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Optimization of an Integrated Solar Combined Cycle

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Abstract. In this paper, combined cycle (CC) power block parameters are optimized for its application coupled to concentrating solar power (CSP) plant. CSP hybrid plant is based on pressurized air receiver technology using natural gas assisted burner while the CC power block consists on high temperature open air Brayton cycle connected to bottoming steam Rankine cycle. Due to plant layout flexibility introduced by CC arrangements, three preferred configurations will be analyzed and optimized based on the intermediate pressure levels of the bottoming cycle. Benefits and drawbacks of each configuration will be discussed along the paper and the optimum solution will be proposed as the reference power block for electricity production at Integrated Solar Combined Cycle (ISCC) power plants. Results demonstrate that using current solar air receiver technology the system efficiency is far (around 47%) from the one expected from modern commercial CC systems (nearly 60%). The lower power cycle efficiency found was mainly based on pressure restrictions (below 6 bar) imposed by current air receiver designs what also implied lower temperature for the gas turbine.

INTRODUCTION

Concentrating solar power (CSP) is one of the most promising ways for electricity production of the upcoming years with high penetration of intermittent renewable energy sources such as wind and solar-photovoltaics. This is due to the fact that CSP when it is coupled to thermal energy storage (TES) system enables for large, inexpensive and flexible energy dispatch, which contributes to energy grid stabilization. At the same time, TES allows for steady operation of the power block by reducing undesirable fluctuations due to weather transient conditions and increasing the number of hours that the power block operates at design conditions [1]. Despite the abovementioned advantages about CSP systems, a step further is needed for electricity cost reduction. Among different research activities involved seeking for CSP cost reduction, improving power block efficiency is being widely explored. On that frame, several studies have been performed considering novel working fluids such as supercritical CO_2 [2–5] or high efficiency plant layouts such as combined cycle (CC) [6–9]. For the latter, several works have been investigated about solar integration of combined cycle using parabolic trough [10,11] and solar tower [12] technologies. In both cases, solar energy was used for water/steam preheating and evaporation steps of the Rankine cycle in combination with the exhaust gases of fossil-fuel gas turbine engine. However, less attention has been paid to Integrated Solar Combined Cycle (ISCC) configurations where solar energy is used for heating-up the air of a topping Brayton cycle in a central receiver [9,13] and considering the solar radiation as the principal heat source of the system [14,15].

The main objective of this paper is to determine the operating parameters of an ISCC that optimizes the energy efficiency considering restrictions introduced by solar receiver peculiarities (described in the following section). Three bottoming cycle configurations will be analysed: with one, two and three working pressures in the Rankine cycle, the most efficient configuration will be determined. Optimum operating conditions will be analysed for the ISCC plant with and without fuel support.

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Nomenclature			
ECO	Economizer	LP	Low Pressure
EVA	Evaporator	NG	Natural Gas
FP	Feed Pump	RH	Reheater
HRSG	Heat Recovery Steam Generator	SH	Superheater
IP	Intermediate Pressure	ST	Steam Turbine
ISCC	Integrated Solar Combined Cycle		

SOLAR POWER PLANT DESCRIPTION

The CSP is based on a classic Combined Cycle plant coupled to a solar central tower with a pressurized air receiver, see Figure 1. The solar receivers are inserted between the air compressor and the gas turbine of the Brayton cycle. In addition, the Brayton cycle has a combustion chamber fed by natural gas to increase the temperature of the air before entering the gas turbine. The air/combustion gases at the outlet of the gas turbine are introduced into a Heat Recovery Steam Generator (HRSG) that increases the enthalpy of the water/steam of the Rankine Cycle.

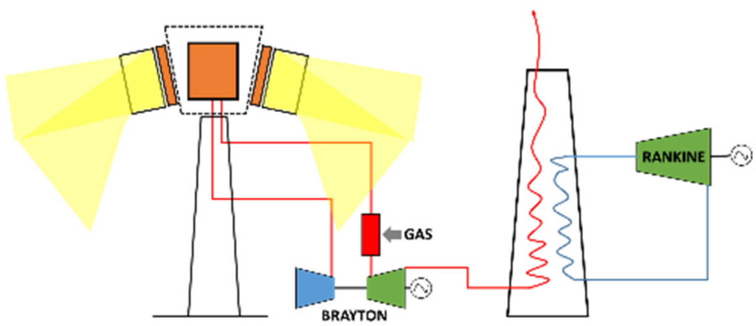


FIGURE 1. ISCC plant layout.

The heliostats form a circular solar field, and the solar receiver is composed of four solar cavity units oriented towards the four cardinal directions. Optimizations of each solar field and the aperture angles were performed using Tonatiuh based on global annual efficiency, main solar field performance parameters appear on TABLE 1. Inside each cavity there is a copper absorber plate with a number of machined pipes through which the pressurized air from the air compressor circulates, see Figure 2. The solar surface of absorber and the machined pipes are covered by a thin layer of Nickel based super alloy to avoid copper oxidation at high temperature. Air receiver design allows absorbing 25 MWth (each receiver) with a solar radiation to thermal energy conversion efficiency of 82.5% at design conditions [16]. In total, the heat absorbed by the air in the solar tower is 100 MWth. Maximum working pressure of the solar receiver is 6 bar (absolute) and due to material properties (copper), maximum outlet temperature of the air from the receiver is 800 ºC.

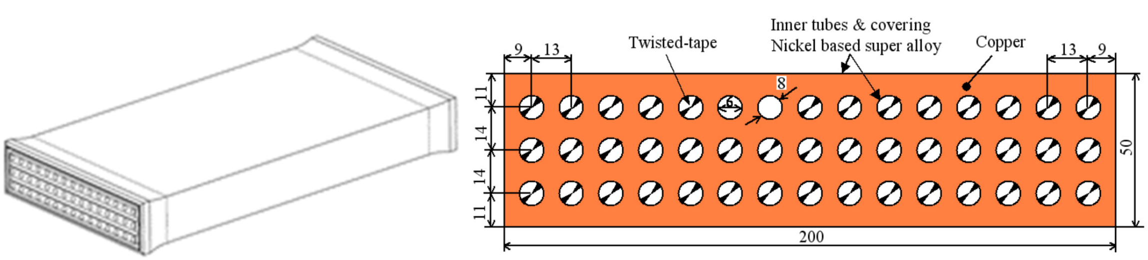


FIGURE 2. PEGASE embedded tube receiver[17].

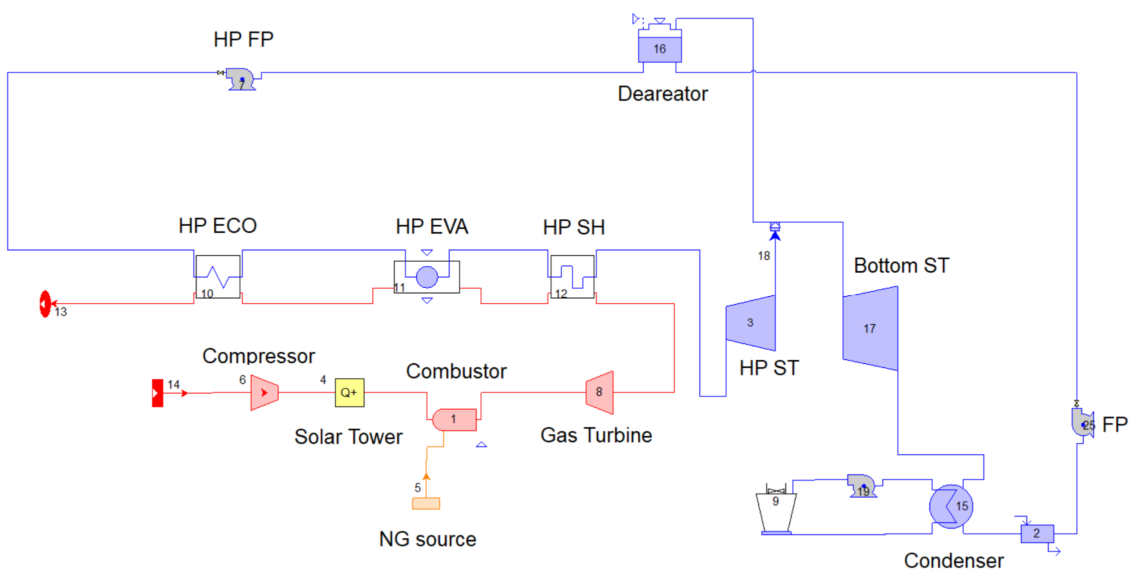
The ISCC plant is located in Seville (Spain), coordinates: 37.4º N, -6.01º W. Solar noon of the summer solstice has been considered as the design point for the solar field. At that moment, the direct solar irradiation is 881 W/m^2. Extreme ambient conditions for Seville (35 °C, 40% RH) were considered for simulations. No thermal energy storage system has been considered for power block optimization process.

TABLE 1. Solar field performance parameters

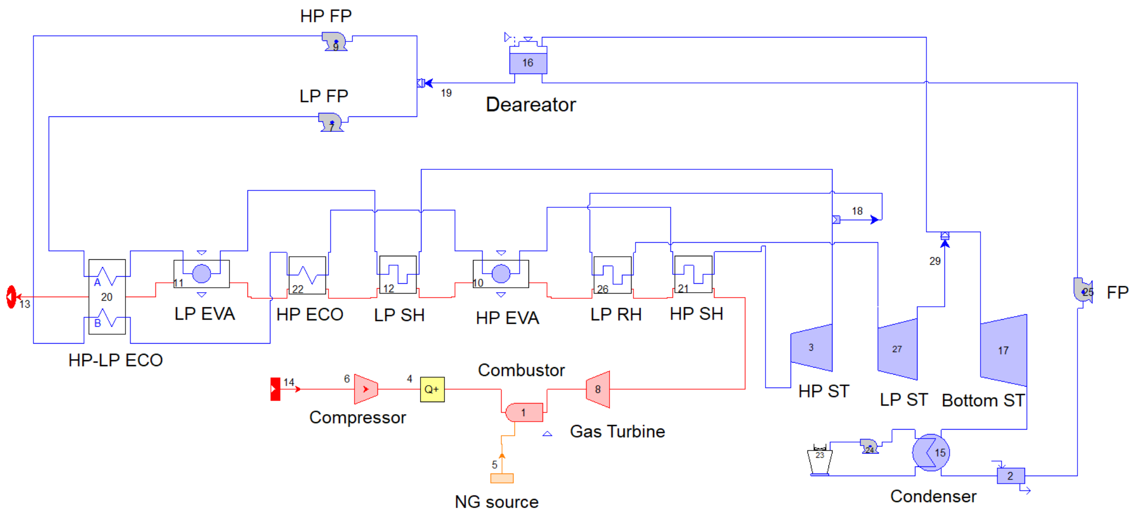
	North	South	East	West	All field
Nº heliostats	6.786	10.657	7.563	7.606	32.612
Area covered [m^2]	241.812	271.401	222.481	224.081	1.036.150
Power at design point [MWth]	30,45	30,14	30,88	30,90	122,37
Annual performance					
Efficiency	0,6171	0,5345	0,5667	0,5597	0,5650
Cosine losses	0,1460	0,3063	0,2152	0,2284	0,2337
Shading	0,0368	0,0365	0,0398	0,0346	0,0369
Absorption losses	0,0817	0,0657	0,0745	0,0737	0,0729
Blocking	0,0150	0,0056	0,0248	0,0256	0,0167
Spillage	0,0619	0,0240	0,0446	0,0440	0,0413
Atmospheric attenuation	0,0415	0,0274	0,0344	0,0340	0,0335

ISCC POWER BLOCK LAYOUTS

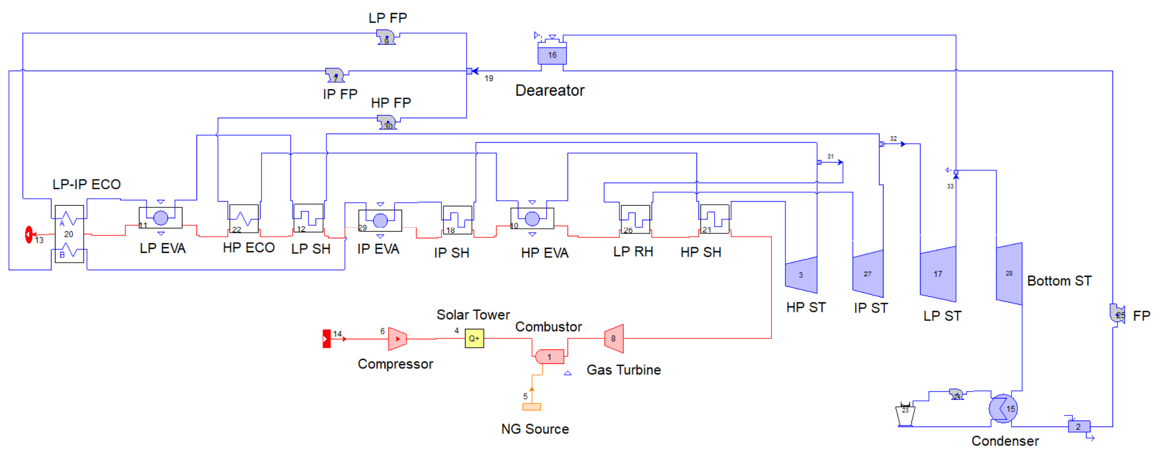
For the analysis, three different configurations for the bottoming cycle (Rankine) have been considered. The difference between them is based on the number of working pressures for the steam cycle: one, two and three pressures (Figure 3 (a), (b) and (c), respectively). For each pressure: an economizer, an evaporator and a superheater have been considered in the HRSG. In the case of two and three pressures, a reheater for the intermediate pressure has also been considered. In all cases, the condenser has been coupled to a cooling tower (wet cooling).



(a)



(b)



(c)

FIGURE 3. ISCC Power block configurations: (a) One pressure **(1)**, (b) Two pressures **(2)**, (c) Three pressures **(3)**.

SIMULATION RESULTS AND DISCUSSIONS

The schemes shown in the previous section have been simulated in two ways; Firstly, considering an exclusive contribution of thermal energy through the solar thermal receiver (solar mode), and secondly, a mixed thermal contribution by solar energy and natural gas (fueled mode), via a combustor located downstream solar receiver and upstream gas turbine inlet natural gas mass flow has been determined for reaching gas turbine outlet temperature of 600 ºC (typical temperature in conventional Combined Cycles[18]). Thermoflex software tool has been used to perform the power block analysis [19].

Simulations results are presented on figures 4, 5, and 6 where the variation of the net combined cycle efficiency is represented against the steam pressure for each of the three configurations of the power blocks described on figure 3. Parametric study on Rankine cycle steam pressures was performed for the three plant layouts shown on figure 3 both for solar mode and fueled one and covering whole pressure range from 10 bar to 110 bar. Figures 4, 5, and 6 show power block net efficiency for both the solar and fueled mode. Cycle net efficiency has been calculated according to equation (1).

$$Net\ efficiency\,(\%) = \frac{P_{block}}{Q_{sun} + m_{NG} \cdot \mathrm{PCI}_{NG}} \cdot 100 \qquad (1)$$

Where P_{block} is the electric net power produced by ISCC, Q_{sun} is the thermal energy gained by air in the solar receiver, m_{NG} is the mass flow of natural gas consumed and PCI_{NG} is the lower heating value of natural gas.

In general, optimum steam pressures found for all configurations are lower in the solar mode than in the fueled mode, this is due to that fact that gas turbine outlet temperature for the solar mode is 437.7 ºC (gas turbine inlet temperature limited to 800 ºC due to air receiver performance). However, for the fueled mode, exhaust gases at 600 ºC can be achieved by fuel assistance (turbine inlet temperature: 1031 ºC). This temperature difference is the reason for the different pressure levels of the steam Rankine cycle. It is also observed that net efficiency slightly depends on the working conditions of the bottoming cycle (± 2% for most of the configurations). The parameter that primarily affects cycle efficiency is the inlet and outlet temperature of gas in the gas turbine (but the outlet temperature is given by pressure ratio and turbine inlet temperature). The higher the temperature the higher the topping cycle (Brayton) efficiency according to second's law of thermodynamics but in both modes (solar and fueled), these temperatures have been fixed since pressure ratio cannot be increased. As it can be observed, two-pressure level Rankine cycle configuration shows higher efficiency than one and three-pressure levels, above 47% for fueled model and 40% for solar mode (lower temperature available). It was also found for the solar mode that increasing steam pressure of HP turbine above optimum value of 15 bar (one-pressure), 40 bar (two-pressure) and 60 bar (three-pressure) will worsen combined cycle optimum efficiency. For the fueled mode, slightly higher pressures were found as the optimum value providing cycle peak efficiency while going beyond that pressure will not impact on cycle net efficiency. Steam pressure levels found in fueled mode are coherent with real CC fed exclusively with natural gas[20]. Cycle efficiencies of ISCC with the assumed boundary conditions are far from real CC by two reasons: Firstly, the inlet temperature of gas in the gas turbine (typical values are between 1300 and 1400 ºC), and secondly, the low gas pressure ratio in Brayton Cycle (in commercial CC is between 17-25). As mentioned above, there is a limitation in the maximum temperature and pressure at the inlet of gas turbine due to solar receiver specifications which reduces the allowable CC efficiency.

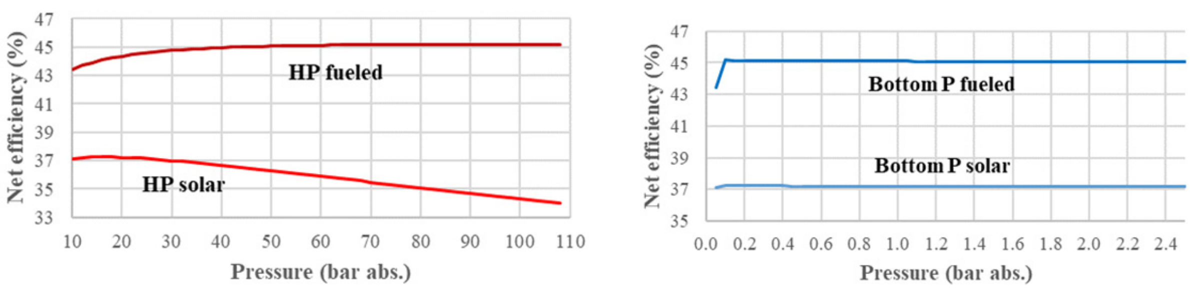


FIGURE 4. Net efficiency of ISCC configuration a (one-pressure level). Left: High pressure steam. Right: Bottom pressure steam.

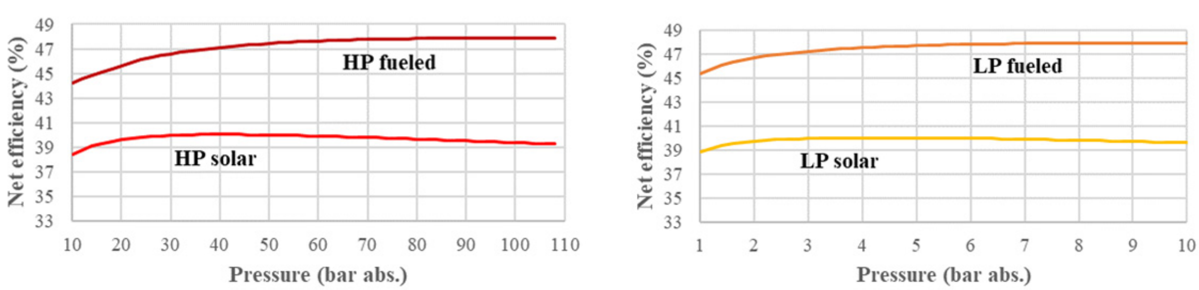


FIGURE 5. Net efficiency of ISCC configuration b (two-pressure levels). Left: High pressure steam. Right: Low pressure steam.

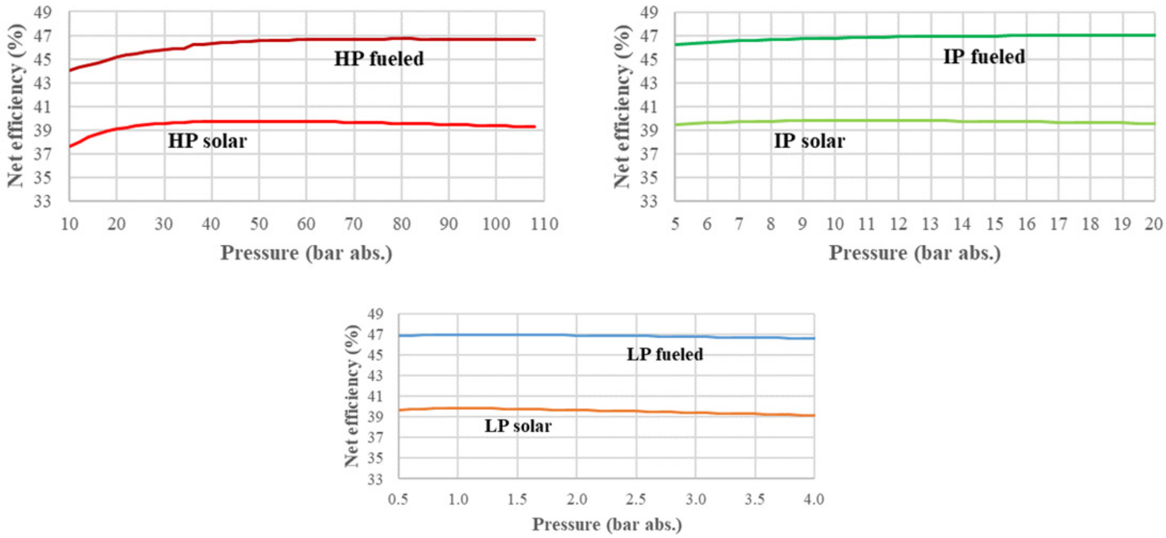


FIGURE 6. Net efficiency of ISCC configuration c (three-pressure levels). Left: High pressure steam. Right: Intermediate pressure steam. Down: Low pressure steam.

TABLE 2 and TABLE 3 show the optimum pressures for each configuration, the net cycle efficiency obtained and the net power produced by the ISCC. On average, the efficiency of the ISSC in fueled mode is 7 points higher compared to same ISCC in solar mode. Also, it has been demonstrated that a two pressure-levels Rankine cycle has a higher efficiency than the same with higher working pressures when the cycle is the bottoming cycle of a CC power plant. This conclusion has been obtained in both operation modes, solar and fueled. TABLE 3 also shows the percentage of thermal energy introduced by solar irradiation to the whole system. As it can be seen, the contribution made by solar energy varies between 54 % and 56 %.

TABLE 2. Optimum operating pressures for ISCC only fed by solar energy.

	PRESSURE (bar abs.)					
CONFIGURATION	**HP**	**IP**	**LP**	**Bottom P**	**Cycle efficency (%)**	**Net Power (MWe)**
a	16.5	-	-	0.1	37.2	37.2
b	38	-	4	0.1	40.0	40.0
c	48	9.5	1	0.1	39.7	39.8

TABLE 3. Optimum operating pressures for ISCC fed by solar energy and natural gas.

	PRESSURE (bar abs.)						
CONFIGURATION	**HP**	**IP**	**LP**	**Bottom P**	**Efficiency (%)**	**Net Power (MWe)**	**Solar contribution (%)**
1	80	-	-	0.1	45.6	68.6	54.2
2	77	-	8	0.2	47.8	71.8	55.4
3	103	17.5	1.5	0.2	47.0	70.6	56.2

A summary of the operating conditions at the inlet and outlet of the steam turbines for the optimum configurations discussed above (b and 2) is provided in

TABLE 4 and TABLE 5 respectively. Values provided for each point are as follows: temperature, pressure and mass flow of steam and the dry step efficiency of the turbine.

TABLE 4. Operating conditions in steam turbine for ISCC only fed by solar energy (configuration b)

	Temperature (ºC)	Pressure (bar)	Steam mass flow (kg/s)	Efficiency (%)
HP inlet	432.6	35	12.25	85
HP outlet	186.1	4		
LP inlet	400.4	4	17.60	85
LP outlet	49.64	0.1		
Bottom inlet	49.65	0.1	17.47	85
Bottom outlet	41.51	0.08		

TABLE 5. Operating conditions in steam turbine for ISCC fed by solar energy and natural gas (configuration 2)

	Temperature (ºC)	Pressure (bar)	Steam mass flow (kg/s)	Efficiency (%)
HP inlet	595	77	19.79	85
HP outlet	288.5	8.16		
LP inlet	507.9	8	24.80	85
LP outlet	106.4	0.2		
Bottom inlet	106.4	0.2	24.62	85
Bottom outlet	41.51	0.08		

CONCLUSIONS

In this work, several bottoming Rankine cycle configurations have been optimized for its coupling into combined cycle arrangements. Different Rankine cycle layouts have been analysed with one, two and three pressure levels, with and without natural gas fuel assistance. Sensitivity study covering full operating pressure range from 10 to 110 bar was performed. Modelling results indicated that Rankine cycle optimum pressures of solar mode combined cycle were lower than the fuelled one and that increasing the number of intermediate pressures contributed to extend cycle optimum efficiency in a wider range of operative conditions. It was also found that two-pressures Rankine cycle layout was preferred rather than three-pressures level, for both solar and fuelled configurations due to higher net efficiency and its simpler arrangement. Results demonstrate that current solar receiver technology used in ISCC for heating air/gas, gives whole system efficiency far from modern conventional CC systems, whose conversion efficiencies are nearly 60% due to pressure limitations for pressurized air receivers.

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