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Dual Loop Line-Focusing Solar Power Plants with Supercritical Brayton Power cycles

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Abstract

Most of the deployed commercial line-focusing solar power plants with Parabolic Troughs (PTC) or Linear Fresnel (LF) solar collectors and Rankine power cycles use a Single Loop Solar Field (SF), Configuration 1 illustrated in Fig. 2, with synthetic oil as Heat Transfer Fluid (HTF) [1, 2]. However, thermal oils maximum operating temperature should be below ~400ºC for assuring no oil degradation, hence limiting the power cycle gross efficiency up to ~38%. For overcoming this limitation Molten Salts (MS) as HTF in linear solar collectors (PTC and LF) were recently experimented in pilot facilities [3, 4]. Direct MS main drawbacks are the equipments and components material corrosion and the salts freezing temperature, requiring heat tracing to avoid any sald solidification, hence increasing the Solar Field (SF) capital investment cost and parasitic energy looses. Concentrated Solar Power plants (CSP) with Dual Loop SF are being studied since 2012 [5] for gaining the synergies between thermal oils and MS properties. In the Dual Loop SF the HTF in the primary loop is thermal oil (Dowtherm A) [6] for heating the Balance Of Plant (BOP) working fluid from ~300ºC up to ~400ºC, and a secondary loop with Solar Salt (60% $NaNO_3$, 40% KNO_3) as HTF, for boosting the working fluid temperature from ~400ºC up to 550ºC [7, 8, 9]. The CSP Dual Loop state of the art technology includes Rankine power cycles, the main innovation of this paper is the integration between Dual Loop SF and the supercritical Carbon Dioxide (s-CO_2) Brayton power cycles [10], see Configurations 2 and 3 illustrated in Fig. 3a, Fig 3b. A secondary innovation studied in this paper is the integration between thermal oil HTF (Dowtherm A) in linear solar collectors, a widely validated and mature technology, with the s-CO_2 Brayton power cycles. This technical solution is very cost competitive with carbon steel receiver pipes, low SF operating pressure, and no requiring any heat tracing.

Two main conclusions are deducted from this researching study. Firstly we demonstrated the higher gross plant efficiency ~44.4%, with 550ºC Turbine Inlet Temperature (TIT), provided by the Dual Loop with the Simple recuperated s-CO2 Brayton cycle with reheating, in comparison with 41.8% obtained from the Dual Loop SF and subcritical water Rankine power cycle. And finally the second conclusion obtained is the selection of the most cost competitive plant configuration with a Single loop SF with Dowtherma A and a s-CO2 Brayton power cycle due to the receiver material low cost and no heat tracing for the thermal oil.

Keywords: Dual Loop Solar Field, Thermal Oil, Molten Salt, Supercritical Brayton.

1. Introduction

Solar Thermal Energy (STE) is a promising renewable energy resource with numerous advantages as: no fossil fuels consumption, clean, no environmental impacts, sustainability, etc. This technology provides an alternative to the traditional fossil fuel power plants, reducing the carbon dioxide emission target stablished recently in the 2015 United Nations Climate Change Conference. Among various solar thermal technologies, the PTC technology is of the most mature. Most of commercial PTC solar power plants use the synthetic oil as HTF, such as SEGS and Andasol [1, 2]. Spain has become the leader country in the world: 43 plants of 50MWe each have been built in this country in last few years; of these 23 plants are provided with heat storage by molten salts, whereas 20 plants do not have heat storage.

The operation temperature of the thermal oil SF should be lower than ~ 420ºC to avoid any HTF degradation. This TIT limitation impacts very negatively in the net power plant performance due to the Carnot principle. The use of MS as HTF and as storage medium was first proposed by Rubbia [11] for overcoming the TIT limitation and increasing the net plant efficiency. The major disadvantage of the molten salt is the high freezing point of ~220ºC (for Solar Salt, 60% $NaNO_3$ and 40% KNO_3) requiring electric heat tracing to avoid any salt solidification during night or cold ambient temperatures. Kearney et al. [12] concluded additional energy consumption for freezing protection was 4% of collected solar energy and ~1% in the Therminol VP-1 reference case. ENEA [13] of Italy experimentally verified the technical performance of MS in PTC with operating temperatures around 550ºC. Wang et al. [14] numerically investigated the performances of the PTC receiver using the molten salt as a HTF, and concluded that the collecting efficiency with the molten salt at 500ºC is only 7.90% lower than that with the oil at 300ºC for the typical working conditions. Giostri et al. [15] reported that the system efficiency can be improved within the range of 6% if salts are used as a HTF instead of the synthetic oil. Zaversky et al. [16] developed a transient performance simulation model of the PTC using the molten salt as a HTF, which successfully

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validated against measurement data obtained at the SOLTERM facility of Italy. Additionally, Raade et al. [17] experimentally invesigated the thermal properties of the mixture of molten salts, and obainted a unique mixture exploits eutectic behavior resulting in a low melting point of 65ºC and a thermal stability limit over 500ºC. Accompanied with the technical efforts like Archimedes company [18],

The Dual Loop system was proposed by Lang and Cuthbert (2012) [5] for gaining the synergies of thermal oils and MS as HTFs in SF. This system utilizes MS as thermal energy storage with no storage for the organic heat transfer fluid. Instead, the organic heat transfer fluid is heat exchanged with molten salt between the medium and cold storage tanks. In this case, molten salt is used as a thermal storage medium for both fluids. Natural gas is used as auxiliary heating to supplement the solar input. The study performed states that the thermal efficiency of the Rankine cycle can be increased to 42%. This is compared to the efficiency of a cycle that uses only organic heat transfer fluid, which is 38% (Lang 2012 [5]).

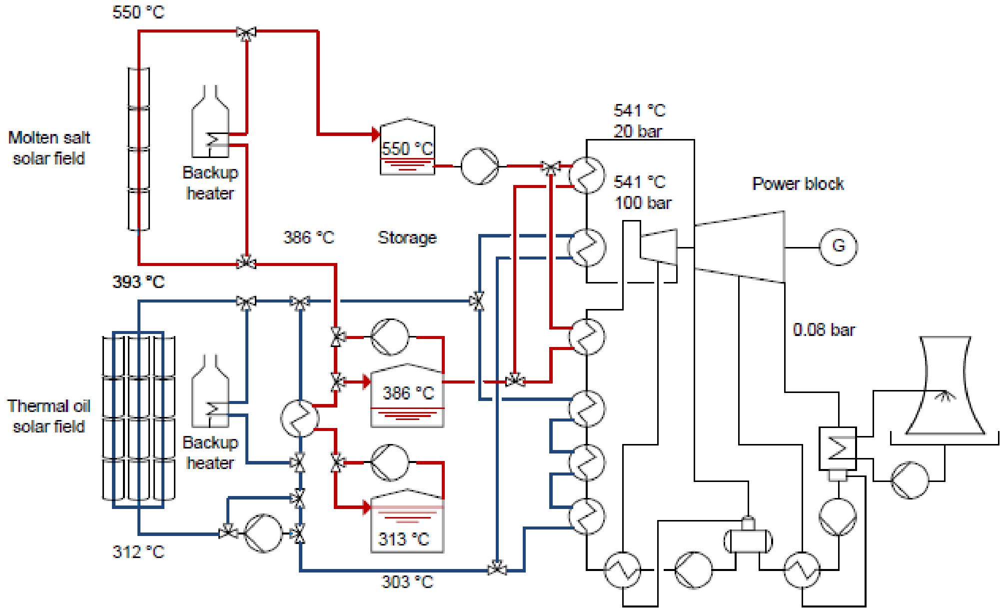


Figure 2. Schematic flow diagram of a dual loop system Vogel 2014 [8].

The study by Vogel [8] analyzing the dual loop system, see Figure 1, scores a mean power block efficiency of 41.87% compared to 37.21% for thermal oil. The system design is similar to the design from Lang. The system utilizes three molten salt storage tanks, and natural gas auxiliary heating. Both of these studies claim an improvement to the power cycle efficiency to approximately 42%. All of these results are corroborated by Shinners 2014 [7]. The dual loop system has an advantage in power cycle efficiency due to access to higher temperatures that increases the net power output for the same collector area. However, the molten salt system has the largest power output out of the three system designs, and this system type was not considered in the other two studies. The molten salt has a higher power output for the same temperatures as the dual loop due to the fact that the parasitic pumping power is significantly lower for salt than for Dowtherm A. Although the thermal losses for salt are higher, the loss of electrical energy in the form of pumping of Dowtherm A is far more significant.

In the present study we continue working about the Dual Loop SF state of the art configuration detailed explained above, and we made the integration of the linear solar collectors (PTC or LF) with the supercritical s-CO_2 Brayton power cycles. For this purpose we designed three solar power plants arrangements illustrated in Fig. 1 to 3. The first design solution Configuration 1, see Fig.1, considered Dowtherm A [6] or Solar Salt (60% $NaNO_3$, 40% KNO_3) in the Main SF and in the Reheating SF. In the Configuration 2, Fig.2, a Dual Loop is adopted in the Main SF and finally in the Configuration 3, Fig.3, the Dual Loop SF is deployed in the Main and in the Reheating SF. The Dual Loop SF is integrated by two SF. The primary SF heats the Dowtherm A up to 400ºC-415ºC and the second SF with Solar Salt as HTF, boost the working fluid temperature up to 550ºC.

2. Methodology

This study was focused on estimating the design-point performance of the Dual Loop (Dowthem A+Solar Salt) linear focusing solar power plants with s-CO_2 Brayton power cycle. The energy balances were modeled and simulated with Thermoflow software [19]. The optimal performance parameters in the s-CO_2 Brayton cycles were obtained via the Subplex algorithm from an adapted version of the software provided in Dyreby [20]. Regarding the s-CO_2 thermodynamic properties, were calculated with REFPROP software, developed by National Institute of Standards and Technology (NIST) and integrated in Thermoflow. In this researching analysis also we detail designed the Shell and Tubes Heat Exchangers (HX) between SF and BOP. The recuperators were Printed Circuit Heat Exchangers (PCHE) and were 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 s-CO_2. The methodology was outlined in Klein and Nellis (2009) [21] and developed by Siedel [22]. Also for the PCHE detail design we considering the Gnielinsky heat transfer coefficient correlation for calculating the heat transferred inside the semicircular channels. Finally the turbomachines detail designed were achieved also with the adapted software provided in Dyreby [20] obtaining the turbines and compressors rotor diameters, nozzle area and shaft speed for the radial turbomachines configurations. In the Thermoflow simulations we considered the 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).

3. Assumptions

In the following Tables 1 to 4 are summarized the data input considered in this paper. As main assumption it was fixed the gross power output 50 MWe in all the solar power plants models in the present study.

Table 1. *Location and ambient conditions.*

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

Table 2. *Solar collectors parameters.*

PTC collector type:	EuroTrough II
PTC aperture width:	5.77 m
PTC focal length:	1.71 m
PTC Cleanliness factor:	0.96
PTC optical efficiency:	0.75
PTC thermal losses:	0.141ΔT+ 6.48e-9 ΔT^4 [23]
LF collector type:	Novatec (SuperNova1)
LF module dimensions:	16.56 m x 44.8 m
LF optical efficiency:	0.647
LF thermal losses:	0.15 ΔT+7.15.10-9 ΔT^4[24]

Table 3. *Receiver parameters [25].*

Outer Diameter:	70 mm
Wall Thickness:	4.191 mm
Material:	Carbon steel for DowTherm A Stainless steel for Solar Salt
Vacuum between outer glass tube and internal pipe	
Roughness:	0.0457 mm

Table 4. *s-CO$_2$ Brayton BOP parameters.*

Turbine Efficiency:	93%
Compressor Efficiency:	89%
HX Effectiveness:	95%
Recuperator pressure drop:	1% Hot side 0.05% Cold side
Pre-Cooler pressure drop: 1% Hot side	
Turbine Inlet Temperature (TIT):	400ºC - 550ºC
Turbine Inlet Pressure:	250 bar
Reheating Pressure: optimized with Subplex	
Compressor Inlet Temperature (CIT):	32 ºC
Compressor Inlet Pressure: optimized with Subplex	
Generator Efficiency: 98.23 (at Design-Point)	

4. Power cycle performance at Design-Point

The s-CO$_2$ Simple Brayton power cycle with ReHeating analysed in this paper for line-focusing solar power plants was previously characterized following the same methodology as stablished by Dyreby [20]. Obtaining the optimized performance parameters via Subplex algorithm, and fixing the recuperator conductance (UA) for different Turbine Inlet Temperatures. The results (net plant efficiency %) obtained are represented in the following Fig. 1.

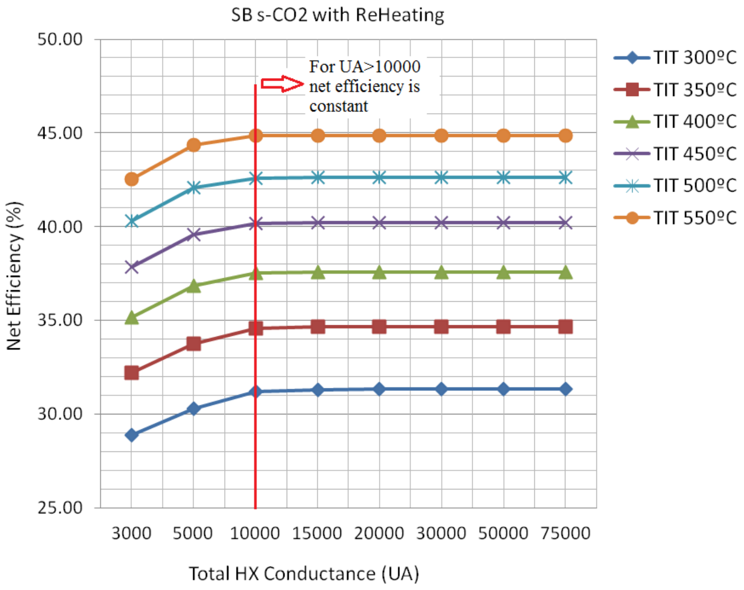


Figure 1. *s-CO2 Simple Brayton cycle with Recuperation and Reheating optimized performance.*

5. Line-Focusing solar power plant configurations

As detailed in the Figures 2a, 2b, 3a and 3b main advantage of the linear solar power plants configuration defined in this paper is the simplicity and low number of equipments in the power cycle.

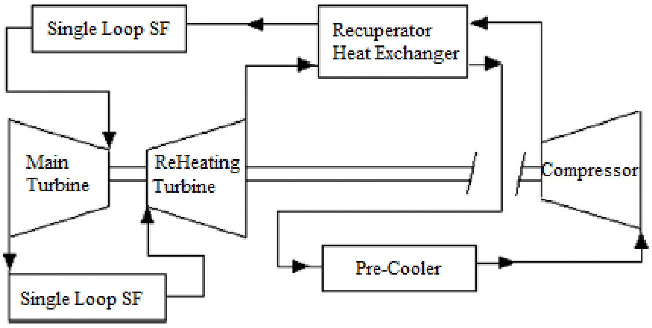
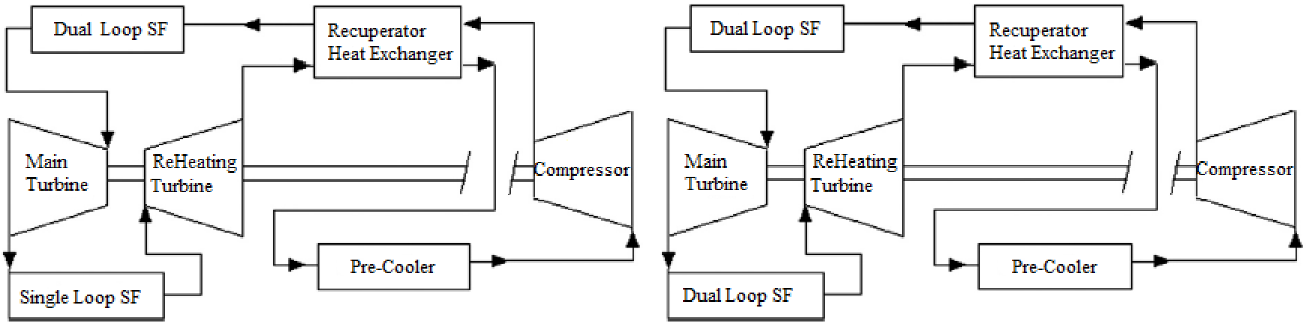


Figure 2*. Configuration 1. Line-Focusing solar power plant with a Simple Brayton power cycle with ReHeating and two Single-Loop SF with Solar Salt (Reference) or Dowtherm A as HTF.*



(a) **(b)**

Figure 3 (a)*. Configuration 2. Line-Focusing solar power plant with a Simple Brayton power cycle with ReHeating and a Dual Loop Main SF with Dowtherm A and Solar Salt as HTF, and a Single Loop ReHeating SF with Solar Salt as HTF.*
Figure 3 (b)*. Configuration 3. Line-Focusing solar power plant with a Simple Brayton power cycle with ReHeating and a Dual Loop Main and Dual Loop ReHeating SF with Dowtherm A and Solar Salt as HTF.*

6. Solar Power plant performance at Design-Point

The recuperator pinch point is very related to the recuperator UA. If we increase the UA values the pinch point temperatures are reduced as detailed in Table 5 and Table 6. The maximum net plant efficiency is limited by the minimum pinch point in the recupertor. For this reason we limit the maximum UA to 5000 kW/K obtaining pinch points ~2.6ºC-4ºC

Table 5*. Line-Focusing SB s-CO$_2$ with ReHeating. Fixed gross power output 50 MWe. Recuperator UA=3000 kW/K.*

				Without ΔP in HXs		With ΔP in HXs	
Config. SF	TIT (ºC)	Main SF HTF	ReHeating SF HTF	Net Effic. (%)	Recuperator pinch point (ºC)	Net Effic. (%)	Recuperator. pinch point (ºC)
1	400	Solar Salt	Solar Salt	34.41	13.25	33.79	13.85
1	400	DowTherm A	DowTherm A	34.41	13.19	33.66	13.99
3	450	DowTherm A	DowTherm A	36.95	12.75	36.19	13.45
2	450	DowTherm A	Solar Salt	36.99	12.73	36.39	13.27
1	450	Solar Salt	Solar Salt	37.04	12.72	36.44	13.25
2	500	DowTherm A	Solar Salt	39.4	12.47	38.76	12.8
1	500	Solar Salt	Solar Salt	39.42	12.46	38.85	12.72
2	550	DowTherm A	Solar Salt	41.57	12.49	40.96	12.4
1	550	Solar Salt	Solar Salt	41.59	12.49	41.06	12.31

The net plant efficiencies in Tables 5 and Table 6 include the Generator efficiency losses and the SF pumps electrical consumptions. However we didn’t considered the Air Cooling Heat Exchanger fan consumptions, this parasitic electrical consumption is estimated as 1% of the net power output, impacting negatively ~ -0.4% in the values tabulated in Table 5 and Table 6. The heat tracing were not detailed quantified for the MS configurations but also have a negative impact in the final power output and depends on ambient temperature, relative humidity and other variables related to the plant location. The maximum gross efficiency 44.4% were obtained for the higher TIT ~550ºC, without considering any energy looses in the cycle, only the power output from turbines and the heat transferred between HX and SF. Another important added value in this section is to quantify the impact HX pressure drop in the final plant efficiency. For that purpose we developed the HXs detailed design as explained in section 2. As can be deducted from the Table 5 an Table 6, the net plant efficiency has a penalty between 0.5%-0.7% due to the pressure drop in HX.

Table 6*. Line-Focusing SB s-*CO_2 *with ReHeating. Fixed gross power output 50 MWe. Recuperator UA=5000 kW/K.*

				Without ΔP in HXs		With ΔP in HXs	
Config. SF	TIT (ºC)	Main SF HTF	ReHeating SF HTF	Net Effic. (%)	Recuperator pinch point (ºC)	Net Effic. (%)	Recuperator. pinch point (ºC)
1	400	Solar Salt	Solar Salt	36.05	3.7	35.48	4.089
1	400	DowTherm A	DowTherm A	36.05	3.683	35.35	4.127
3	450	DowTherm A	DowTherm A	38.67	3.073	37.94	3.585
2	450	DowTherm A	Solar Salt	38.7	3.073	38.15	3.436
1	450	Solar Salt	Solar Salt	38.75	3.073	38.22	3.394
2	500	DowTherm A	Solar Salt	41.17	2.621	40.59	3.037
1	500	Solar Salt	Solar Salt	41.2	2.618	40.67	2.949
2	550	DowTherm A	Solar Salt	43.42	2.314	42.84	2.688
1	550	Solar Salt	Solar Salt	43.44	2.314	42.93	2.613

7. Capital Investment Cost

One of the main reasons of adopting the Dual Loop SF technical solution is the lowest corrosion requirements with Dowtherm fluid in comparison with the Solar Salt. To highlight this advantage in this study we considered Carbon Steel in the solar receivers for Dowtherm A and Stainless Steel AISI 347 for Solar Salt. The receivers material cost have a important impact in plant capital investment cost as detailed in Table 7 and Table 8. But the optimal cost competitive plant configuration is also very influenced by the ultimate heat sink (UHS) design, the pre-cooler. The UHS heat rejecting requirements has a great dependence with the TIT and the plant net efficiency. The pre-cooler cost optimization was studied by Gavic [26] concluding the best UHS configuration for minimizing water usage and minimizing the equipments dimensions is an hybrid cooling system composed by a water PCHE for s-CO2 refrigeration and an Air Cooling Heat Exchanger (ACHE) for cooling the water closed loop. For this reason we considered an unitary price for the Pre-Cooler between 200-300 USD/kWe, composed by a PCHE (100 USD/kWe) and a ACHE (150 USD/kWe). Adopting the optimum UHS design solution is also a keystone for selecting the Dowtherm A as HTF avoiding as much as possible the heat tracing in Solar Salt systems. Hence the optimum configuration should balance the UHS (pre-cooler) and the SF and HX costs.

Table 7*. PTC solar power plant cost estimation. Fixed gross power output 50 MWe.*

Solar Field Config	TIT (ºC)	Recuperator UA =3000 kW/K				Recuperator UA =5000 kW/K			
		SF Cost (Millo.$)	HX Cost (Millo.$)	Pre-Cooler (Millo.$)	Total (Millo.$)	SF Cost (Millo.$)	HX Cost (Millo.$)	Pre-Cooler (Millo.$)	Total (Millo.$)
1	400	110.31	22.06	23.68	156.05	105.12	23.08	21.94	150.14
1	400	83.05	21.94	23.82	**128.81**	79.16	22.96	22.08	**124.21**
3	450	90.83	28.94	21.25	141.02	88.66	30.25	19.73	138.64
2	450	92.72	25.47	21.10	139.29	90.00	26.24	19.54	135.78
1	450	104.97	22.17	21.07	148.21	100.24	23.19	19.50	142.94
2	500	93.04	26.48	19.04	138.56	91.02	27.18	17.67	135.87
1	500	102.01	22.53	18.97	143.52	97.89	23.58	17.60	139.07
2	550	96.69	26.27	17.36	140.32	95.12	26.90	16.06	138.08
1	550	101.70	22.97	17.29	141.96	97.57	23.94	15.98	137.48

Note: PTC CS receiver for Dowtherm A: 324 USD/m2. PTC SS347 receiver for Solar Salt: 432 USD/m2.
LF CS receiver for Dowtherm A: 207 USD/m2. LF SS347 receiver for Solar Salt: 275 USD/m2.
Installation cost factor: 1.16 x aperture area cost. PCHE: 92 USD/kWe. ACHE 250 USD/kWe.

The cost estimation results are summarized in Table 7 and Table 8 showing the most cost competitive technical solution the Configuration 1 (TIT = 400ºC) with Dowtherm A as HTF in the main and reheating SF. And the second plant configuration with lowest capital investment cost would be the Configuration 2 (TIT = 500ºC) with a LF Dual Loop Main SF and a LF Single Loop with Solar Salt as HTF in the Reheating SF. The same conclusion is obtained for the recuperator

UA=3000 kW/K and for UA=5000 kW/K, in the second case the differences are 5% higher between the most cost competitive solutions and the rest or alternatives.

Table 8. *LF solar power plant cost estimation. Fixed gross power output 50 MWe.*

Solar Field Config	TIT (ºC)	Recuperator UA =3000 kW/K				Recuperator UA =5000 kW/K			
		SF Cost (Millo.$)	HX Cost (Millo.$)	Pre-Cooler (Millo.$)	Total (Millo.$)	SF Cost (Millo.$)	HX Cost (Millo.$)	Pre-Cooler (Millo.$)	Total (Millo.$)
1	400	83.05	22.54	23.68	129.27	79.84	23.12	21.93	124.89
1	400	62.59	21.94	23.82	**108.35**	59.68	22.98	22.08	**104.74**
3	450	68.99	28.92	21.25	119.16	66.58	30.28	19.72	116.57
2	450	69.25	25.45	21.10	115.80	67.09	26.22	19.54	112.84
1	450	78.29	22.17	21.07	121.52	74.74	23.19	19.50	117.43
2	500	78.33	26.50	19.04	123.87	66.77	27.18	17.66	111.60
1	500	74.76	22.53	18.97	116.26	72.22	23.58	17.60	113.40
2	550	69.90	26.27	17.36	113.53	68.29	26.90	16.05	111.24
1	550	72.97	22.93	17.29	113.19	69.91	23.94	15.98	109.83

8. Conclusion and Future Works

The purpose of this study is gaining the synergies provided by the Dual Loop SF with Dowtherm A and Solar Salts as HTF integrated with the s-CO2 Brayton power cycle. Two line-focusing plants arrangements are studied, Configurations 2 and 3, illustrated in Fig. 3a and 3b. The Gross Power output 50MWe was fixed in all the configurations analyzed. The Dual Loop + s-CO2 Brayton cycle provided 44.4% gross power plant efficiency at TIT = 550ºC. Comparing with the Andasol thermal oil turbine with a gross efficiency of 38.2% [2], and with the Dual Loop turbine with a Rankine cycle [8] reaching 41.8%, we could conclude the innovative Dual Loop configurations with a Brayton power cycle provide 2.4% higher gross efficiency than the state of the art Dual Loop with Rankie power cycles.

Talking about the point of view of the most cost competitive plant configuration, the components and materials cost plays a more important role than the net plant efficiency. For this reason we demonstrated the Configuration 1 (with TIT 400ºC) with LF solar collectors in the Main and Reheating SF and Dowtherm A as HTF fluid, is the solution with lowest capital investment cost for producing the fixed gross power 50 MWe. The keystone decision for obtaining this economical conclusion is deducted for selecting Carbon Steel receiver pipes for the Dowtherm A HTF and Stainless Steel AISI 347 receiver pipes for the Solar Salt HTF. The BOP equipments material selected was Stainless Steel AISI 347 to avoid any corrosion (carburization) at high temperatures due to the s-CO2 working fluid.

For future works we recommend achieving the similar study with more sophisticated Brayton cycles configurations: with recompression, with partial cooling and recompression, and with recompression and main compression intercooling. Also it would be advisable to calculate the annual plant performance for each configuration and integrating the Thermal Energy Storage system in the solar power plant design for optimizing the power generation flexibility and performance.

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