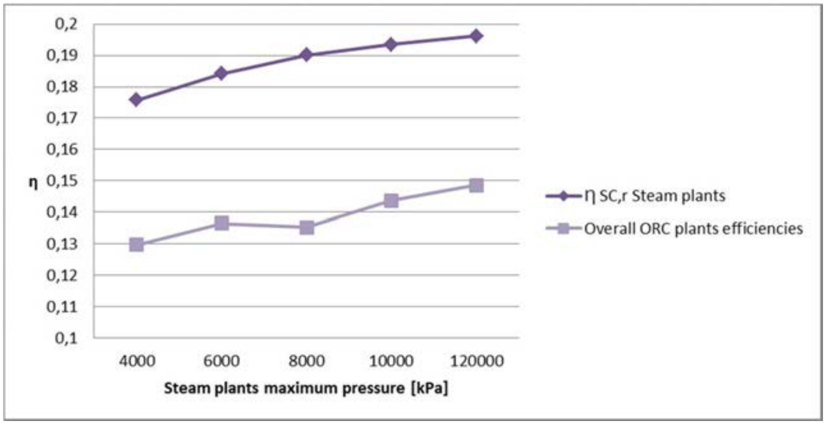

Fig. 5: Evolution of $\eta_{SC,r}$ *and* $\eta_{g,ORC}$ *versus the* $p_{max,st}$.

5. Conclusion

The paper focused on a particular hybridization technique of solar plants within biomass fuelled steam plants , based on substitution of steam bleed regeneration with water preheating by solar energy. The analysis highlighted that , by this technique, higher conversion efficiencies can be realized, with respect to solar plants working with the same thermal fluid and temperature ranges. However the percentage of power obtained by solar source must be somewhat low in this plant synergy. Anyway it can be a smart strategy of solar energy exploitation in all cases where a big amount of biomass is available too. This can be also a cheaper mode to produce energy by sun, thanks to lower installation costs of such plants.

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