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Supercritical Steam Power Cycle For Line-Focusing Solar Power Plants

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ABSTRACT

A recent study between Sandia National Laboratories and Siemens Energy, Inc., published on March 2013 [11], confirmed the feasibility of adapting the Siemens turbine SST-900 for supercritical steam in concentrated solar power plants, with a live steam conditions 230-260 bar and output range between 140-200 MWe. In this context, this analysis is focused on integrating a line-focus solar field with a supercritical Rankine power cycle. For this purpose two heat transfer fluids were assessed: direct steam generation and molten salt HITEC XL. The design-point conditions were 550ºC and 260 bar at turbine inlet, and 165 MWe Gross power output. Plant performance was assessed at design-point in the supercritical power plant (between 43-45% net plant efficiency depending on balance of plant configuration), and in the subcritical plant configuration (~40% net plant efficiency with one DRH, and up to ~41% with two DRH stages). Direct Reheating was adopted in Rankine power cycle to avoid any intermediate heat exchanger. Seven feed-water heaters optimized the plant performance power output.

Keywords: Supercritical water, Supercritical Rankine, Direct Steam Generation, Molten salt, Line-focusing, Parabolic Trough, Linear Fresnel.

1. INTRODUCTION

Solar thermal power plants generate carbon dioxide-free electricity by the transformation of solar light radiation into thermal energy. Despite, solar power plants not consume any fossil fuel, the target is to minimize plant capital investment cost reducing the equipments volume, complexity and components manufacturing secondary environmental impacts. The power plant efficiency is the selected key parameter for measuring power plant design-point performance and limited by Carnot principle.

In the legacy PTC solar power plants, like Andasol 1 (Spain), the HTF was synthetic oil with an operating limit around 390 ºC to avoid any oil degradation. For this reason the live steam operating parameters were limited to 380ºC and 100bar 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 = 380ºC 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 innovative Direct Steam Generation (DSG) [1, 2, 3, 4] in linear solar collectors, Parabolic Trough collectors (PTC) or Linear Fresnel (LF) collectors, combined with Subcritical water Rankine cycles provides net plant efficiencies up to 40-41%, see results in Table 7 to 10.

Another latest tendency in solar field technology is adopting Direct Molten Salt (DMS) as Heat Transfer Fluid (HTF) in the linear solar collectors (PTC or LF) [5, 6, 7], for increasing live steam turbine inlet temperature and improving plant performance.

On the other for gaining synergies with the fossil power plants, supercriticial turbines, operating above 22.1 MPa and 374.1ºC water critical point, are being studied as an alternative for increasing net plant efficiency in solar power plants.

In this paper it is demonstrated how the supercritical Rankine power cycles combined with DSG or DMS solar fields (SF), offers 43- 45% net efficiency at design-point (550ºC and 260 bar at turbine inlet), see Tables 7 to 10. With live steam pressure at turbine inlet above water critical point, turbine pressure levels and number of turbines extractions could be increased; hence SF feed-water inlet temperature is enhanced. We considered in the innovative supercritical Rankine cycle proposed in this paper seven feed-water pre-heaters, as stated in [8], and five feed-water pre-heaters in the subcritical Rankine cycle. A more detailed assignment of the turbine pressure levels are detailed in [9].

Supercritical water provides an important physical property key advantage, the higher supercritical water density in comparison with steam water. With a proper

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steam paths and blades design turbines stages efficiencies could be improved and secondary losses reduced. A recent study between Sandia National Laboratories and Siemens [11], concludes high-speed and high pressure Siemens turbine SST-900 could be upgraded to reduce secondary losses in steam blade path and also takes the advantage of supercritical steam for an output range of 140 to 200 MWe. This turbine would be developed for short startup times, daily cycling, and rapid load changes required in solar power plants. The supercritical turbines technology foundation also relies on more sophisticated materials with better mechanical properties (T91, 347 SS, Inconel, etc) [12] already manufactured for supercritical and ultra supercritical fossil power plants.

According to Carnot principle the plant efficiency is improved for higher live steam pressure and temperature, but temperature is limited by receivers' selective coating materials, and is fixed to 550ºC. DMS HITEC XL and Direct Steam Generation (DSG) are the Heat Transfer Fluids (HTF) selected, not suffering any degradation at 550º C operating temperature.

Also two scenarios were considered in this paper for line-focus solar field design, Parabolic Trough collectors (PTC) or Linear Fresnel (LF) collectors. PTC optical efficiency is better than LF, but the flat mirrors and lack of movable joints in LF make this alternative solar collector competitive with traditional linear PTC. SF design optimization, is quantify in terms of the Unitary Power Output, as the relation between net power output and the solar field effective aperture area. The target is to maximize this parameter to reduce SF dimensions for a fixed power output. Mass flux (kg/m^2 s) was also limited in main SF and in reheating SF to reduced pressure drops and obtaining a fluid velocity not producing vibration, erosion, etc inside receivers, neither in headers pipes.

Other important key issue impacting directly in plant efficiency is the number of reheating stages in High Pressure (HP) and intermediate pressure (IP) turbines. Steam reheating provides another way of optimizing plant performance, but number of reheating stages are limited by pressure drops and by turbine design. Direct ReHeating (DRH) was adopted avoiding any intermediate heat exchanger [9, 10]. Supercritical live steam pressure at turbine inlet (260 bar) permits to integrate one, two or even three DRH stages in the power cycle, see Fig. 3 and Fig. 4; always assuring reheating solar field pressure drops not impacts too much in power cycle, and steam quality leaving last turbine stage is above 0.9, avoiding blades damages due to water droplets.

2. METHODOLOGY

This paper is focus on assessing the design-point performance of supercritical line-focus (PTC and LF) solar power plants integrating supercritical water Rankine cycles. For this purpose, plants modeling and simulations were developed with Thermoflow 23. Water properties were calculated according to IFC-67 steam tables. DMS (HITEC XL) properties were calculated with internal Thermoflow 23 tabulated data.

Preheating and superheating receivers heat transfer coefficients (HTC) are calculated with Dittus-Bölter (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.

3. MODELING ASSUMPTIONS

Main calculation assumptions were summarized in Table 1 to Table 6

Table 1. 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 2. Receiver parameters.

Pipe material:	Stainless Steel
Outer diameter:	70 mm
Thickness:	4-8 mm
Internal roughness:	Ra = 0.0457 mm
Max. DSG velocity (m/s)	40-50
Max. DMS velocity (m/s):	2-4

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:	$0.141\Delta T+6.48e\text{-}9\ \Delta T^4$ [13]

Table 4. LF solar collectors' parameters

Collector type:	SuperNova1 (Novatec)
Aperture Area:	5.77 m
Dimensions:	1.71 m
Optical Efficiency:	0.67 (boiling); 0.647 (superheating)
Thermal losses:	$1.06\ \Delta T + 1.2e\text{-}8\ \Delta T^4$ (boiling) [14]
Thermal losses:	$0.15\ \Delta T + 7.15e\text{-}9\ \Delta T^4$ (superheated) [14]

Table 5. SubCritial Balance Of Plant parameters

HP turbine inlet (bar):	87.7
HP turbine inlet (ºC):	550
Turbines isentropic efficiency (%):	0.85
Nº of HP stages:	2
Nº of IP stages:	3
Nº of LP stages:	4
Reheating outlet (ºC):	550
LP turbine quality:	Above 0.9
Condenser (bar):	0.08
Preheater units:	5
Deareator (bar):	6.18
Preheaters TTD (ºC):	5
Preheaters DCA (ºC):	5

Table 6. Supercritical Balance Of Plant parameters

HP turbine inlet (bar):	260
HP turbine inlet (ºC):	550
Turbines isentropic efficiency (%):	0.85
Nº of HP stages:	2
Nº of IP stages:	3
Nº of LP stages:	4
Reheating outlet (ºC):	550
LP turbine quality:	Above 0.9
Condenser (bar):	0.08
Preheater units:	7
Deareator (bar):	8.5
Preheaters TTD (ºC):	5
Preheaters DCA (ºC):	5

4. LINE-FOCUS SOLAR FIELD WITH DIRECT STEAM GENERATION AND SUBCRITICAL RANKINE POWER CYCLE (REFERENCE CONFIGURATION)

Following the latest trend in line-focus solar power plants technology development, for the present study was adopted, as reference configuration, a solar power plant with linear collectors (PTC or LF) with DSG and a Subcritical Rankine power cycle, see Fig.1 and 2, and results summarized in Tables 7, 8, 9 and 10.

The DSG recirculation mode was selected in this analysis, and was validated in DISS researching project, and also industrial scale power plants were constructed and are operating with PTC DSG (Kimberlina project) and with LF DSG (Puerto Errado project). DSG with recirculation mode is integrated by a preheating and boiling SF delivering a 80% saturated steam quality; the steam liquid phase is separated in a tank and the vapor is superheated in other solar collectors before entering the HP turbine, for more details see Fig.1. DSG as HTF main advantages are: no environmental impact, no HTF solidification, no heat tracing required, no operating temperature either pressure limit, reduced pipe corrosion, etc.

In relation to BOP, the most relevant feature is the DRH (550ºC) between HP and IP turbine. By means of one reheating stage, net plant efficiency is increased up to ~40% in comparison with the solution without reheating providing only 38.4% net efficiency. With two DRH stages the plant performance up to ~41%. The reference Subcritical Rankine configuration is illustrated in Fig. 2

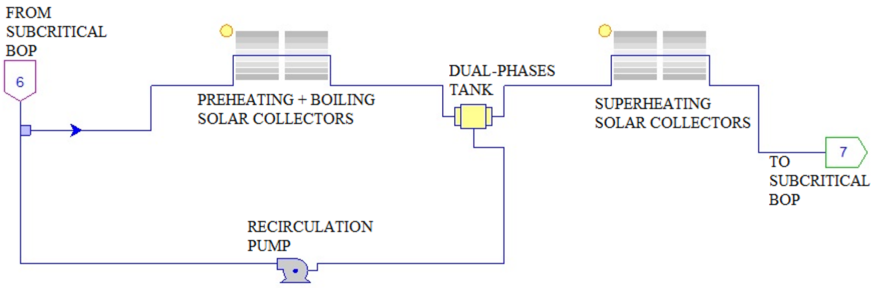

Figure 1. Direct Steam Generation Solar Field (PTC or LF) with Recirculation mode.

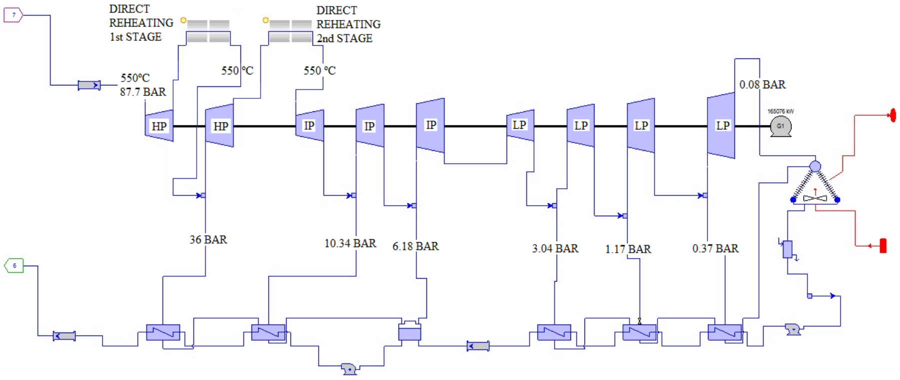

Figure 2. Subcritical Rankine power cycle with 5 preheaters and a deareator.

5. LINE-FOCUS SOLAR FIELD WITH DIRECT STEAM GENERATION AND SUPERCRITICAL RANKINE POWER CYCLE

Instead of DSG with recirculation mode (reference Configuration illustrated in Fig.1), in this study it is proposed an innovative DSG alternative, linear solar collectors operating only with steam above saturated conditions, see Fig. 3.The saturated steam is produced at plant start-up by means of an auxiliary fossil boiler connected in parallel with the solar collectors. During normal operation conditions superheated steam not condensates inside solar collectors, reducing number of auxiliary equipments (recirculation pumps, separation dual-phases tanks and simplifying control strategies), see Fig. 3.

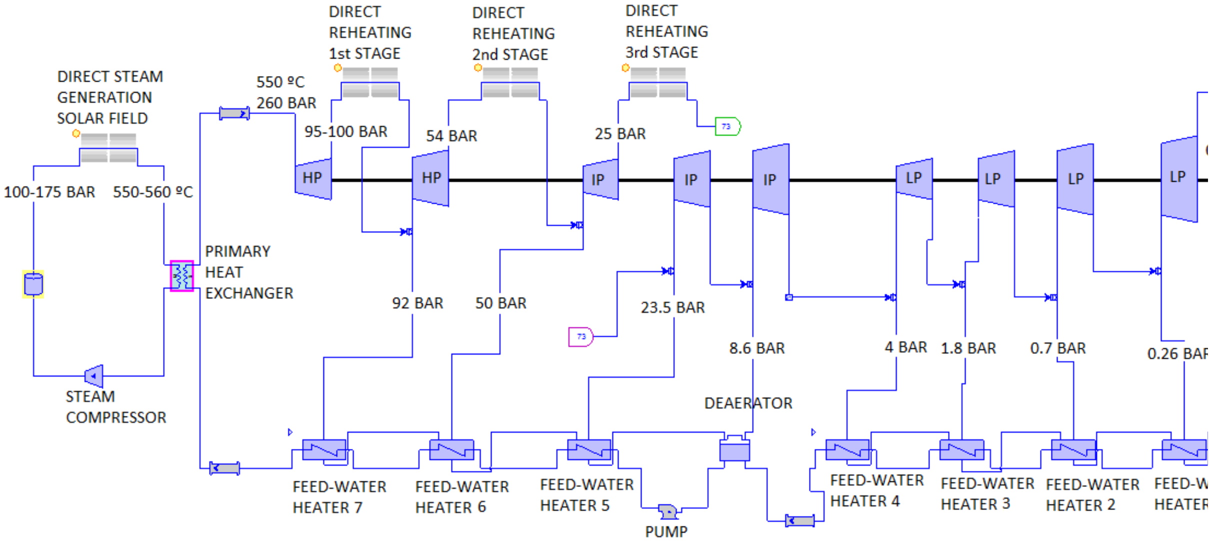

Figure 3. Direct Steam Generation Solar Field (PTC or LF) with Supercritical Steam Rankine power cycle.

Main challenge in this configuration is the industrial development of the steam compressors to operate under the thermodynamic conditions detailed in this study and with a high isentropic efficiency to decrease auxiliary steam compressor electrical consumptions. For this purpose SF operating pressures from 150 bar to 250 bar were simulated and results confirm higher

SF steam pressures reduce steam compressor electrical consumptions. Three different materials were selected for each pressure range (Carbon Steel 100-125 bar, ferritic stainless steel T91 150-175 bar and austenitic stainless steel 347SS 200-250 bar). Maximum receiver thickness was limited to 9 mm to avoid any disturbing in heat correlations provided by experiments and validations [13] and [14]. For summarizing requirements only 150 bar SF operations conditions results are detailed in Table 7 and 8.

The main SF design and configuration is very important to minimize pressure drops along receivers and along SF headers. For this purpose it was limited the collector maximum length fixing the mass flux (kg/m^2 s) limits. Other way of reducing pressure drops is to increase receiver diameter from 70 mm to 90 mm. For this reason receiver thickness was increased from 7.6 mm to 8.6 mm without considering the corrosion thickness requirements. Finally mass flux limits were: 750 kg/m^2 s in 70 mm receivers and 650 kg/m^2 s in 90 mm receivers.

Also to minimize pressure drops in DRH solar collectors mass flux was limit in the 1st and 2nd reheating stages up to 600 kg/m^2 s and in the 3rd reheating stage up to 300 kg/m^2 s.

As detailed in Table 7 and Table 8 it was confirmed higher net plant efficiency values are obtained with supercritical Rankine power cycles with seven feed-water pre-heaters. The plant configuration providing better efficiency is integrated by three DRH stages, however this configurations was not yet deployed neither validated in a industrial plant and is subjected to turbine manufacturers constrains confirmation. The plant configuration with only one DRH stage is the most common and also increase net plant efficiency from 40% to ~ 42.7% in supercritical Rankine cycles. Talking about the SF dimensions, the unitary power defined as the relation between net power output and SF effective aperture area, with supercritical Rankine power cycles unitary power output is increased from 0.22 to 0.23 (around 5% increment).

Table 7. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a LF with DSG solar power plant, (550 ºC HP inlet).

Power cycle	**subcritical Water** (reference)	**subcritical Water** (reference)	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 3	Fig. 3	Fig. 3	Fig. 3
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
Main SF pressure (bar)	104	104.5	150	150	150	150
HP inlet pressure (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.44	40.16	42.66	44.32	43.9	43.56
Unitary power (W/m^2)	226.5	222.1	227	235	234.2	232.2

In Table 8 are summarized the results for PTC solar collectors. We obtained higher unitary power output values (~ 16%) due to better PTC optical performance in relation with LF collectors. However, a future cost study should conclude which is the optimum alternative. PTC and LF are two technologies under continuous industrial development processes and both alternatives should be considered

Table 8. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a PTC with DSG solar power plant, (550 ºC HP inlet).

Power cycle	**subcritical Water** (reference)	**subcritical Water** (reference)	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 3	Fig. 3	Fig. 3	Fig. 3
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
Main SF pressure (bar)	104.6	104.7	150	150	150	150
HP inlet pressure (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.41	40.09	42.9	44.52	43.81	43.78
Unitary power (W/m^2)	265.8	263.7	268.8	276.8	273.2	274.4

6. MOLTEN SALT LINE-FOCUS SOLAR FIELD WITH SUPERCRITICAL WATER RANKINE POWER CYCLE

The solar power plant configuration illustrated in Fig.4, with DMS as HTF fluid in linear solar collectors (PTC or LF), is an alternative to DSG linear solar collectors. This configuration main advantage is to minimize auxiliary SF parasitic electrical consumption. DMS recirculation pump consumes much lower electricity in comparison with steam compressor. HTF salt velocity is limited to 2-3 m/s, optimizing SF pressure drops, pipes corrosion and erosion. HITEC XL salt was selected for reducing heat tracing requirements and avoiding salt solidification inside receivers. DMS other advantages are: reduced operating pressures, good heat transfer coefficient (HTC) in solar field heat exchangers, etc.

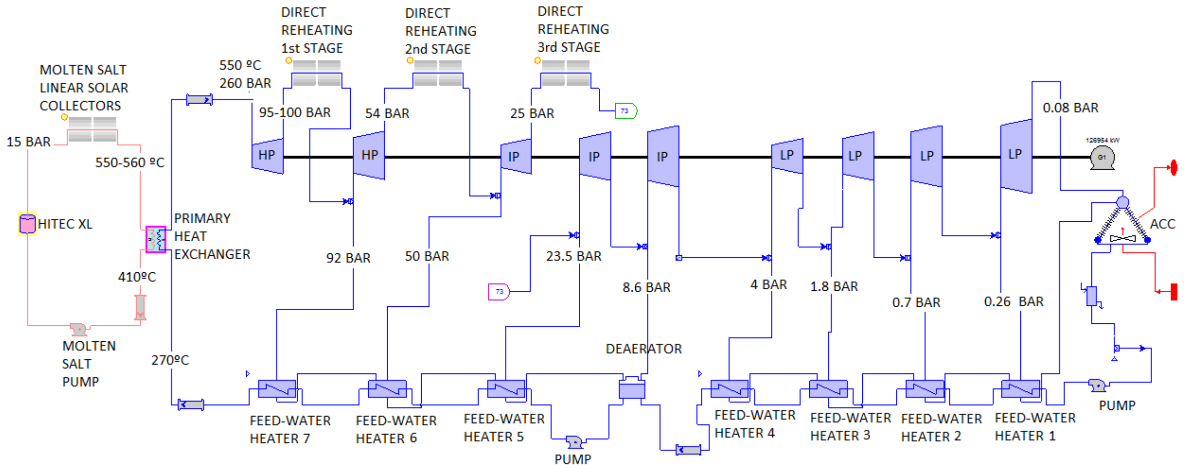

Figure 4. Molten Salt Solar Field (PTC or LF) with Supercritical Steam Rankine power cycle.

In Table 9 and 10 is confirmed how the net plant efficiency with DMS and supercritical Rankine cycles is 3-5% better in comparison with subcritical Rankine solar plants. Also if we compared the results obtained with DSG and supercritical Rankine cycle, we confirmed DMS solution provide between 0.5-1% higher plant efficiencies, see Table 7 and 8 results in comparison with Table 9 and 10 results.

Table 9. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a LF with DMS solar power plant, (550 ºC HP inlet).

Power cycle	**subcritical Water** (reference)	**subcritical Water** (reference)	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 4	Fig. 4	Fig. 4	Fig. 4
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
SF pressure (bar)	104	104.5	15	15	15	15
HP inlet (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.44	40.16	43.77	45.06	44.62	44.27
Unitary power (W/m^2)	226.5	222.1	235.6	240	238.9	236.9

Table 10. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a PTC with DMS solar power plant, (550 ºC HP inlet).

Power cycle	**subcritical Water** (reference)	**subcritical Water** (reference)	**supercritical Water**	**supercritical Water**	**supercritical Water**	supercritical **Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 4	Fig. 4	Fig. 4	Fig. 4
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
SF pressure (bar)	104.6	104.7	15	15	15	15
HP inlet (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.41	40.09	43.82	44.72	44.39	43.82
Unitary power (W/m^2)	265.8	263.7	274.7	277	276.2	273.4

7. CONCLUSION

Line-focus solar power plant with Supercritical Rankine power cycles provides higher net plant efficiency up to 43-45% in comparison with DSG Subcritical Rankine power plants, providing up to ~40% net plant efficiency with one DRH stage, and ~41% with two DRH stages, see simulations results in Tables 7 to 10. Seven feed-water pre-heaters [8], and two or even three direct reheating stages are main advantages in Supercritical Rankine solar power plants.

Supercritical turbines should be industrial developed for line-focus solar power plants and Supercritical Rankine power cycles, as proposed in [11].

It was demonstrated HITEC XL transfer fluid provides higher net plant efficiency than DSG in Supercritical Rankine solar power plants, saving steam compressors energy consumption required in DSG plants. However, DSG has no environmental impact either any heat tracing electrical consumes. For future works, thermal energy storage systems will be integrated in the solar plants configurations studied in this paper for increasing power plant operational flexibility and improving annual power plant performance

8. NOMENCLATURE

DSG	Direct Steam Generation
DRH	Direct Reheating
DMS	Direct Molten Salt
HTC	Heat Transfer Coefficient
PTC	Parabolic Trough solar collector
LF	Linear Fresnel solar collector
SF	Solar Field
BOP	Balance Of Plant
HTF	Heat Transfer Fluid
HP	High Pressure
IP	Intermediate Pressure

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