New generation Line-Focusing Solar Power Plants with Molten Salts and Supercritical Carbon Dioxide Joule-Brayton Cycles

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New generation Line-Focusing Solar Power Plants with Molten Salts and Supercritical Carbon Dioxide Joule-Brayton Cycles

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Abstract

Nowadays there is no dominant technology for the concentrated solar power plants that means there is still a way to go. Within this context, new concepts for solar fields and power cycles are being studied. One of them is the proposed on this paper: the integration of line-focusing solar field, with parabolic trough or linear Fresnel solar collectors, with molten salts as heat transfer fluid and supercritical carbon dioxide Joule-Brayton power cycles. This concept works as a feasible design solution to increase efficiency and reduce final energy cost in solar electricity production. In this work, four Joule-Brayton cycles configurations were assessed and compared with the considered reference, a concentrated solar power plant with direct steam generation in the solar field and a Rankine power cycle. The studied Joule-Brayton cycles are: simple cycle, recompression cycle, partial cooling with recompression cycle and recompression with main compression intercooling cycle. The common operation conditions for all the configurations are that at design-point the high pressure turbine inlet temperature value is 550ºC, this limit was established considering maximum temperature allowed by selective coating material in linear receivers. Also is analyzed the hypothetical scenario of increasing the turbine inlet temperature to 650ºC, extrapolating the receivers heat losses regressions. The innovative configurations of solar field and supercritical carbon dioxide power cycles increase plant efficiency, for recompression cycle configuration, up to 46.84% (550ºC turbine inlet) and 50.85% (650ºC turbine inlet), and reduces required solar field effective aperture area and land area for a fixed plant power output. Proposed configurations, parabolic trough collector and linear Fresnel coupled with a Joule-Brayton cycle decreases the solar field required for the same net power. Relating to power block, the supercritical carbon dioxide higher density in comparison with water steam, reduces turbines and compressors dimensions, footprint and final cost, but is a technology nowadays under industrial development and final turbo machines cost could not be assessed in this study. Another important keystone in Joule-Brayton cycle costs are the heavy duty heat exchangers required. Printed circuit heat exchangers are the most advisable solution proposed for supercritical carbon dioxide recuperators, mainly due to higher compactness and better heat transfer coefficient inside channels. However, in this paper it is demonstrated how common shell & tube heat exchangers, with AISI 347 (austenitic) stainless steels, are competitive and feasible solutions for the primary and reheating molten salts – carbon dioxide heat exchangers.

Keywords: Supercritical solar power plants, Supercritical carbon dioxide, Molten salt, Line-focusing solar collector.

1. Introduction

Concentrated Solar Power Plants (CSP) future developments will be aligned with supercritical fluids deployment in power plants to get higher operating pressures and temperatures increasing net plant efficiency. In this sense, two main technologies are being developed: supercritical Carbon Dioxide (sCO2) Joule-Brayton power cycles (or Brayton), in the followings, and supercritical Water Rankine power cycles (s-Water). In this context, sCO2 cycles will play an important role, as an innovative solution for increasing net plant efficiency, reducing turbines dimension and volume, obtaining a more compact balance of plant (BOP) and decreasing electricity cost. On the other hand, steam turbines and Rankine power cycles continue being optimized, integrating new materials and more efficient equipments. Clear examples of them are the Supercritical steam water (250 bar turbine inlet) and Ultra Supercritical (350 bar turbine inlet) fossil power plants.

Regarding the optimum Heat Transfer Fluid (HTF) for line-focusing thermosolar plant, there are two main alternatives to replace thermal oils, Direct Steam Generation (DSG) and Molten Salts (MS). DSG main advantages are: no environmental impact, higher operating temperature and pressures, and no intermediate heat exchangers between solar field and Rankine cycle. However, MS is an important competitor as confirmed in Ref. [1], due to these reasons: control simplicity, single phase fluid, reducing number of equipments and cost. MS operating pressure is around 15 bar, mechanical stresses are not very high in receivers and headers, so stainless steel with Molybdenum (AISI 316) could be

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selected to overcome corrosion and reduce receiver wall thickness. MS could operate under high temperatures without degradation or evaporation. However, the main disadvantage of MS is the heat-tracing electrical-consumption to avoid any solidification deposits in equipments and pipes. Also MS is the working fluid more investigated in other power generation technologies, like in next generation nuclear power plants, as the most suitable fluid to get higher efficiency and lower energy cost.

In this study were selected line-focusing Parabolic Trough (PT), Eurotrough II, and Linear Fresnel (LF), Novatec Supernova 1, solar collectors, as an alternative to central tower heliostat field. Nowadays, the most of thermosolar plants integrates linear collectors, being consolidated as a competitive technology with lower civil work and higher manufacturing modularization in comparison with heliostat field with central tower and stirling dishes technologies.

Other important elements in solar plants are the receivers. Archimedes Solar Energy receivers HCEMS-11 (for molten salt) and HCESHS-12 (for DSG) are considered the optimum commercially available; they could operate until 580ºC without any degradation. According to receivers' supplier, it is defined 550ºC turbine inlet as design-point condition, to preserve selective coating material. However, due to a conservative decision, the heat thermal losses correlations for PTC and LF receivers, were obtained for previous Schott's PTR70 receivers widely validated.

The integration between the explained technologies: PT or LF collectors, MS as HTF, and sCO2 Brayton power cycles, is proposed in this paper as a feasible design solution to increase efficiency and reduce final energy cost in line-focusing solar plants. Four BOP configurations are proposed by National Renewable Laboratory (NREL), see Ref. [2], with sCO2 as working fluid: Simple Brayton cycle (SB), see Fig. 1, Recompression cycle (RC), see Fig. 2, Partial Cooling with Recompression cycle (PCRC), see Fig. 3, Recompression with Main Compression Intercooling cycle (RCMCI), see Fig. 4, and compared with the reference solar plant, a DSG with Rankine power cycle, see Fig. 5 and Fig. 6. Plant efficiency at design-point (550ºC turbine inlet) is 40.81%, for the reference DSG+Rankine plant, however this value is increased up to 46.84% for MS+RC solar plants, see Table 1 and Fig. 7. With 650ºC turbine inlet temperature, considering an extrapolation in heat losses regressions for receivers, efficiency goes up to 50.85% for RC.

The improvements in net plant efficiency with innovative MS+sCO2 configurations is translated in Solar Field (SF) Effective Aperture Area savings for a fixed plant power output. In the present study SF aperture area are quantified with the parameter Unitary Power Output (Net Power Output/SF Effective Aperture Area), see results in Fig. 8.

2. Methodology

This study is focused on the thermodynamic performance of proposed MS+sCO2 solar power plants. Energy balances were modeled and simulated with Thermoflow 23 software. sCO2 thermodynamic properties were calculated with REFPROP software, developed by National Institute of Standards and Technology (NIST) and integrated in Thermoflow 23. REFPROP has been coded in Fortran language and employed equations extracted from the original work published by Span and Wagner Ref.[3]. sCO2 behaves in compressor and turbines as a real gas, and deviation between real and ideal gas conditions were assessed by means of compressibility factor (z) and turbo-machines isentropic efficiencies (η). The recuperators are modeled as counter-flow and via the effectiveness number-of transfer units (ε-NTU) method, utilizing a series of sub-heat exchangers to account for the changing physical properties of sCO2.

3. MS + sCO2 solar power plants

Simple Brayton configuration SB, is the most compact and low cost configuration, see Fig. 1, however plant efficiency is the lowest value in comparison with the rest of alternatives. In RC configuration, see Fig.2, a fraction of gas flow (split fraction) is pre-cooled before entering the compressor; the other splitting fraction will be compressed without any pre-cooling. RC configuration key parameter is to choose the optimum split fraction in each case according to no-steady external ambient conditions (DNI, ambient temperature, etc).

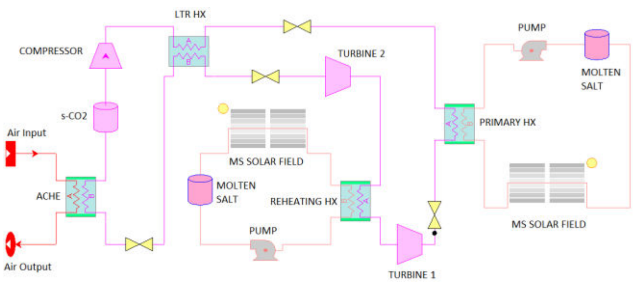

Figure 1. *MS SF with Simple Brayton cycle (SB).*

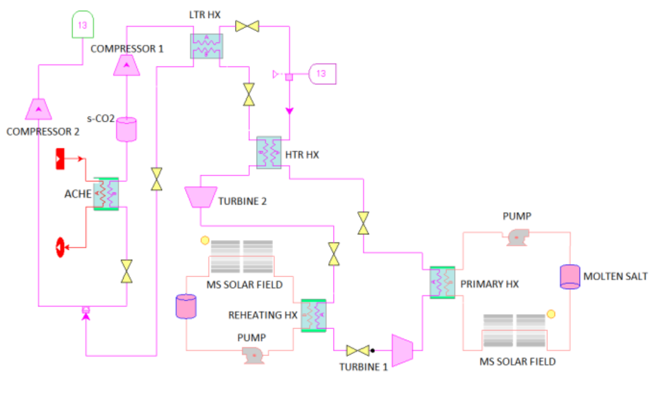

Figure 2. *MS SF with Recompression cycle (RC).*

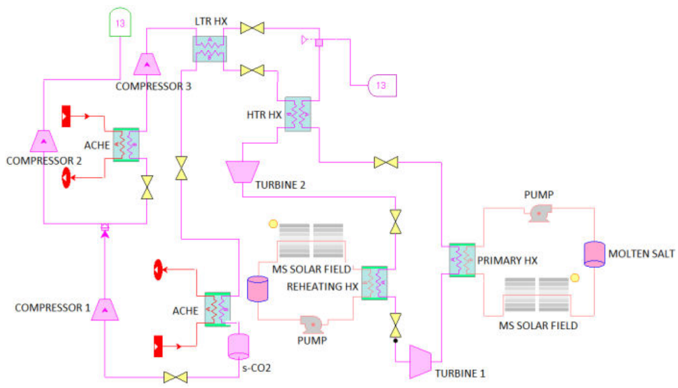

Figure 3. MS SF with Partial Cooling Recompression (PCRC).

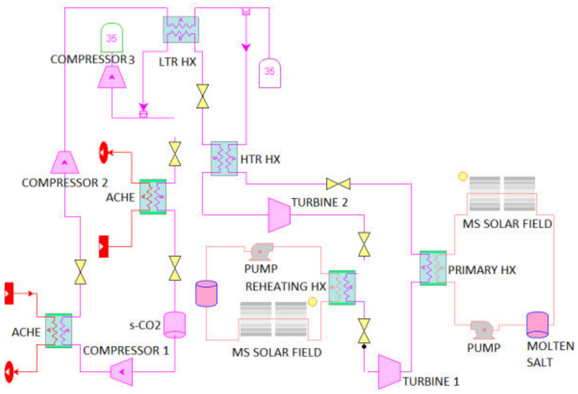

Figure 4. MS SF with Recompression with Main Compression Intercooling (RCMCI).

Regarding RCMCI configuration, see Fig. 4, the most relevant advantage is reducing heat exchanger (HX) overall heat transfer coefficient (UA) in relation with RC for similar plant efficiency, see Table 1. RCMCI includes two inter-cooling stages. The optimum number of inter-cooling stages should be assessed conditioned by heat losses and pressure drops in Air Cooling Heat Exchangers (ACHE), and compressors and ACHE costs. Finally, the PCRC, see Fig. 3, offers the advantages of optimizing UA, see Table 1, but net plant efficiency is between SB and RC. At each case should be confirmed net energy required for gas pre-cooling is lower than energy required for gas compressing.

***Table 1.** Main results configurations comparison .Values for 55 MWe Net plant and 550ºC high turbine inlet.*

Plant Configuration	DSG	SB	RC	PCRC	RCMCI
Total Overall heat transfer coefficient UA(kW/ºC) (*)	-	7766.4	17828	11507.6	15142.8
Plant Net Efficiency (%)	40.81	40.49	46.84	43.1	46.52

(*) Note: Overall heat transfer coefficients (UA) in table 1 were calculated adding UA in recuperators (LTR, HTR), Primary HX and Reheating HX.

2. DSG + Rankine solar power plant (Reference Configuration)

A line-focusing SF with DSG and a Rankine power cycle, with 40.81% net efficiency, was defined as the reference solar plant, as shown in Fig. 5 and Fig. 6. The DSG operational mode is liquid phase recirculation, but also is applicable to Once-Through steam production, with liquid water injections to avoid hot spots and “dry-out” at boiling-ends.

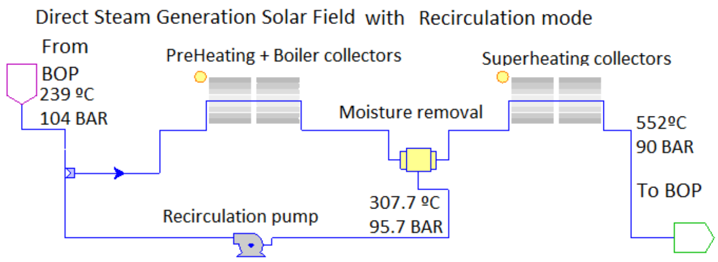

Figure 5. Direct Steam Generation solar field with Recirculation mode.

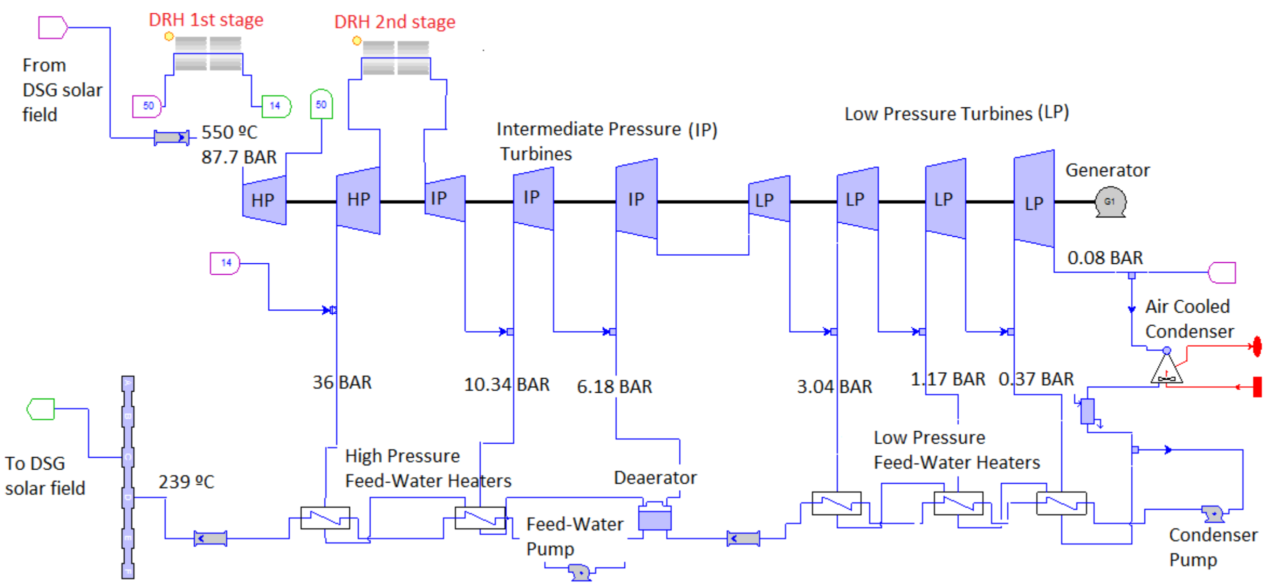

Figure 6. Direct Steam Generation solar field and Subcritical Rankine power cycle with Direct Reheating.

Direct Reheating (DRH) is a relevant technology in linear solar plants to be highlighted, avoiding any intermediate Heat Exchanger (HX) after high pressure turbine stages. In this case, as an innovation, two DRH stages were included, one in High Pressure turbine (HP), and other between HP and Intermediate Pressure turbine (IP). The key design feature in DRH is to limit receiver mass flow and receiver maximum length, to minimize steam pressure drops in reheating SF.

3. Validation of modeling

In order to confirm Thermoflow 23 is capable to achieve sCO2 Brayton power cycles simulations, prior commencing this paper analysis; it was modeled the Fusion reactor power cycle defined in Ref. [4]. Similar thermodynamic results were obtained, concluding Thermoflow 23 with REFPROP integrated, is a sufficient tool to simulate new generation sCO2 Brayton power cycles.

4. Modeling assumptions

All simulations were calculated at design-point with the following high pressure turbine inlet temperatures: 400ºC, 450ºC, 500 ºC and 550ºC. Rest of calculation assumptions are summarized in Table 2 to Table 7.

Table 2. *Location and Ambient conditions.*

Location:	Dagget,CA, USA.
Latitude:	34.86 º
Longitude:	-116.8 º
Hourly zone:	-8
Time:	11:30 hr
DNI:	986 W/m^2
Ambient temperature:	25 ºC
Altitude:	588 m

Table 3. *Receiver parameters.*

Outer Diameter:	70 mm
Wall Thickness:	4.191 mm
Material:	Stainless steel
Roughness:	0.0457 mm

Table 4. *PTC solar collectors parameters.*

Collector type:	EuroTrough II
Aperture Width:	5.77 m
Focal Length:	1.71 m
Collector unit row pitch / collector unit width:	2.5
Cleanliness factor:	0.96
Optical Efficiency:	0.75
Thermal Losses:	$0.141\,\Delta T + 6.48 \cdot 10^{-9}\,\Delta T^4$ Schott PTR70 NREL Ref.[5]

Table 5. *LF solar collectors parameters*

Collector type:	SuperNova 1 (Novatec)
Module Dimensions:	16.56 m (width) x 44.8 m (length)
Aperture area:	513.6 m^2/per Module
Optical Efficiency:	0.67 (boiling) 0.647 (superheating)
Thermal losses:	$1.06\,\Delta T + 1.2 \cdot 10^{-8}\,\Delta T^4$ (boiling) Novatec, Ref. [6]
Thermal losses:	$0.15\,\Delta T + 7.15 \cdot 10^{-9}\,\Delta T^4$ (superheated) Novatec, Ref. [6]

Table 6. *Steam Rankine BOP parameters.*

HP Turbine:	2 stages (87.7 bar; 36 bar)
IP Turbine:	3 stages (16.5 bar; 10.34 bar; 6.18 bar)
LP Turbine:	4 stages (5.17 bar; 3.04bar; 1.17 bar; 0.37 bar)
Turbine Efficiency:	85%
Condenser Pressure:	0.08 bar
Generator Efficiency:	98.23% (at Design-Point)
Auxiliary BOP:	0.01% (Gross Power)
Terminal Temperature Difference (TTD):	5 ºC
Drain Cooling Approach :	5 ºC
Deaerator pressure:	6.17 bar

Table 7. *sCO2 Brayton BOP parameters.*

Turbine Efficiency:	93%
Compressor Efficiency:	89%
HX Effectiveness:	95%
No HX Pressure Drop	
Turbine Inlet Temperature:	550ºC
Turbine Inlet Pressure:	250 bar
Reheating Pressure:	173 bar
Compressor Inlet Temperature:	32 ºC
Compressor Inlet Pressure:	74 bar
Splitting fraction:	71% and 29%
Auxiliary BOP:	0.01% (Gross Power)
Generator Efficiency:	98.23 (at Design-Point)

5. Results

MS+sCO2 solar plants provide higher net plant efficiency rather than DSG+Rankine reference plant configuration for all turbine inlet temperatures, see Fig.7. Main reason is higher sCO2 energy density and hence better turbines efficiency. Above 500 ºC HP inlet temperature, MS+RC is the configuration providing higher efficiency, however, for lower temperatures MS+RCMCI is more efficient. At design-point, 550ºC turbine inlet temperature, MS+RC and MS+RCMCI efficiencies are above 45%, and with DSG+Rankine technology around 40%, for the reheating arrangement. MS+PCRC configuration offers intermediate efficiencies values between MS+RC and MS+RCMCI configurations. A detailed cost study should give more information if UA savings compensate lower efficiency values.

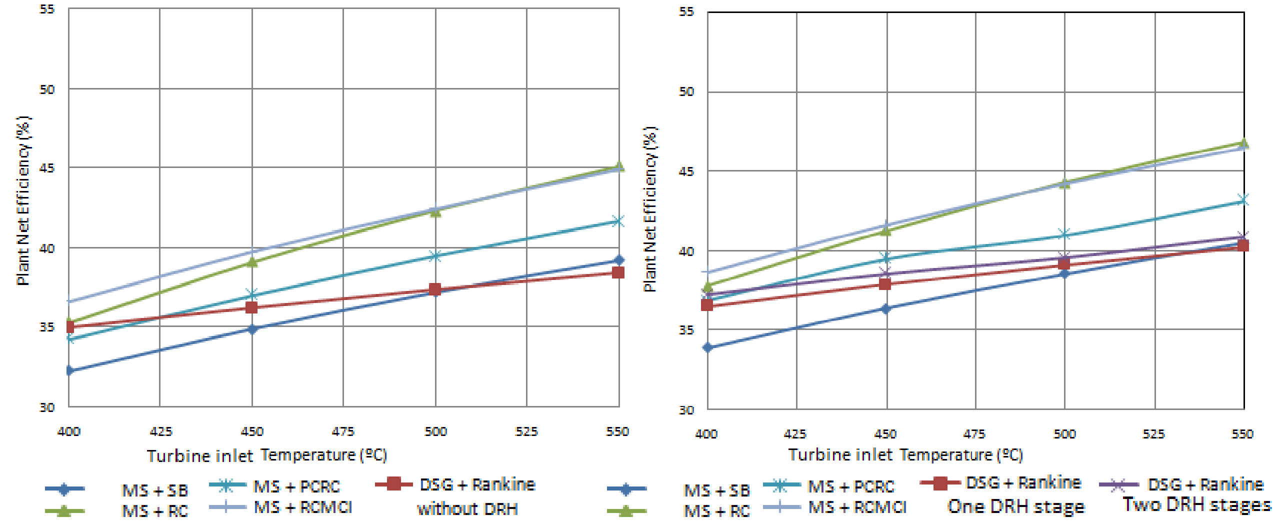

Figure 7. *Net Plant Efficiency without Reheating (left Fig.), with Reheating (right Fig.).*

Savings in SF effective aperture area were computed by means of Unitary Power Output, defined as the relation between Net Power Output and SF Effective Aperture Area, see Fig.8. With PTC and MS+RC plant configuration, the effective aperture area savings are around 6% in relation with PTC DSG+Rankine, and SF land area savings 13.5%. With LF collectors, the SF effective area saving is around 10% for LF MS+RC, in comparison with LF DSG+Rankine, and SF land area reduced about 23.76%.

Also higher Turbine Inlet Temperatures (TIT), from 400ºC to 550ºC, increases unitary power output from 0.249 to 0.282 for PTC MS+RC configuration, and from 0.209 to 0.249 for LF MS+RC configuration, see Fig. 8 right.

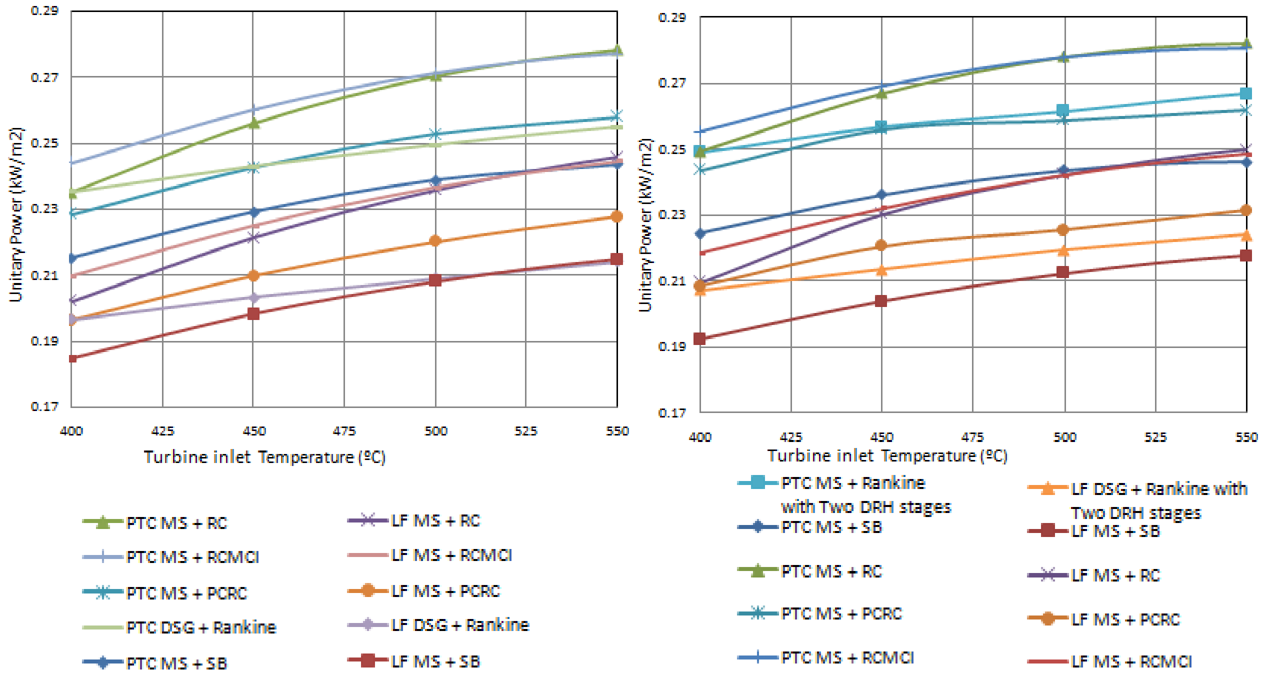

Figure 8. *Unitary Power Output (Net Power output / SF Effective Aperture Area) versus Turbine inlet temperature, without Reheating (left Fig.), with Reheating (right Fig.).*

6. Primary Heat Exchanger and Reheating Heat Exchanger detailed design

Another important feature in sCO2 Joule-Brayton cycles are the heavy duty heat exchangers required. Printed Circuit Heat Exchangers (PCHE) is the most advisable solution proposed for sCO2 recuperators, low pressure (LTR), and high pressure (HTR), mainly due to higher compactness and better Heat Transfer Coefficient (HTC) inside channels. However, in this paper, see Table 8, it is demonstrated how common Shell & Tube Heat Exchangers, with AISI 347 stainless steel Ref.[7, 9, 10], is a feasible solution for Primary Heat Exchanger (PHX) and Reheating Heat Exchangers (RHX) designs, where sCO2 is flowing in tube-side and MS in shell-side. Main advantages of this solution are: Shell & Tube heat exchanger is a widespread and not classified technology, and avoiding MS solidification inside channels. In Table 8 are summarized PHX and RHX unitary cost for Shell and Tube heat exchanger type, and if they are compared with PCHE unitary costs (92 $/kW) Ref.[8], it is concluded PCHE should reduce actual cost to be competitive with Shell & Tubes HX and to expand sCO2 power cycles technology at industrial large scale.

Table 8. *MS+sCO2 line-focusing solar plant Primary HX and Reheating HX detailed-design at design-point conditions, 550ºC HP inlet temperature and 55 MWe Net power output.*

			Shell Length (m)	Shell Diameter (m)	Cost ($)	Units (Uds.)	Total Cost ($)	Heat (kW)	**Unitary Cost** ($/kW)	APtubes (bar)	APshell (bar)
RC	AISI 347	PHX	12.86	1.141	1368503	6	8211018	87174	94.19113	0.1299	0.4956
	AISI 347	RHX	8.759	1.349	1149167	6	6895002	30420	226.6602	0.06	0.1415
	Total				2517670		15106020	117594	**128.459**		
PCRC	AISI 347	PHX	12.17	1.005	1054814	6	6328884	103218	61.31	0.133	0.6962
	AISI 347	RHX	7.688	1.215	876287	6	5257722	24414	215.35	0.0561	0.1554
	Total				1931101		11586606	127632	**90.78**		
RCMCI	AISI 347	PHX	12.04	1.057	1126809	6	6760854	92244	73.29316	0.1277	0.6074
	AISI 347	RHX	7.983	1.255	946542	6	5679252	26130	217.346	0.0571	0.1405
	Total				2073351		12440106	118374	**105.0915**		

Note: PCHE unitary costs 92$/kW, Ref. [8].

6. Conclusions

As base-line a DSG solar power plant was defined: a line-focusing SF with DSG, and a subcritical Rankine power cycle integrating two DRH stages, see Fig.5 and Fig.6. This plant net efficiency is 40.81% for design-point (550ºC and 87.7 bar at HP turbine inlet). Legacy thermal oil solar plants, type Solar Energy Generating Systems (SEGS), net efficiency is ≈ 35% (385ºC and 100 bar at HP turbine inlet). New generation line-focusing solar plants integrating PTC or LF collectors, with MS as HTF, and sCO2 Brayton power cycles were defined, see Fig. 1, Fig, 2, Fig. 3 and Fig.4. Net plant efficiencies were calculated for different turbine inlet temperatures, see results in Fig.7. MS+RC and MS+RCMCI provide better efficiency 46% (550ºC and 250 bar HP inlet). Regarding Brayton power cycles configurations, RCMCI provides optimal relation between SF effective aperture area, net plant efficiency and UA, for a fixed net power output. Also was confirmed MS+sCO2 plants reduces SF aperture area as illustrated with Unitary Power Output results, see results in Fig. 8. It is very important to highlight, sCO2 plant equipments performance were defined as target assumptions, with same values as defined by NREL publications Ref.[2]; nowadays turbines, compressors and heat exchangers are being under industrial development in researching laboratories as Sandia National Lab, see Ref. [8]. Also in relation to sCO2 cycles, it was demonstrated how Shell & Tube heat exchangers for primary, reheating and thermal storage heat exchangers with MS flowing in shell-side, and sCO2 flowing in tube-side, are competitive in comparison with Printed Circuit Heat Exchanger, nowadays a classified technology with only very few international suppliers as Heatric. Future works will involve Thermal Energy Storage System integration in MS+sCO2 line-focusing solar power plants.

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