Integration between direct steam generation in linear solar collectors and supercritical carbon dioxide Brayton power cycles

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ABSTRACT

Direct Steam Generation in Parabolic Troughs or Linear Fresnel solar collectors is a technology under development since beginning of nineties (1990's) for replacing thermal oils and molten salts as heat transfer fluids in concentrated solar power plants, avoiding environmental impacts. In parallel to the direct steam generation technology development, supercritical Carbon Dioxide Brayton power cycles are maturing as an alternative to traditional Rankine cycles for increasing net plant efficiency and reducing balance of plant equipments dimensions and costs. For gaining synergies between these two innovative technologies, in this paper, Direct Steam Generation and Brayton power cycles are integrated in line focusing solar power plants. Four configurations are studied: Configuration 1 consists on installing a condenser between solar field and power cycle; condensing the heat transfer fluid (steam water) with the balance of plant working fluid (carbon dioxide). The condenser would be a shell & tubes type. Along tubes carbon dioxide flows, and steam water condensates at shell side. Main advantage of the condenser equipment is the high heat transfer coefficient at water condensing side, reducing condenser dimension and weight. The main disadvantage of this configuration is the high operating pressure required in solar field for condensing steam into liquid water. This pressure should be between 150 bar and 175 bar for obtaining 400°C at turbine inlet. In the Configuration 2, the superheated steam delivered by solar collectors transfers the heat energy in a primary heat exchanger to the balance of plant working fluid. In this configuration the steam not condensate into liquid water, and only reduces the temperature from 550°C 560°C to 420°C. The steam pressure drops in solar field along receivers, headers and heat exchangers are compensated by means of steam compressors. This second solution is compatible with higher turbine inlet temperatures, up to 550° C. The keystones of this second configuration are the steam conditions at compressor inlet, pressure ~175 bars and temperature ~420°C, for minimizing steam compressor electrical consumption. The third design solution (Configuration 3) includes a solar field with direct steam generation in solar collectors with boiling recirculation mode, but the balance of plant is integrated by two Brayton power cycles in cascade. The first power cycle operating at 550°C turbine inlet, and the second cycle at 410°C turbine inlet. Main advantage is the integration between a validated direct steam generation technology (recirculation boiling mode) with the Brayton power cycles avoiding steam compressors, a technology not yet commercially available, and main drawback of this design is the increasing number of balance of plant equipments. The Configuration 4 is very similar to the Configuration 2, with the same direct steam generation solar field with superheated steam without condensing, and a single reheating stage solar field with molten salt as heat transfer fluid.

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The Configuration 1 provides similar efficiency and net power output, for similar solar field effective aperture area, as obtained with molten salt solar collectors with supercritical carbon dioxide power cycle (recompression with main compression intercooling cycle provides 36.6% net efficiency, for a maximum 400 °C turbine inlet). The second design solution (Configuration 2) net efficiency is not very much impacted for steam compressor electrical consumption recompression cycle net efficiency is 43.6% with steam solar field, versus 45.16% with molten salt solar field, in both cases with 550°C turbine inlet. The Configuration 3 performance is ~39.7% with two cascade Brayton power cycles with recompression and main compression intercooling. Finally, the Configuration 4 optimum plant performance is obtained for the recompression cycle with a net efficiency ~45.77%, and is constrained by the molten salt drawbacks (material corrosion, material cost, environmental impact, etc).

Nomenclature		TES	thermal energy storage system
s CO ₂	supercritical carbon dioxide	DISS	direct solar steam
DSG	direct steam generation	DUKE	Durchlaufkonzept e Entwicklung und Erprobung
BOP	balance of plant	NREL	National Renewable Laboratory (in U.S.)
CSP	concentrating solar power plant	TSE 1	Thai Solar Energy Co., Ltd.
DRH	Direct ReHeating	PSA	Plataforma Solar de Almería
HP	High Pressure Turbine	SB	simple sCO ₂ Brayton power cycle
HTF	heat transfer fluid	RC	recompression sCO ₂ Brayton cycle
IAM	incident angle modifier	PCRC	partial cooling with recompression cycle
ISCC	integrated combined cycle	RCMCI	recompression with main compression intercooling cycle
LCOE	levelized cost of Energy	LTR	Low Temperature Recuperator
LF	linear Fresnel	HTR	High Temperature Recuperator
DNI	direct normal irradiance	PHX	primary heat exchanger
NREL	National Renewable Laboratory (U.S.A)	RHX	reheating heat exchanger
OT	once through boiling mode in DSG	ACHE	air cooled heat exchanger
PE 1	Puerto Errado 1	HX	heat exchanger
PE 2	Puerto Errado 2	TIT	turbine inlet temperature
PTC	parabolic trough collector	HTC	heat transfer coefficient
RC	recirculation Boiling mode in DSG	U	overall heat transfer coefficient
SAM	system advisor model	A	heat transferring area in heat exchanger
SF	solar field	UA	heat exchanger conductance

Introduction

The most common steam boilers technology in conventional fossil power plants are the liquid water recirculation (RC) boilers with steam drums, and once through (OT) steam boilers without steam drums, the Benson boilers. Concentrated Solar Power Plants (CSP) are gaining synergies from these fossil fuel boilers technologies, adapting them to solar energy power plants, and particularly substituting boiler tubes by solar receivers in Parabolic Troughs (PT) and in Linear Fresnel (LF) solar collectors. This is the so called Direct Steam Generation (DSG) technology.

The first DSG plant was built in U.S. in 1870's by John Ericsson [1]. A larger DSG plant with 1250 m² of mirror area was built by Frank Shuman in Egypt [2]. The plant delivered saturated steam at 10 bar for driving a pumping station. Intensive research on DSG systems with the target of generating superheated steam started in the 1990's which finally led to the erection of the DISS test plant [3] at Plataforma Solar de Almería (PSA) located in Spain, for adapting RC boiling mode in PTC solar collectors. The DISS facility was the first test plant for DSG, with a 500 m DSG loops based on LS3 solar collectors. The main results of this project were a general proof of water boiling modes, and evaluation of pressure losses in horizontal

tubes [4]. Within the European INDIPET project, two additional Eurotrough 100 collectors were installed for increasing the thermal power for testing the compact phase separators [5]. Further components tests have been performed in the projects DIVA [6] and Real DISS, and latter ones in a small test SF connected to a coal fired power station in Carboneras, Spain, for steam parameters up to 500 °C and 110 bar were performed [7]. An integrated storage system composed by a Phase Change Component (PCM) and a concrete storage system were tested at this facility [8,9]. Recently since 2012, to assess the OT operation, the DISS facility has been extended in the frame of the DUKE project [10–13], and the equipments and instrumentation retrofitted for delivering steam up to 110 bar/550 °C. The research project DUKE aims at the development and demonstration of a commercially applicable OT boiling mode in DSG solar collectors.

In 2009, Novatec Solar commenced the operation of 1.4 MWe LF test facility Puerto Errado 1 (PE 1) located in Clasparrá, Spain. The two collector rows were first used for demonstrating the Fresnel collector and the saturated steam process for pressure up to about 50 bar [14]. In 2011, an additional superheater loop was erected and successfully tested for temperatures of about 500 °C [15]. Also a LF with DSG demonstration system is operated at the Themis solar energy R&D platform in the Pyreneans [16]. Areva Solar erected the 7.8 MWth Kimberlina test plant at Bakersfield, California in order to demonstrate its OT compact LF collector technology [17]. A 30 MWe electric plant based on Novatec Solar's NOVA 1 LF collectors went into operation in early 2012 in Calasparra, Spain [18,19]. The same year, a small solar boiler of 9.3 MWth went into operation at the Liddell coal fired power station in Australia [20].

Regarding PTC solar collectors with DSG, after the DISS project, the most remarkable industrial facility was the Tresert PTC plant in Phitsanulok, Thailand, it went into operation in 2012 demonstrating the co generation of electricity [21]. The worlds' first large scale DSG plant based on PTC technology went into operation in early 2012 in Kanchanburi, Thailand [22,23]. The plant delivers steam at 30 bar/330 °C to a 5 MW steam turbine. The first plant experience confirmed the system operated well even under transient Direct Normal Irradiance (DNI).

Other recent development related with DSG in line focusing collectors, is the application of this technology to avoid any intermediate heat exchanger in ReHeating steam between High Pressure Turbine and Intermediate or Low Pressure Turbine. This technology is called Direct ReHeating (DRH), see Refs. [24,25].

In relation to DSG receiver pipes, selective coating material are being developed for increasing SF steam temperature delivered to Balance of Plant (BOP). We mention the company Schott PTR70 solar receiver (4th Generation) operating up to temperatures around 550 °C [26]. Also the company Archimedes Solar developed the HCESHs 12 [27] receivers for DSG technology. The inner steel tube of the HCESHs 12 has geometry and a thermo mechanical strength such as to optimize the performance and durability for the purpose of direct steam generation to high pressure and temperature. The HCESHs 12 has been designed to operate with superheated steam at pressures higher than 100 bar, with a fluid

temperature of 550 °C. The HCESHs 12 uses pill getter into the vacuum annulus. This getter permits a safe and efficient operation for the whole expected receiver life absorbing the residual gases desorbed by the metal.

DSG main advantages in relation to other Heat Transfer Fluid (HTF) are: no working fluid degradation, a clean technology with no environmental impact, no Heat Exchanger (HX) between Solar Field (SF) and BOP, industrial scalable, already validated in commercial plants, temperatures and pressures at turbine inlet only limited by receivers and headers mechanical stresses, low piping corrosion and low maintenance costs, no heat tracing required to avoid HTF solidification, etc.

In parallel to DSG technology development, supercritical fluid Brayton power cycles, with supercritical Carbon Dioxide (s CO₂) as working fluid, are maturing as the most promising technology for increasing actual steam Rankine power cycles efficiency, and for reducing BOP foot print and costs. The ability of the s CO₂ cycle to reach high efficiency comes from the reduced compressor work as the compressor inlet conditions approach the critical point of CO₂. The density of the supercritical fluid increases dramatically. The increased density close to the critical point reduces the compressor work.

In 1997 an investigation of the s CO₂ cycle for possible use in new power plants was conducted at the Czech Technical University in Prague, Czech Republic [Petr et al., 1997]. The recompression cycle with re heating gave the best cycle efficiency. It was found that this type of cycle is mainly suited for high temperature nuclear reactor application. The work about s CO₂ Brayton cycles for power generation continued. In the United States the investigation of the recompression supercritical CO₂ cycle was resumed in the year 2000 at MIT under collaboration with INEEL. An indirect supercritical CO₂ recompression cycle was designed for a lead–bismuth eutectic cooled reactor [Dostal et al., 2001]. A net efficiency of 41% was calculated for a compressor outlet pressure of 20 MPa and LBE reactor outlet temperature of 555 °C. At Argonne National Laboratory the recompression cycle was evaluated for the STAR LM reactor [Moisseytsev et al., 2003], and at INEEL the CO₂ Brayton cycle with multiple inter coolers operating at temperatures above 900 °C is being investigated for thermal spectrum gas cooled reactors [Oh, 2002]; both are NERI projects. s CO₂ recompression cycles have been investigated at MIT for several years, beginning in 2000. Dostal in 2004 published an important reference thesis in this field, titled: “A supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors”. Since 2007 a biannual Symposium focus on s CO₂ Power Cycle is being organized to advance this technology. The first Symposium was held at the MIT in 2007, and the most recent one in 2014 has just held in Pittsburgh, Pennsylvania, US. In 2013 was published by NREL, in U.S. a study proposing different sCO₂ Brayton power cycles configurations for Concentrated Solar Power Plants (CSP). Four Brayton power cycles arrangements were proposed [28–30]: simple Brayton cycle (SB), Recompression sCO₂ Brayton cycle (RC), Partial Cooling with Recompression cycle (PCRC) and Recompression with Main Compression Intercooling cycle (RCMCI). See Figs. 1–4. The main important s CO₂ Brayton power cycle researching project, nowadays under

development, is headed by NREL in U.S., designing and constructing a real 10 MWe facility for power generation, see Ref. [31].

Adaptation s CO₂ Brayton cycles to interface with various heat sources will be imperative for its adoption as an industry manufactured technology. Interfacing the solar resource with a s CO₂ Brayton cycle requires a receiver to absorb the solar thermal energy from the incident concentrated flux and transfer the energy to a transport media. This paper is focus on integrating DSG in linear solar collectors (PTC and LF) with s CO₂ Brayton power cycles, see Fig. 7. For this purpose four DSG + s CO₂ power plants configurations are proposed, see Fig. 8 (Configuration 1), Fig. 9 (Configuration 2), Fig. 10 (Configuration 3) and Fig. 11 (Configuration 4). The Configuration 1 and 2 could be integrated in one plant arrangement as illustrate in Fig. 7. These innovative solar power plant were compared with the reference, a solar plant with line focusing collectors (PTC or LF) with DSG and a Rankine power cycle without reheating, illustrated in Figs.5 and 6.

In Configuration 1 the superheated steam (400 °C) from SF is condensed into liquid water for heating up the BOP working fluid (s CO₂), firstly in the super heater and afterwards in the condenser, sees Fig. 8. Configuration 1 is advisable for low TIT up to 400 °C. SF generates steam in RC boiling mode, with 0.8 steam quality at SF output, and SF operating pressure is between 150 and 175 bar.

In Configuration 2, illustrated in Fig. 9, steam generated in SF, goes to primary heat exchanger (PHX) and transmits the heating energy to s CO₂ in BOP, but in this case steam not condenses into liquid water, leaves the PHX in vapour phase with a temperature around 420 °C. The TIT range for this configuration is up to 550 °C, and is schematically illustrated in Fig. 9. For transitory periods, with low Sun irradiation or for the transition between both configurations operating modes, it should be installed a fossil fuel boiler as back up heat energy source, as illustrated Fig. 7. For simplicity, in Figs. 7–9 the RC Brayton power cycle is represented, but in this paper were analysed also the SB, PCRC and RCMCI cycles. Also it is important to highlight the Configuration 1 and 2 plants have no reheating stage in Brayton cycle.

The Configuration 3 is similar to the Configuration 1, with a DSG SF but with two Brayton power cycles connected in cascade. This plant design integrates a single reheating in the first Brayton power cycle operating at 550 °C TIT, see Fig. 10.

Configuration 4 is an evolution from Configuration 2 with a MS SF and a DSG SF both delivering heat energy for obtaining 550 °C at TIT, see Fig. 11.

Fig. 1 – Simple recuperated s-CO₂ Brayton power cycle (SB).

Methodology

This study is focused on calculating the innovative DSG + s CO₂ solar power plants thermodynamic performance at design point. Energy balances were modelled and simulated with ThermoFlow 23 software. This software capability for calculating supercritical Brayton power cycles energy balances was validated with the BOP designed for the nuclear fusion reactor [32].

s CO₂ 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 [33]. S–CO₂ 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 modelled as counter flow and via the effectiveness number of transfer units (ϵ NTU) method, utilizing a series of incremental sub heat exchangers to account for the changing physical properties of s CO₂. The steam compressors are modelled calculating thermodynamic parameters (pressure and temperature) at inlet and outlet, and deducting real enthalpy according to equipment isentropic efficiency. As first estimation, 80% compressor isentropic efficiency was assumed. However, in future researching works steam compressor should be detailed designed and manufactured for this innovative application.

DSG solar field water properties are calculated according to steam tables. Preheating and superheating receivers heat transfer coefficients (HTC) are calculated with Dittus Bolter (1930) correlation, and pressure drops according to Darcy–Weisbach equations. For boiling receivers, Kandlikar (1990) correlation is considered for HTC calculations, and pressure drops in two phase state is computed with Friedel (1979) expression.

Line-focus solar power plant with DSG and a subcritical Rankine power cycle without reheating (Reference Configuration)

As base line was considered a Line Focus (with PTC or LF solar collectors) with DSG and Subcritical Rankine power cycle without reheating (DSG + Rankine), as illustrated in Figs. 5 and 6.

Fig. 2 – Recompression s-CO₂ Brayton power cycle (RC).

Fig. 3 – Partial cooling with recompression Brayton s-CO₂ power cycle (PCRC).

Fig. 4 – Recompression with main compression intercooling s-CO₂ Brayton power cycle (RCMCI).

Modelling assumptions

All solar power plants simulated in this study were modelled considering the performances parameter summarised in the following Tables 1–5.

Line-focusing DSG + s-CO₂ solar power plant (Configuration 1)

The solar plant is integrated by two main zones: linear solar collectors (PTC or LF) with DSG and a Brayton power cycle with s CO₂ as working fluid. The SF are subdivided in three zones, see Figs. 7 and 8: solar collectors for water preheating and boiling, a steam superheating collectors zone and a fossil fuel boiler. A PHX transfers energy between SF to BOP. The Brayton power cycles configurations are defined in Refs. [28,29]. In Configuration 1 the saturated vapour is generated in SF or in fossil boiler, and afterwards superheated in SF. The plant start up and operation under Sun no steady periods, is backed with the fossil boiler. This equipment also could be very useful for the transitory operating modes between Configuration 1

Fig. 5 – Line-focusing DSG solar field with RC mode (Reference Configuration).

and 2. An optimum plant design should warranty the Configuration 1 and 2 interchangeability depending on the Sun irradiation conditions.

This operating mode was designed for low TIT up to 400 °C, also it is advisable for low Sun radiation periods. SF and BOP mass flows are adjusted to warranty only liquid water at feed water pump inlet avoiding any cavitations damages. The PHX is subdivided in two equipments, see Fig. 8: the Superheater HX, steam leaving linear solar collectors heats up s CO₂ without condensing; in the second equipment, the Condenser HX, the steam generated in SF is condensed into liquid water transferring the latent heat to s CO₂; water latent heat energy storage is an optimum mechanism for heat transferring, and due to this reason condenser dimensions are lower than superheater. In order to condensate the steam generated in solar collectors, is necessary to increase SF operating pressure between 150 and 175 bar. For this reason receiver material and thickness should be selected to withstand pressure up to 175 bar. The carbon steel pipes with wall thickness ~8 mm is the optimum choice in price and in mechanical properties. Receiver thickness not should be increased too much due to HTF corrosion phenomenon, since water is not as aggressive as MS.

Line-focusing DSG + sCO₂ plant (Configuration 2)

In Configuration 2 the steam generated in the solar collectors is also superheated steam but not condensate into liquid water in SF, see Fig. 9. The steam compressors compensate pressure drops along receivers' pipes. For compensating steam leakages or for absorbing fluctuation in steam thermodynamic conditions, in parallel with superheater solar collectors are connected a SF boiling modules and a back up fossil fuel boiler, see Fig. 7.

The solar plant arrangement illustrated in Fig. 9, was designed for TIT above 400 °C up to 550 °C. With this solution, superheated steam generated in collectors is delivered to the PHX, transferring heat energy to BOP working fluid. However, in this case the steam leaving the PHX is superheated with thermodynamic conditions above water saturation point, and as mentioned not condensates before entering again in the solar collectors. Other important parameter is the SF inlet temperature (~427 °C–175 bars), for optimizing PHX design and reducing as much as possible steam density for minimizing steam compressors electrical consumptions. The commitment is explained as follows: if steam temperature leaving PHX is very low, the temperature difference between hot and cold fluid is not very high, hence PHX final dimension will be increased. On the other hand, if steam temperature entering the compressor is very high, steam density is going to be lower and compressor electrical consumption and efficiency is going to be impacted negatively. Talking about receiver pipes material, T91 or AISI 316Ti (ferritic or austenitic stainless steels), could be selected as the optimum material to withstand with high temperature steam corrosion, and also with high pressure levels, 560 °C and 175 bar. But for economical reason carbon steel receivers were finally adopted with higher wall thickness ~8 mm.

Fig. 6 – Subcritical Rankine power cycle without reheating (Reference Configuration).

Fig. 7 – DSG + RC s-CO₂ solar power plant with PTC or LF solar collectors (Configuration 1, Configuration 2).

Fig. 8 – DSG + s-CO₂ solar power plant (Configuration 1), TIT up to 400 °C.

Fig. 9 – DSG + s-CO₂ solar power plant (Configuration 2), TIT from 400 °C up to 550 °C.

As mentioned, in Configuration 2, steam compressor electrical consumption should be optimized to avoid a great impact in net plant efficiency. In this sense, another key parameter is the maximum mass flux in receivers. This parameter was limited to 1000 kg/m²·s in LF collectors, and up to 850 kg/m²·s in PTC collectors. Limiting mass flux warranties maximum pressure drop in SF, and hence, provides an optimum SF arrangement design. Also steam compressor electrical consumption depends on the SF

operating pressure. The higher pressure values in SF increase steam density and reduces compressor work. However, increasing SF operating pressure requires high cost material in receivers pipes and higher pipe wall thickness and adequate movable joint design. An economical study is necessary to conclude the optimum SF operating pressure in relation with material cost. Higher pressure is most suitable for LF collectors without any movable joint and stiffer piping design.

Fig. 10 – DSG + s-CO₂ solar power plant (Configuration 3), TIT up to 550 °C.

Fig. 11 – DSG + MS (ReHeating) + s-CO₂ solar power plant (Configuration 4), TIT up to 550 °C.

Table 1 – Location and ambient conditions.

Location:	Dagget, CA, USA.
Latitude:	34.86°
Longitude:	116.8°
Hourly zone:	8
Time:	11:30 h
DNI:	986 W/m ²
Ambient temperature:	25 °C
Altitude:	588 m

Table 2 – Receiver parameters.

Pipe material:	Stainless steel
Outer diameter:	70 mm
Thickness:	4 – 8 mm
Internal roughness:	Ra = 0.0457 mm

Line-focusing DSG + two RCMCI s-CO₂ cycle in cascade (Configuration 3)

The purpose of this plant design solution (Configuration 3) is integrating the DSG solar collectors technology with the s CO₂ Brayton power cycles but without utilizing any steam compressors and obtaining higher TIT ~550 °C. The steam compressors as already mention are not yet commercially

Table 3 – PTC solar collectors' parameters.

Collector type:	EuroTrough II
Aperture width:	5.77 m
Focal length:	1.71 m
Cleanliness factor:	0.96
Optical efficiency:	0.75
Thermal losses:	0.141 ΔT + 6.48e 9 ΔT ⁴ (boiling superheated DSG) [34]

Table 4 – LF solar collectors' parameters.

Collector type:	SuperNova1 (Novatec)
Module dimensions:	16.56 m (width) × 44.8 m (length)
Aperture area:	513.6 m ² /per module
Optical efficiency:	0.67 (boiling); 0.647 (superheating)
Thermal losses:	1.06 ΔT + 1.2e 8 ΔT ⁴ (boiling DSG) [35]
Thermal losses:	0.15 ΔT + 7.15e 9 ΔT ⁴ (superheated DSG) [35]

available for this application. Final industrial design will be constrained by the real isentropic efficiency and performance, key stone for confirming the Configuration 2 industrial feasibility.

The Configuration 3 general arrangement is illustrated in Fig. 10, and it is integrated by an RC boiling solar field with DSG solar collectors (PTC or LF) and two Brayton cycles in cascade. The steam delivered by the superheater solar collectors with a temperature around 550 °C will enter into the first RCMCI Brayton power cycle transferring the heat energy to the BOP working fluid. The temperature difference in the

Table 5 – s-CO₂ Brayton BOP parameters.

Turbine efficiency:	93%
Compressor efficiency:	89%
HX effectiveness:	95%
No HX pressure drop	
Turbine inlet:	550 °C
Turbine inlet:	250 bar
Reheating pressure:	173 bar
Compressor inlet (°C):	32 °C and 74 bar
Auxiliary BOP:	0.01% (Gross power)
Generator efficiency:	98.23 (Design Point)

primary heat exchanger in the first power cycle is in the range of 550 °C and 410 °C. This first cycle also integrates a single reheating stage for heating the working fluid up to 550 °C after the High Pressure turbine (HP). The steam vapor leaving the primary heat exchanger in the first cycle will go into the second power cycle at a temperature around 410 °C. In this second power cycle the water steam will be condensate into saturated liquid water at 350 °C, for this purpose the SF operating pressure is 175 bar (water saturation temperature 354.63 °C). Main advantage of Configuration 3 is the plant performance, very similar than the DSG + Rankine solar power plants with Reheating ~40%.

There are some design parameters and ratios to respect in this Configuration 3 for obtaining the optimum plant performance. The first one is the relation between s CO₂ the mass flow in the cycle 1 and the s CO₂ mass flow in the cycle 2, this relation should be ~6.2, in order for obtaining saturated liquid water at SF inlet. Another two important parameters should be fixed, the temperatures in the PHX1 (410 °C steam outlet and 550 °C s CO₂ outlet), see Fig. 10. The steam water splitting fraction to the RHX in the first power cycle is 55% of the total superheated steam flow delivered by the DSG SF. And finally the flow fraction before compressing in both cycles was fixed to 60%–40%.

Also the Configuration 3 performance could be optimized fixing the recuperators conductance (LTR and HTR) in both cascade cycles. This is a practice proposed in Ref. [38] and increases the net plant efficiency ~1% for this particular case.

DSG + MS ReHeating + s-CO₂ Brayton solar power plant (Configuration 4)

Based on the results obtained for the DSG + s CO₂ solar power plants without ReHeating (Configuration 2), we designed other solar power plant layout for decreasing SF and HXs total capital investment cost and increasing net plant efficiency. The target is introducing a Single ReHeating stage in Configuration 2, another turbine, for maximizing the plant efficiency, as demonstrated by [MIT, Dostal 2004]. Also we maintained the main SF with DSG, and the additional ReHeating SF will be integrated by MS field with PTC or LF solar collectors. The innovative dual loops plant Configuration 4 layout is illustrated in Fig. 11.

Results

Net plant efficiency at design-point

In the legacy PTC solar power plants, like Andasol 1 (Spain), the HTF was synthetic oil with an operating limit around 390 °C to avoid any oil degradation. For this reason the live steam operating parameters were limited to 380 °C and 100 bar at turbine inlet. With these conditions and a legacy Rankine power cycle, with Reheating and only 3 low pressure feed water heater, a deareator and 1 high pressure feed water heater, the net plant efficiency was around 35%. With latest Rankine power cycle configurations, with same TIT 380 °C and 100 bar, with Reheating, 4 low pressure feed water

heaters, a deareator, 3 high pressure feed water heaters, the net plant efficiency is ~37.5%.

The state of the art DSG + Rankine power cycle with DRH [24,25,39,40] also could provide net plant efficiency up to ~41% for TIT 550 °C and two reheating stages at same temperature, see Table 10. This configuration could play an important role in the next generation solar power plants, because despite the higher Brayton s CO₂ solar power plants net efficiency, the material and equipment cost in the innovative s CO₂ power cycles should be optimized for being competitive with the steam Rankine power plants, with equipments made of carbon steel.

In this paper we considered as the reference plant the DSG + Rankine technology without reheating as illustrated in Figs. 5 and 6, delivering live steam at 400 °C 90 bar to the BOP. This configuration net plant efficiency is ~35%, detailed results are listed in Tables 6 and 7.

With the innovative DSG + s CO₂ (Configuration 1) proposed in this paper, a net plant efficiency ~36.65% is obtained with same TIT 400 °C and also BOP equipments size and volume is reduced in comparison with legacy steam Rankine turbines, detailed results in Tables 6 and 7.

If we increase TIT up to 550 °C in DSG + Rankine solar plants the net plant efficiency is increased up to 38.4%, see detailed results in Tables 8 and 9. If we substitute the Rankine cycle with an s CO₂ Brayton power cycle, as in Configuration 2, the net plant efficiency is increased up to ~43.6%, see detailed results in Tables 8 and 9. The RC s CO₂ cycle configuration is the optimum one providing higher net plant efficiency. If we consider the MS + sCO₂ solar plant configuration, the net plant efficiency is improved up to ~44.9%. The difference between MS and DSG sCO₂ solar power plants is due to the steam compressor electrical consumption. The target is to optimize the steam compressors industrial design in order to reduce as much as possible the parasitic energy losses in the solar power plant.

It is very important to highlight the Configuration 1 and Configuration 2, not include any Reheating stage after main HP turbine, constituting this issue a handicap in the final plant performance. Configuration 3 integrates a Single Reheating stage and the plant performance at 550 °C TIT is ~39.7%. For more details about the Configuration 3 performance see Table 10.

As explained in this paper, the Configuration 4 was defined for integrating a Single ReHeating stage in the Configuration 2. This plant design maximum net plant efficiency is for the RC s CO₂ power cycle ~45.7%, much higher than the maximum DSG + s CO₂ (RC) solar plant with maximum efficiency 43.68%, see Configuration 4 performance results in Tables 11 and 12.

Solar field effective aperture area

The net plant efficiency is translated in this chapter into SF aperture area savings. For a comparison between different solar plant configuration, we define a parameter called Net Unitary Power and calculated with the following mathematical expression:

Net unitary power (W/m²) Solar field effective aperture area (m²)/plant net Power output (W)

For Configuration 1 as mentioned in the chapter before the optimum s CO_2 solar plant configuration is the RCMCI. The net unitary power difference between DSG + Rankine plant and DSG + RCMCI s CO_2 solar plant is around 4.5% similar as the difference between both plant configuration net efficiency. Configuration Unitary Power Output results are detailed in Table 13 and 14.

For Configuration 2 the Unitary Power Output results are listed in Tables 15 and 16, the optimum s CO₂ solar plant configuration is the RC. The main difference in the net power unitary power between DSG + sCO₂ and MS + sCO₂ are due to steam compressor electrical consumption.

Other important issue to be considered is the similarity in net plant efficiency with PTC or LF solar collectors as detailed in [Tables 6–10](#). Parasitic energy losses in both configurations are similar with the assumptions considered in chapter 5. The different optical efficiency between both type solar collectors (75% with PTC, and between 64.% and 67% with LF, as detailed in chapter 5) is reflected in the different unitary power outputs. For Configuration 1 (TIT = 400 °C), if we consider LF optical efficiency 64.5% and PTC efficiency 75%, the relative difference between optical efficiencies is around 14%, and similar results are obtained comparing the net unitary power, see results in [Tables 13 and 14](#). For Configuration 2 (TIT = 550 °C) If we consider LF optical efficiency 66% and PTC efficiency 75%, the relative difference between optical efficiencies is around 12%, and similar results are obtained comparing the net unitary power between [Tables 15 and 16](#).

For Configuration 3 with two RCMCI Brayton power cycles in Cascade the aperture area for a TIT 550 °C is 247764 m² and the corresponding unitary power 221.98 W/m² with LF solar collectors, and with PTC the aperture area is 212845 m² and the unitary power output 258.4 W/m².

Regarding Configuration 4, the RC configuration is the optimum one minimizing the required aperture area in SF. The relative differences in aperture area in relation with the Configuration 2 are 3.5% for LF and 4% for PTC collectors. Rest of detailed results are listed in [Tables 17 and 18](#).

Solar field capital investment cost estimation

The main variables impacting in SF capital cost is the solar collector type: LF or PTC, and the receiver' pipes material cost. In DSG SF the carbon steel is the optimum material for reducing material cost and compatible with water as HTF. Steam water receiver pipes not require any high alloy steel material, because water corrosion not impacts too much in pipes material; for warranting this issue it would be advisable to treat chemically the water in the SF.

In the following Tables 19 and 24 are summarized the differences between the final SF capital investment cost with MS and with DSG SF. MS SF capital investment cost is higher than in DSG SF, the main reason for this discrepancy is because MS requires stainless steel receivers to avoid the salts corrosion phenomenon. Stainless steel is more expensive than carbon steel mainly due to the nickel alloy.

The solar plant configuration with lowest capital investment cost is the RCMCI with a DSG field, for TIT = 400 °C, it is to say for the Configuration 1. For the Configuration 2 the most advisable plant arrangement in the RC cycle. However, in Configuration 4 both solutions RCMCI and RC provide similar economical results.

Heat exchangers conductance

In this chapter we compare the conductance (UA), product of the Overall Heat Transfer Coefficient (U) by the total heat exchanging Area (A), in all the solar power plants configurations analysed in this paper.

Low Temperature Recuperators (LTR) and High Temperature Recuperators (HTR) conductance in DSG + sCO₂ and MS + sCO₂ solar plants configurations (with MS and DSG as HTFs) are similar. As an example for Configuration 1 (with TIT 400 °C) the LTR conductance UA in the RCMCI configuration with DSG solar collectors is 7228 kW/°C and with MS solar collectors 7227 kW/°C. Also the difference in recuperators UA between Configuration 1 (Tables 25 and 26) and Configuration 2 (Table 27 and 28) are not very representatives. The supercritical cycle arrangement PCRC requires lowest recuperators conductance for a fixed power output as detailed in comparison with rest of sCO₂ power cycles configurations SB, RC, and RCMCI.

Regarding PHX the saving in conductance is very important in Configuration 1 (TIT = 400 °C) in the DSG + sCO₂ power plant arrangement in comparison with the MS + sCO₂ plants due to the water (HTF) steam condensation phenomenon, increasing HTC in PHX and reduce the required area for heat transferring. As an example, in Table 25, for the RC configuration, with DSG, the PHX conductance is 2337 kW/°C, and with MS, the PHX conductance is 6275 kW/°C, around 60% saving. Another important issue to highlight in PHX is the high HTC in HTF side, permits to adopt the Shell and Tube HX configuration for PHX, as a competitive alternative to the PCHX.

The Air Cooled Heat Exchangers (ACHE) for cooling the BOP working fluid before entering the compressors is another important component in s CO₂ power plants. It is important to mention the RC supercritical Brayton optimizes the required ACHE conductance. The difference with rest of configurations is important between 15% and 25% depending on the Brayton configuration.

Table 6 – LF solar power plants net plant efficiency, TIT 400 °C (Configuration 1).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net plant efficiency (%)	35.01	32.25	32.3	35.58	35.34	34.25	34.31	36.65	36.69

Note: All BOP without ReHeating.

Table 7 – PTC solar power plants Net Plant efficiency, TIT 400 °C (Configuration 1).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net plant efficiency (%)	35.18	32.24	32.26	35.53	35.3	34.2	34.27	36.65	36.65

Note: All BOP without ReHeating.

Table 8 – LF solar power plants net plant efficiency TIT 550 °C (Configuration 2).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net plant efficiency (%)	38.39	37.9	39.28	43.68	45.16	40.23	41.71	43.45	44.94

Note: All BOP without ReHeating.

Table 9 – PTC solar power plants net plant efficiency TIT 550 °C (Configuration 2).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net plant efficiency (%)	38.36	37.85	39.24	43.66	45.12	40.19	41.66	43.43	44.9

Note: All BOP without ReHeating.

Table 10 – LF solar power plants net plant efficiency TIT 550 °C (Configuration 3).

Power cycle	Rankine One DRH	Rankine Two DRH	RCMCI
HTF	DSG	DSG	DSG
Net plant efficiency (%)	40.23	40.79	39.7

Table 11 – LF DSG + MS (ReHeating) + sCO₂ solar power plant net plant efficiency, TIT 550 °C (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
Net plant efficiency (%)	39.39	45.76	42.01	45.4

Table 12 – PTC DSG + MS (ReHeating) + sCO₂ solar power plant net plant efficiency, TIT 550 °C (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
Net plant efficiency (%)	39.38	45.77	41.97	45.37

Heat exchanger capital cost estimation

For obtaining a first approach about the HX total cost in the s CO₂ solar power plants, we consider as the main assumption the HX are PCHE typology for reducing volume and size in these equipments. We consider the PCHE unitary cost is 92 \$/kWth as stated in Ref. [36]. Based on that assumption we calculate a first approximation of the total cost of HXs, see Table 29–36 .

The first commentary to this result is about the PCRC configuration. Despite the total UA values in solar plant with PCRC are the lowest ones in comparison with rest of plants: SB, RC, and RCMCI, the total cost of HX in RC solar plants are the lowest ones. The main reason is the temperature difference in heat exchangers since heat transfer is directly proportional to the product of UA and to the Temperature Differences in the HXs.

Another important issue is the material cost for sCO₂ working fluid. s CO₂ requires austenitic stainless steel, and for operating temperatures up to 550 °C the recommended material is AISI 347 with Niobium (Nb) and Molibdenum (Mo), see Ref. [31]. However, the working fluid and HTF in the DSG + Rankine solar power plants is water, and this transfer

Table 13 – LF solar power plants unitary power output, TIT 400 °C (Configuration 1).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net unitary power (W/m ²)	196.5	181.6	184.7	198.8	201.7	193.4	196.2	206.4	209.6

Table 14 – PTC solar power plants unitary power output, TIT 400 °C (Configuration 1).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net unitary power (W/m ²)	236.4	212.2	215.1	231.4	234.6	225.9	228	240.8	243.8

Table 15 – LF solar power plants unitary power output, TIT 550 °C (Configuration 2).									
Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net unitary power (W/m ²)	214.2	206	214.5	235.7	245.4	217.5	227.4	234.2	244.4

Table 16 – PTC solar power plants unitary power output, TIT 550 °C (Configuration 2).									
Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
Net unitary power (W/m ²)	254.81	234.2	243.6	267.7	278.2	247.2	257.9	266.08	276.7

Table 17 – LF DSG + MS ReHeating + s-CO ₂ solar power plants unitary power output, TIT 550 °C (Configuration 4).				
Power cycle	SB	RC	PCRC	RCMCI
Net unitary power (W/m ²)	211.99	244.66	208.9	242.18

Table 18 – PTC DSG + MS ReHeating + s-CO ₂ solar power plants unitary power output, TIT 550 °C (Configuration 4).				
Power cycle	SB	RC	PCRC	RCMCI
Net unitary power (W/m ²)	240.93	277.57	255.63	274.22

fluid is not as corrosive as MS, hence, the selected material for Rankine solar plants is Carbon Steel (CS), with a much lower cost in comparison with SS 347. This matter is reflected in Tables 29–36. The total savings in Rankine plants due to CS material is around 50% in all the HXs. This issue is a pending item for solving in the future s CO₂ plants for gaining competitiveness against Rankine plants. The solution could be reducing sCO₂ corrosive behaviour adding other chemical inhibitors. Also the Brayton cycles loops could be subdivided depending on the maximum operating temperature, for optimizing the material selection. In this study we consider all s CO₂ equipments with same SS347 material.

Manufacturing cost also play an important role to be optimized in PCHE. These HX reduced dimensions, with ~2 mm channels, oblige to adopt very sophisticated manufacturing processes governed by metallurgical processes and controlling stainless steels grains growing between adjacent channels plates.

The state of the art HX design solutions for s CO₂ Brayton power plants are also focus on reducing the pressure drops across this type of PCHE. Pressure drops in HX have a very important impact in sCO₂ Brayton power cycles net efficiency, and also impact in the final electricity cost and power plant

capital investment cost amortization. The latest PCHE designs introduce new geometry in channel cross sections similar to “airfoil” fin or with s shaped fin, for decreasing pressure drops in s CO₂ HXs, see Ref. [37].

SF capital cost plus HXs cost

Combining SF and HX Capital cost we could obtain a first approach estimation about the optimum solar plant configuration. As shown in Tables 37–42, the LF + Rankine plant is the optimum economical design solution, with the unitary cost assumptions considered in this paper, see Notes below Table 24 for SF cost estimations criteria and chapter 8 [36] for HX capital cost estimation criteria.

With Configuration 1 the DSG + Rankine plants total cost is about 13% lower than the RCMCI s CO₂ Brayton, see Tables 37 and 38. For Configuration 2, as summarized in Tables 39 and 40, the cost in DSG + Rankine plants is between 16% and 19% lower than in RC s CO₂ solar power plants. Configuration 4 most economical plant layout is also the DSG + Rankine solar plant, and the optimum cost Brayton plant is the RC with slightly differences respect the RCMCI.

Conclusions

Supercritical s CO₂ Brayton power cycles are under research and development since 2000. First Supercritical s CO₂ power cycles are recently commercially available. This technology constitutes an important revolution in the power generation field, a solid alternative to the subcritical and supercritical Rankine cycle in solar power plants. However, important key issues as equipment material cost and heat exchanger pressure drops, manufacturing cost, etc, are still pending issues under investigation. The target of this paper is to integrated this revolutionary power generation technology with the recently matured DSG solar power plants. We proposed four

Table 19 – LF solar power plants SF aperture area and capital cost, TIT 400 °C, 40 MWe net power output (Configuration 1).									
Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
SF aperture area (m ²)	203470	220231	216547	201166	198254	207329	204020	194248	190957
SF capital cost (Millo. USD)	48.75	51.084	75.356	47.504	68.991	47.954	70.997	45.365	66.451

Table 20 – PTC solar power plants SF aperture area and capital cost, TIT 400 °C, 40 MWe net power output (Configuration 1).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
SF apperture area (m ²)	169199	188476	186009	172880	170471	177465	175425	166086	164067
SF capital cost (Millo. USD)	63.590	70.835	93.211	64.974	85.425	66.697	87.907	62.421	82.215

Table 21 – LF solar power plants SF aperture area and capital cost, TIT 550 °C, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
SF apperture area (m ²)	256780	266901	256377	233342	224113	252887	241858	234824	225029
SF capital cost (Millo. USD)	61.523	69.66	89.217	60.9	77.99	66	84.16	61.28	78.3

Table 22 – PTC solar power plants SF aperture area and capital cost, TIT 550 °C, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	DSG	MS	DSG	MS	DSG	MS	DSG	MS
SF apperture area (m ²)	215841	243817	225964	205290	197838	222363	213358	206702	198791
SF capital cost (Millo. USD)	81.119	91.634		77.154	99.138	83.571	106.92	77.7	99.62

Table 23 – LF solar power plants SF aperture area and capital cost, TIT 550 °C, 55 MWe net power output (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
SF apperture area (m ²)	259439	224798	263272	227098
SF capital cost (Millo. USD)	72.368	63.943	73.345	63.868

Table 24 – PTC solar power plants SF aperture area and capital cost, TIT 550 °C, 55 MWe net power output (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
SF Apperture Area (m ²)	228274	198143	215150	200566
SF capital cost (Millo. USD)	91.704	81.218	86.327	81.284

Notes: Unitary cost data: LF DSG Rankine: 206.55 USD/m² LF DSG Brayton (8.5 mm thickness): 225 USD/m² LF MS Brayton: 300 USD/m². PTC DSG Rankine: 324 USD/m², PTC DSG Brayton (8.5 mm thickness): 324 USD/m², PTC MS Brayton: 432 USD/m². The above prices should be multiplied by 1.16 factor to include the Installation Cost.

configurations: Configuration 1, see in Fig. 8, Configuration 2, see Fig. 9, Configuration 3, see Fig. 10, and Configuration 4, see in Fig. 11. The Configuration 1, is suitable for turbine inlet temperature up to 400 °C and the Configuration 2, 3 and 4 for TIT up to 550 °C. All these innovative configurations were compared with the reference (baseline) configuration, a line focus solar power plant with DSG and Subcritical Rankine power cycle, as illustrated in Fig. 5 and Fig. 6.

Net plant efficiency provided by DSG + RCMCI (Configuration 1) was 36.6%, better than 35% obtained in DSG + Rankine (baseline), SF aperture area is also reduced at design point a 2% (with PTC) and 5% (with LF). More detail about Configuration 1 simulations results are summarized in Tables 6 and 7 Net plant efficiency provided by DSG + RC (Configuration 2) was 43.6%, better than 38.39% obtained in DSG + Rankine (baseline), SF aperture area is reduced at design point a 5% (with PTC) and 9% (with LF). More detail about Configuration 2 simulations results are summarized in Tables 8 and 9 Regarding Configuration 3, this solution net plant performance up to 39.7%, see Table 10, very near to the DSG + Rankine with DRH solar plant providing between 40 and 41% depending on the number of DRH stages. Other possible solar power plant design (Configuration 4) was studied combining MS and DSG. It is a dual loop solar field arrangement as illustrated in Fig. 11. The main inconvenient is

Table 25 – LF + sCO₂ solar power plant heat exchangers conductance. 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	MS	DSG	MS	DSG	MS	DSG	MS
LTR UA (kW/°C)	3253	3247	7606	7692	4230	4219	7228	7227
HTR UA (kW/°C)			3322	3196	2882.6	2875.5	3419	3413
PHX UA (kW/°C)	1829.3	4057	2337	6275	1706.8	3208	1948.7	3661
ACHE UA (kW/°C)	4615	4604	3913	3965	5942.1	5927.2	5158.5	5150

Table 26 – PTC + sCO₂ solar power plant heat exchangers conductance, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	MS	DSG	MS	DSG	MS	DSG	MS
LTR UA (kW/°C)	3253	3251	7623	7715	4239	4232	7227	7228
HTR UA (kW/°C)			3330	3206	2891.7	2883.2	3419	3417
PHX UA (kW/°C)	1856.9	4069	2061.5	6326	1889.3	3213	1653.8	3662
ACHE UA (kW/°C)	4615	4610	3923	3975	5965.5	5942.1	5158.5	5158.5

Table 27 – LF + sCO₂ solar power plant heat exchangers conductance, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	MS	DSG	MS	DSG	MS	DSG	MS
LTR UA (kW/°C)	3491	3297	7797	7355	5049	4757	7986	7532
HTR UA (kW/°C)			6123	5779	3161	2976	3944	3717
PHX UA (kW/°C)	4228	3864	5130	4812	3297	3253	3564	3542
ACHE UA (kW/°C)	4769	4460	3766	3524	6347.9	5919.8	5325.7	4980.2

Table 28 – PTC + sCO₂ solar power plant heat exchangers conductance, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	SB	SB	RC	RC	PCRC	PCRC	RCMCI	RCMCI
HTF	DSG	MS	DSG	MS	DSG	MS	DSG	MS
LTR UA (kW/°C)	3634	3302	7809	7367	5060	4765	8000	7540
HTR UA (kW/°C)			6131	5787	3167	2980.8	3949	3724
PHX UA (kW/°C)	4411	3876	5138	4828	3308	3251	3572	3544
ACHE UA (kW/°C)	5003	4468	3770	3529	6362.3	5930.6	5334.1	4992

Table 29 – LF solar power plants HXs capital investment cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF		DSG	DSG	DSG	DSG
LTR (MWth)		87.346	83.548	28.086	56.810
HTR (MWth)			26.602	86.065	68.701
PHX (MWth)		124.303	112.574	117.034	109.340
ACHE (MWth)		82.846	71.222	75.573	67.920
Total HX capital cost (Mill. USD)	15.187	27.093	27.04	28.22	27.85

Table 31 – PTC solar power plants HXs capital investment cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF		DSG	DSG	DSG	DSG
LTR (MWth)		87.347	83.738	28.174	56.812
HTR (MWth)			26.664	86.357	68.702
PHX (MWth)		124.305	112.832	117.435	109.338
ACHE (MWth)		82.845	71.385	75.833	67.919
Total HX capital cost (Mill. USD)	15.212	27.093	27.1	28.31	27.85

the MS drawbacks: heat tracing to avoid solidification, MS corrosion in receiver pipes, environmental impact due to leakages, etc. However, with this alternative the net plant performance is increased up to 45.7% for TIT 550 °C. The Configuration 4, integrates a single Reheating stage in s CO₂

Brayton cycles by means of an MS SF. The plant efficiency is better than in Configuration 1 and 2 without any Reheating stage. Detailed performance for Configuration 4 are listed in [Tables 11 and 12](#).

Table 30 – LF solar power plants HXs capital investment cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine (without ReHeating)
Feed water heaters 1 to 5 (Mill. USD)	1.182634
Deaerator (Mill. USD)	0.388250
ACC (Mill. USD)	13.616860
Total HX capital cost (Mill. USD)	15.187

Table 32 – PTC solar power plants HXs capital investment cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine (without ReHeating)
Feed water heaters 1 to 5 (Mill. USD)	1.189
Deaerator (Mill. USD)	0.3885
ACC (Mill. USD)	13.635
Total HX capital cost (Mill. USD)	15.212

Table 33 – LF solar power plants HXs capital investment cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF		DSG	DSG	DSG	DSG
LTR (MWth)		163.117	90.476	37.844	68.488
HTR (MWth)			104.138	154.689	137.637
PHX (MWth)		148.468	129.315	140.290	130.043
ACHE (MWth)		88.394	69.185	80.028	69.858
Total HX capital cost (Mill.USD)	17.457	36.8	36.166	37.982	37.354

Table 34 – LF solar power plants HXs capital investment cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine
Feed water heaters 1 to 5 (Mill. USD)	1.188636
Deaerator (Mill. USD)	0.3987
ACC (Mill. USD)	15.87
Total HX capital cost (Mill. USD)	17.457

Table 35 – PTC solar power plants HXs capital investment cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF		DSG	DSG	DSG	DSG
LTR (MWth)		169.818	90.564	37.891	68.589
HTR (MWth)			104.239	154.888	137.825
PHX (MWth)		154.571	129.435	140.469	130.223
ACHE (MWth)		92.029	69.247	80.131	69.955
Total HX capital cost (Mill.USD)	17.47	38.31	36.2	38.03	37.4

Translating the net plant efficiency improvements into SF aperture area savings, and comparing the DSG + s CO₂ plants configurations with the reference DSG + Rankine plant, we concluded the Brayton power cycles reduces the collectors area required for a fixed net power output in comparison with the Rankine plants. The detailed results in this sense are summarized in [Tables 13–18](#)

Carbon steel receivers (with 8.5 mm thick) were selected for DSG + s CO₂ plants instead of stainless steel receivers required in Direct Molten Salts solar collectors, avoiding Nicquel allow high cost. The solar field capital investment cost estimation details are calculated in [Tables 19–24](#). The optimum configuration is DSG + s CO₂ RCMCI plant design with lowest economical cost a better net efficiency.

Table 36 – PTC solar power plants HXs capital investment cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine
Feed water heaters 1 to 5 (Mill. USD)	1.191
Deaerator (Mill. USD)	0.3987
ACC (Mill. USD)	15.88
Total HX capital cost (Mill. USD)	17.47

Table 37 – LF solar power plants Solar Field cost plus Heat Exchangers cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF	DSG	DSG	DSG	DSG	DSG
SF capital cost (Millo. USD)	48.75	51.084	47.504	47.954	45.365
HX capital cost (Mill. USD)	15.187	27.093	27.04	28.22	27.85
Total (SF + HXs) Cost (Mill. USD)	63.937	78.177	74.544	76.174	73.215

Table 38 – PTC solar power plants Solar Field cost plus Heat Exchangers cost, 400 °C TIT, 40 MWe net power output (Configuration 1).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF	DSG	DSG	DSG	DSG	DSG
SF capital cost (Millo. USD)	63.590	70.835	64.974	66.697	62.421
HX capital cost (Mill. USD)	15.212	27.093	27.1	28.31	27.85
Total (SF + HXs) Cost (Mill. USD)	78.802	97.928	92.074	95.007	90.271

Also the heat exchanger cost conductance a capital cost was quantified for all the solar power plants configurations proposed. The PCRC sCO₂ cycle arrangement is the optimum one talking about the point of view of the lowest conductance versus net plant performance, see [Tables 25–28](#) For obtaining a reliable cost estimation comparison between different solar power plants configuration in [Tables 37–42](#) are added the solar field and the heat exchanger capital investment cost. Despite better net plant performance in Brayton solar power plants, the DSG + Rankine solar power plants are nowadays the most cost competitive solution in comparison with the sCO₂ Brayton solar plants, and the main reason is the equipments material and manufacturing high cost in the Brayton solar plants [\[39,40\]](#).

As future works, Thermal Energy Storage System (TES) integration is considered for increasing and optimizing annual plant performance. Primary Heat Exchangers (with sCO₂ in tube side and DSG in Shell side) are the main key components to be detailed design to warranty the DSG + sCO₂ solar power plants industrial deployment. As a first approach two designs are proposed PCHE and Shell&Tube HX. Steam condenser, with sCO₂ as cooling fluid, should also be detailed design and are not yet commercially available. OT boiling DSG technology [\[10–13\]](#), is being developed for industrial deployment, the integration with sCO₂ Brayton cycles should be assessed with similar solar power plants configurations proposed in this paper. And finally, steam compressors detailed design, real behaviour

Table 39 – LF solar power plants solar field cost plus heat exchangers cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF	DSG	DSG	DSG	DSG	DSG
SF capital cost (Millo. USD)	61.523	69.66	60.9	66	61.28
HX capital cost (Mill. USD)	17.457	36.8	36.166	37.982	37.354
Total (SF + HXs) Cost (Mill. USD)	78.98	106.46	97.066	103.982	98.634

Table 40 – PTC solar power plants solar field cost plus heat exchangers cost, 550 °C TIT, 55 MWe net power output (Configuration 2).

Power cycle	Rankine	SB	RC	PCRC	RCMCI
HTF	DSG	DSG	DSG	DSG	DSG
SF capital cost (Millo. USD)	81.119	91.634	77.154	83.571	77.7
HX capital cost (Mill. USD)	17.47	38.31	36.2	38.03	37.4
Total (SF + HXs) Cost (Mill. USD)	98.589	129.944	113.354	121.601	115.1

Table 41 – LF solar power plants solar field cost plus heat exchangers cost, 550 °C TIT, 55 MWe net power output (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
LTR (MWth)	173.491	87.391	40.513	66.459
HTR (MWth)		117.232	175.795	147.444
PHX (MWth)	114.558	90.975	116.515	96.481
RHX (MWth)	27.673	31.740	27.538	27.309
ACE (MWth)	82.915	63.522	80.030	64.492
Total HX capital cost (Millo. USD)	36.674	35.959	40.516	37.001

Table 42 – PTC solar power plants solar field cost plus heat exchangers cost, 550 °C TIT, 55 MWe net power output (Configuration 4).

Power cycle	SB	RC	PCRC	RCMCI
LTR (MWth)	173.786	87.344	37.669	66.566
HTR (MWth)		117.171	163.415	147.664
PHX (MWth)	114.750	90.928	108.305	96.624
RHX (MWth)	27.720	31.723	25.599	27.351
ACE (MWth)	83.053	63.490	74.398	64.586
Total HX capital cost (Millo. USD)	36.736	35.940	37.663	61.550

and efficiency (real electrical consumption) should confirm the Configuration 2 feasibility.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.ijhydene.2015.05.011>.

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