Assessment of point-/line-focus hybrid scheme for CSP plant

Jie Sun**, *Qibin Liu, Zhang Bai and Hui Hong

Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China,
**sunjie@mail.etp.ac.cn*

Abstract:

The point-/line-focus hybrid scheme for concentrating solar power (CSP) plant is proposed. In the solar field, the solar tower with molten salt is used for the superheating and reheating stages while the linear Fresnel (LF) or parabolic trough (PT) with direct steam generation (DSG) is used for the preheating and evaporation stages. The hybrid scheme benefits from the high concentration ratio of point-focus technology and low cost of line-focus technologies. Performance and economic assessments have been carried out for a 50 MWe CSP plant with the proposed hybrid scheme and existing single scheme for solar field, including solar tower (molten salt), linear Fresnel (DSG) and parabolic trough (DSG and thermal oil). The results show that the hybrid scheme case is superior to single liner-focus scheme cases in efficiency (annual total efficiency increases from 10.7~15.6% to 12.7~15.9%) and to single point-focus scheme case in cost and scalability (high cost and up-scaling barriers are overcome). Specifically, the tower-LF hybrid scheme case suggests the highest potential in practical application by giving the equally lowest levelized cost of electricity (LCOE) of 0.188 $\$\cdot kWh^{-1}$ as parabolic trough with thermal oil, the currently most commercialized technology, in a 30-year lifetime economic assessment.

Keywords:

Solar energy, Concentrating solar power (CSP), Direct steam generation (DSG), Levelized cost of electricity (LCOE).

1. Introduction

Concentrating solar power (CSP) has been recognized as one of the most promising solutions for long-term green and renewable power supplies. Currently, there are four main CSP technologies, the predominant three types of parabolic trough (PT), linear Fresnel (LF) and tower and a fourth type of parabolic dish (PD). PT and LF are called linear-focus technologies while tower and PD are called point-focus technologies [1]. Table 1 compares the four main technologies.

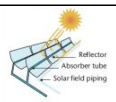
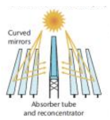
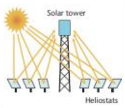
The PT is the most mature and commercialized CSP technology up to now because it was firstly introduced in 1880s [2] and has been developed ever since then. In this type, the receiver tube (heat collector element) and the concentrator (parabolic mirror) are integrated in one module called collector. The solar radiation is concentrated by the concentrator and then absorbed by the receiver, where the radiative heat is transferred into heat transfer fluid (HTF). The sunlight tracking of collector is driven in one-axis. Thermal oil (TO) is widely used as HTF in PT CSP plants, e.g. SEGS series in California, US in 1980s and Andasol series in Aldiere, Spain in 2000s [3]. However, due to the fact that TO generally decomposes above 400 ºC, the efficiency of thermodynamic cycle for a PT CSP plant is thus largely limited. Besides, it is not environmentally-friendly. To further increase the efficiency, other types of HTF are introduced, e.g. molten salt (MS) and water. The MS has higher working temperature above 550 ºC but with freezing problem below 290 ºC. Therefore it is suitable for high temperature conditions. The water is an ideal option because of the following advantages: (1) Environmentally risks of fire and leakage are eliminated; (2) The maximum temperature of the thermodynamic cycle can be increased over 400 °C, normally the limitation of TO, for higher steam turbine efficiency; (3) Overall plant efficiency is higher because the oil/steam heat-exchanger is unnecessary; (4) Plant configuration is simplified because the heat-exchangers and auxiliary TO systems are eliminated, which lowers the investment; (5) Operation and maintenance costs are reduced because there must be an auxiliary heating system for TO and 3% must be replaced annually. The above advantages could reduce the cost of the power produced by about 15% [4].

The LF was the last to appear but it has been a fast-developing technology in recently decades. The concept originates from the so-called Fresnel lens. Unlike the PT, the receiver tube is fixed while the discrete concentrators are set on the ground with one-axis sunlight tracing in the LF. The main advantages are simplicity, robustness, low wind load and low capital cost as well as the diversity of design. Because of similar concentration ratios (see Table 1), the HTFs for PT all apply for LF. It is noteworthy that since the receiver is stationary, the LF is inherently superior to the PT for DSG due to higher reliability and safety. It is reported that the largest commercial PT CSP plant so far based on DSG has a capacity of only 5 MWe but a LF CSP plant of more than 100 MWe uses DSG [1]. Currently, the development is focused on improving the annual optical performance by new configurations [5, 6].

The tower is the second most commercialized CSP technology nowadays. In this type, a heliostat field is used to concentrate the solar radiation with two-axis sunlight tracing while a receiver cavity is used to absorb and transfer the heat. Due to higher concentration ratios (see Table 1), the tower is usually used for high temperature applications, where the efficiency of thermodynamic cycle is apparently higher compared to the linear-focus technologies. MS is widely used as HTF. It is noteworthy that the optical efficiency decreases monotonically with up-scaling heliostat filed due to the attenuation from long distance [7]. Therefore, the single tower CSP plant is theoretically restricted by scale. Although multi-tower scheme seems an alternative for up-scaling, the inter-tower connections further reduce the efficiency. In addition, the cost of the tower technology is generally higher than the others.

Due to the distinct difference between PD (usually needs a Stirling engine and electricity is directly produced without HTF) and the other three (usually electricity is produced by steam turbine and generator with HTF), the former is not concerned in the large-scale commercial power plant and is therefore beyond the present scope.

Table 1. Technical comparison between the four main CSP technologies [1, 8].

Collector type		Relative thermodynamic efficiency	Operation temp. range / °C	Relative cost	Concentration ratio / sun
Parabolic trough (PT)		Low	50-550	Low	15-45
Linear Fresnel (LF)		Low	50-550	Very low	10-40
Tower		High	300-2000	High	150-1500
Parabolic dish		High	150-1500	Very high	100-1000

As mentioned above, the features of linear-focus technologies (PT and LF) are low cost, high scalability but low efficiency while those of point-focus technology (tower) are high efficiency but high cost and low scalability. To benefit in a mutually complementary way, the point-/line-focus hybrid scheme for solar field of CSP plant is proposed in the present work. This hybrid scheme benefits from the high concentration ratio of point-focus technology and low cost of line-focus technologies, as well as a good scalability. Our previous work has shown that the performance and scale of a PT CSP (TO) plant could be greatly improved by integrating tower technology [9]. To obtain a broader evaluation involving the commercially mature and recently fast-developing CSP technologies, performance and economic assessments have been carried out for a 50 MWe CSP plant with the proposed hybrid schemes of tower (MS)+PT/LF (DSG) and existing single schemes, namely tower (MS), LF (DSG) and PT (DSG/TO). Distinct advantages of the hybrid scheme are exhibited.

2. Methodology

The schematics of the proposed hybrid schemes, i.e. tower (MS)+PT/LF (DSG), and the reference schemes, i.e. tower (MS), LF (DSG) and PT (DSG/TO), for the solar field of a 50 MWe CSP plant are shown in Fig. 1, respectively. The CSP plant is assumed located in Gaggett, CA, US (34º51' N, 116º49' W) and basically comprised of solar field and power block. The main difference between schemes lies in the configuration of solar field. Note that the thermal energy storage is not considered; auxiliaries load within the power plant is neglected; the solar multiple is set to be unity. The performance and economic assessments are focused on simultaneously.

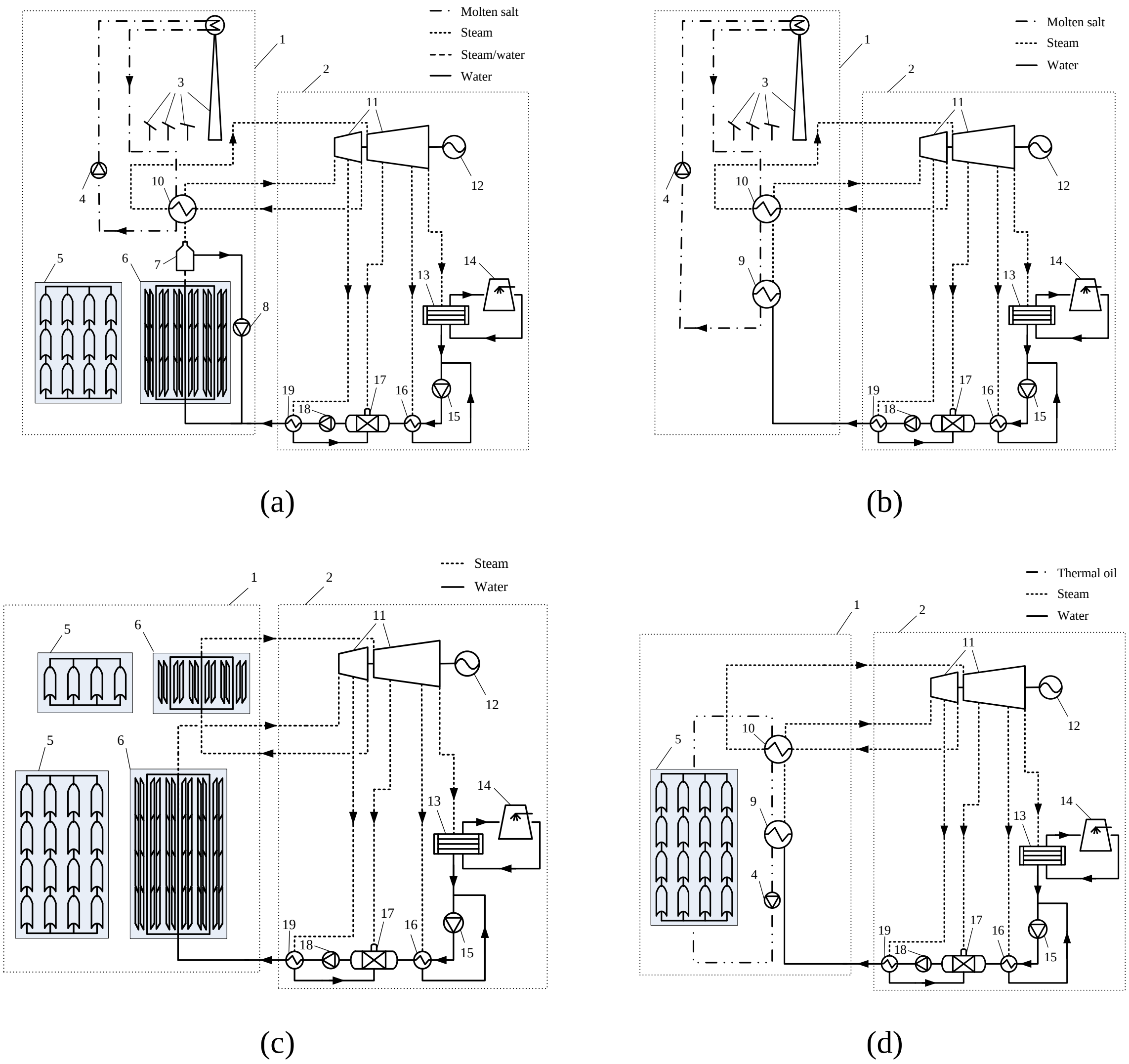


Fig. 1. System schematics: a) point-/line-focus hybrid scheme (MS+DSG), b) point-focus scheme (MS), c) line-focus scheme (DSG), d) line-focus scheme (TO). 1-solar field, 2-power block, 3-point-focus solar field (tower), 4-molten salt/thermal oil pump, 5-line-focus solar field (parabolic trough), 6-line-focus solar field (linear Fresnel), 7-steam/water separator, 8-recirculation pump, 9-preheater/evaporator, 10-superheater/rehearter, 11-steam turbine, 12-generator, 13-condenser, 14-cooling tower, 15-condenser pump, 16-low-pressure feed water heater, 17-deaerator, 18-feed water pump, 19-high-pressure feed water heater.

2.1. Performance assessment

For the solar field, the energy and exergy balances are:

$$Q_{\text{total}} = Q_{\text{gain,sf}} + Q_{\text{loss,sf}}, \quad (1)$$

$$E_{\text{total}} = E_{\text{gain,sf}} + E_{\text{loss,sf}} + IR_{\text{sf}}, \quad (2)$$

where $Q_{\text{total}} = DNI \cdot A_{\text{total}}$ is the total solar radiation (DNI being the direct normal irradiance and A_{total} being the total aperture area of the solar field); $E_{\text{total}} = Q_{\text{total}} = DNI \cdot A_{\text{total}} \cdot \psi$ is the total exergy by solar radiation ($\psi \equiv 1 + (T_{\text{amb}} / T_{\text{sun}})^4 / 3 - 4T_{\text{amb}} / 3T_{\text{sun}}$ being the exergy-to-energy ratio for solar radiation [10]); $Q_{\text{gain,sf}}$ and $E_{\text{gain,sf}} = Q_{\text{gain,sf}} (1 - T_0 / T_{\text{out,sf}})$ are the energy and exergy gained by HTF in the solar field; $Q_{\text{loss,sf}}$ and $E_{\text{loss,sf}}$ are the energy and exergy losses in the solar field (IR_{sf} being the irreversibility). The energy and exergy efficiencies of solar field are then expressed as:

$$\eta_{\text{sf}} = Q_{\text{gain,sf}} / Q_{\text{total}}, \quad (3)$$

$$\eta_{\text{sf}}^{\text{ex}} = E_{\text{gain,sf}} / E_{\text{total}}, \quad (4)$$

Note that the heat transfer process of DSG is solar radiation → steam/water directly while that of MS/TO process is solar radiation → MS/TO → steam/water. Therefore, additional energy and exergy losses exist for these MS/TO (indirect) routes, which are implicitly included in Eqs. (1)~(4). This point will be addressed in exergy analysis later.

For the power block, the energy and exergy balances are:

$$Q_{\text{gain,sf}} = E_{\text{net}} + W_{\text{loss,pb}} + Q_{\text{loss,pb}}, \quad (5)$$

$$E_{\text{gain,sf}} = E_{\text{net}} + E_{\text{loss,pb}} + IR_{\text{pb}}, \quad (6)$$

where E_{net} is the net electricity production, $W_{\text{loss,pb}}$, $Q_{\text{loss,pb}}$ and $E_{\text{loss,pb}}$ are the work, energy and exergy losses in the power block (IR_{pb} being the irreversibility). The energy and exergy efficiencies of power block are then expressed as:

$$\eta_{\text{pb,net}} = E_{\text{net}} / Q_{\text{gain,sf}}, \quad (7)$$

$$\eta_{\text{pb,net}}^{\text{ex}} = E_{\text{net}} / E_{\text{gain,sf}}, \quad (8)$$

The overall solar-to-electricity energy efficiency (referred to as overall efficiency for short) of a CSP plant is commonly used for energetic performance evaluation, which is generally expressed as:

$$\eta_{\text{overall}} = E_{\text{net}} / Q_{\text{total}} = \eta_{\text{opt}} \cdot \eta_{\text{therm}} \cdot \eta_{\text{pipe}} \cdot \eta_{\text{pb,net}} \cdot \eta_{\text{aux}} = \eta_{\text{sf,net}} \cdot \eta_{\text{pb,net}}, \quad (9)$$

where η_{opt} is the optical efficiency of solar field; η_{therm} is the thermal efficiency of solar field; η_{pipe} accounts for piping thermal loss of solar field; $\eta_{\text{pb,net}}$ is the net thermal-to-electricity efficiency of power block; η_{aux} accounts for impact of solar field circulating pumps and checking consumptions on the net power block output; E_{net} is the net electricity production. Similarly, the overall solar-to-electricity exergy efficiency is calculated as:

$$\eta_{\text{overall}}^{\text{ex}} = E_{\text{net}} / E_{\text{total}}, \quad (10)$$

In the present work, the componential efficiencies ($\eta_{\text{opt}} \sim \eta_{\text{aux}}$) in Eq.(9) are directly cited from open publications of practical/quasi-practical CSP plants instead of theoretical calculations or numerical simulations (see Table 2). The reason is two-folded: (1) The aim of present work is to assess the proposed hybrid scheme cases under conditions closest to practical engineering; (2) The deviation of calculation/simulation from practice is unavoidable due to simplification. Interpolation and extrapolation may be used where it is needed. It is seen that the annual overall efficiency varies obviously according to diverse technologies. Generally, the tower technology shows the highest efficiency (13.7~18.34%), followed by PT (10.6~18%) and LF (8.7~10.69%) technologies. In addition, the efficiencies of DSG seem slightly lower than those of non-DSG for the same type of CSP technology simply due to immaturity and unoptimization. Therefore, the inherent advantages of DSG have not been fully exhibited at the current phase.

Table 2. Performance comparison of current CSP technologies.

	Tower (DSG)	Tower (MS)	PT (DSG)	PT (TO)	LF (DSG)	LF (TO)
			Design-point performance			
η_{sf} / %	74.87[11][4]	66.34[11][8]	66.9~65.1[12][2]	76.00[11][5] 67.27[13][6]	63.65[11][7] 60.60[13][7]	57.64[13]
$\eta_{pb,net}$ / %	N.A.	N.A.	24.9~25.9[12][2]	36.74[13][6]	31.88[13][7]	36.71[13]
η_{aux} / %	N.A.	N.A.	N.A.	95.23[13][6]	99.62[13][7]	97.78[13]
$\eta_{overall}$ / %	19.55[11][4]	23.62[11][8]	16.2~16.4[12][2]	22.09[11][5] 23.53[13][6] 21[14]	18.07[11][7] 19.25[13][7]	20.69[13] 20[14]
			Annual performance			
η_{sf} / %	59.39[11][4] 65.79[15][9]	42.89[16][3] 47.57[11][8]	47.9~49.3[17][10]	38.86[16][1] 50.46[11][5] 48.25[13][6]	35.84[11][7] 35.51[13][7] 31.8~32.7[17]	32.00[13]
$\eta_{pb,net}$ / %	27.33[11][4] 22[15][9]	34.99[16][3] 39.07[11][8]	around 21[12][2] 33~34[17]	28.37[16][1] 35.77[11][5] 34.45[13][6]	29.23[11][7] 28.77[13][7] 32[17]	34.00[13]
η_{aux} / %	98.85[11][4] 96.04[15][9]	92.0[16][3] 98.69[11][8]	N.A.	96.1[16][1] 95.60[11][5] 96.57[13][6]	99.52[11][7] 99.47[13][7]	98.29[13]
$\eta_{overall}$ / %	16.05[11][4] 13.9[15][9]	13.7[16][3] 18.34[11][8]	13.2~13.5[12][2] 14.5~15.0[17]	10.6[16][1] 15.41[11][5] 16.05[13][6] 17~18[14]	10.43[11][7] 10.16[13][7] 8.7~9.3[17]	10.69[13] 9~11[14]

[1]SEGS IV, United States, 1989, 30 MWe
[2]INDITEP, Spain, 2001, 5 MWe
[3]Solar Tres, United States, 2004, 15 MWe (plan)
[4]PS10, Spain, 2007, 11 MWe,
[5]Andasol-1, Spain, 2008, 50 MWe
[6]Andasol-2, Spian, 2009, 50 MWe
[7]Puerto Errado 1, Spain, 2009, 1.4 MWe
[8]Gemasolar, Spain, 2011, 20 MWe
[9]Dahan, China, 2012, 1 MWe
[10]Only optical and thermal efficiencies considered
N.A.: not available

2.2. Economic assessment

The economic assessment is based on the levelized cost of electricity (LCOE) between different cases. The simplified method used in [17] is employed in the present work, as:

$$LCOE = \frac{C_{\text{invest}}\left(f_{\text{annuity}} + f_{\text{ins,ann}}\right) + C_{\text{O\&M,ann}}}{E_{\text{net,ann}}\, f_{\text{avail,plant}}}, \qquad (11)$$

with $f_{\text{annuity}} = \dfrac{(1+i)^n\, i}{(1+i)^n - 1}$

$$C_{\text{invest}} = \left(A_{\text{sf}} c_{\text{sf}} + c_{\text{land}} A_{\text{sf}} + E_{\text{pb}} c_{\text{pb}}\right)\left(1 + f_{\text{EPC}}\right)$$

where $C_{\text{O\&M,ann}}$ is annual cost for operation and maintenance. The reference data related to economic assessment are directly cited from open publications of practical/quasi-practical CSP plants (see Table 3). It is seen that the cost of tower (MS) is slight higher than that of PT (TO) while the cost of LF (TO) is only about half of those of tower (MS) and PT (TO). The distinct advantage of PT technology in economics is clearly seen. On the other hand, for the same type of CSP technology, the capital and annual O&M costs for DSG are generally higher due to high-standard (high pressure and temperature) instruments for DSG and maturity and industrialization of currently non-DSG CSP technologies.

Table 3. Economic comparison of current CSP technologies.

	Tower (DSG)	Tower (MS)	PT (DSG)	PT (TO)	LF (DSG)	LF (TO)
Spec. S.F. Cost /$ m_{aper}^{-2}	N.A.	279~315[3, 18]	350[17][1]	275[18] 280[13][1]	192[17][1] 160[13][1]	149[13][1]
Reduction[2] /%	N.A.	85	100	79	50	43
Capital Cost / $ kW^{-1}	N.A.	6300~7500[18]	3641[17][1]	4600[18] 3147[13][1]	3030[17][1] 2457[13][1]	2395[13][1]
Annual O&M Cost /$ kWh^{-1}	N.A.	0.029~0.036[18]	0.042[17][1]	0.029~0.036[18] 0.033[13][1]	0.045[17][1] 0.035[13][1]	0.035[13][1]
Reduction[2] /%	N.A.	77	100	78	95	83
LCOE / $ kWh^{-1}	N.A.	0.17~0.29[18]	0.218[17][1]	0.14~0.36[18] 0.193[13][1]	0.218[17][1] 0.193[13][1]	0.193[13][1]

[1]EUR to USD exchange rate is chosen as 1:1.273
[2]Relative percentage regardless of unit
S.F.: solar field
N.A.: not available

3. Results and discussion

Two hybrid and four single schemes for solar field of a 50 MWe CSP plant at Daggett, CA, US (34º51’ N, 116º49’ W) have been considered, i.e. tower (MS)+LF (DSG), tower (MS)+PT (DSG), tower (MS), LF (DSG), PT (DSG) and PT (TO). These typical schemes involve the promising DSG applications and currently the most mature CSP technologies, i.e. tower (MS) and PT (TO). The tower (DSG) is not chosen due to lack of reference data. The following comparative results are based on identical net electricity production (50 MWe) at design point (*DNI*=750 Wm^{-2}). The system simulations were carried out in Aspen Plus while the performance and economic evaluations were done in Microsoft Excel.

The design-point thermodynamic performances of different cases are listed in Table 4. The main steam temperature of PT (TO) case is lower than the others due to the decomposition of TO above 400 ºC. Consequently, the efficiency of power block is also lower. This highly restricts the total efficiency of PT (TO) case. All the other operational parameters, e.g. main steam pressure, reheat steam temperature and pressure, feed water temperature and pressure, are identical for different cases. The hybrid solar fields of tower (MS)+LF/PT (DSG) cases are determined as follows. (1) The point-focus solar field aperture area is calculated according to the requirement of superheating and reheating; (2) The line-focus solar field aperture area is calculated according to the requirement of preheating and evaporation. The efficiency of point-focus solar field of tower (MS)+LF/PT (DSG) cases is higher than that of tower (MS) case because the efficiency of point-focus concentration monotonically decreases with the increasing distance between the heliostat and the central receiver due to attenuation over long distance. That means theoretically the larger scale of point-focus solar field, the lower solar field efficiency. On the contrary, the efficiency of line-focus solar field of tower (MS)+LF/PT (DSG) cases is equal to that of LF/PT cases because the efficiency is theoretically independent of scale. The auxiliary efficiency is higher for DSG cases because the system is more simplified. The auxiliary efficiencies of hybrid scheme cases are calculated by aperture-area-weighted average of single scheme cases. The comparative results show that the PT(DSG) case gives the highest total efficiency (26.2%) while the PT(TO) case the lowest (23.4%), corresponding to the smallest and largest solar field aperture areas, respectively. The tower (MS)+PT (DSG) and (MS)+LF (DSG) cases stand second (26.0%) and third (25.4%) highest, respectively. The hybrid scheme cases exhibit excellent performance by benefitting high efficiency of comparatively small-scale point-focus solar field and high efficiency of thermodynamic cycle by DSG cases.

Table 4. Design-point performance of a 50 MWe CSP plant with different schemes for solar field

	Tower+LF (MS+DSG)	Tower+PT (MS+DSG)	Tower (MS)	LF (DSG)	PT (DSG)	PT (TO)
Design-point performance						
Direct normal irradiance (*DNI*) / W m^{-2}			750			
Net electricity productiion / kWe	50051	50051	50051	50051	50051	50057
Point-focus solar field efficiency / %	66.3	66.3	62.5	-	-	-
Line-focus solar field efficiency / %	63.7	66.9	-	63.7	66.9	67.3
Overall solar field efficiency / %	64.7	66.7	62.5	63.7	66.9	67.3
Point-focus solar field aperture area / m^2	97066	97066	269296	-	-	-
Line-focus solar field aperture area / m^2	163195	155389	-	264223	251584	271557
Total solar field aperture area / m^2	260261	252455	269296	264223	251584	271557
Main steam temperature / ºC	500	500	500	500	500	370
Main steam pressure / bar	100	100	100	100	100	100
Main steam mass flow rate / kg s^{-1}	45.6	45.6	45.6	45.6	45.6	56.4
Reheat steam temperature / ºC	500	500	500	500	500	370
Reheat steam pressure / bar	17.1	17.1	17.1	17.1	17.1	17.1
Reheat steam mass flow rate / kg s^{-1}	39.5	39.5	39.5	39.5	39.5	48.8
Feed water temperature / ºC	235	235	235	235	235	235
Feed water pressure / bar	105	105	105	105	105	105
Net power block efficiency / %	39.7	39.7	39.7	39.7	39.7	36.5
Auxiliary efficiency / %	99.0	98.9	97.8	99.6	98.6	95.3
Total efficiency / %	**25.4**	**26.0**	**24.2**	**25.2**	**26.2**	**23.4**

The proportional energy and exergy balances for different cases are shown in Figs. 1-2, respectively. In view of proportions, the main energy losses lie in solar field (32.70~37.50%) and condenser of power block (36.98~42.09%). This is mainly due to the heat losses to the environment and to the cooling water, respectively. The former could be reduced by enhancing the thermal isolation between the receiver tube and the environment while the latter could be utilized by heat recovery. The dominant exergy loss (63.89~66.28%) lies in solar field because of the radiation-to-heat conversion. It is also seen that the non-DSG cases generally give higher exergy loss due to additional heat exchangers. Following the total efficiency orders, the comparative results show that the PT (DSG) case gives the highest total exergy efficiency (28.4%) while the PT (TO) case the lowest (26.21%). The tower (MS)+PT (DSG) and tower (MS)+LF (DSG) cases stand second (28.3%) and third (27.45%) highest, respectively.

The componential energy and exergy balances for different cases are shown in Figs. 3-4, respectively. In view of componential amounts, the highest energy and exergy losses are found in condenser of power block (86.154 MW) and solar field (125.605 MW) of PT(TO) case, respectively. Therefore, the largest solar field aperture area (271557 m^2) is needed for this specific case (see Table 4). The lowest exergy loss in solar field is found in the PT (DSG) case (112.594 MW), followed by the tower (MS)+PT (DSG) case (113.222 MW) and tower (MS)+LF (DSG) case (118.691 MW).

The above results indicate that in terms of thermodynamic performance at design point, the PT (DSG) case is the most efficient against the PT (TO) case the least. Besides, the hybrid scheme cases show excellent performances.

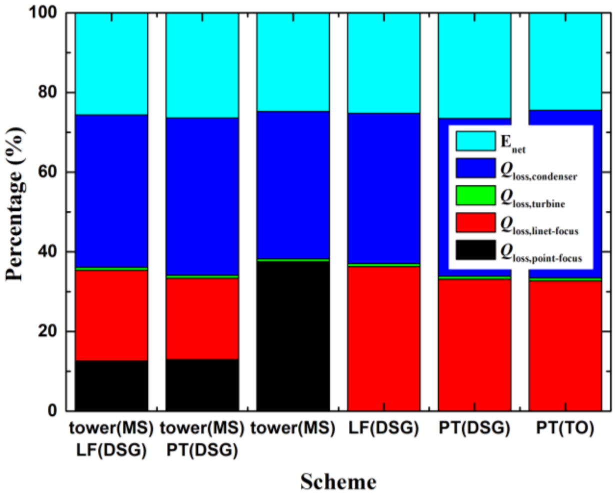


Fig. 2. Proportional energy balances of a 50 MWe CSP plant with different schemes for solar field

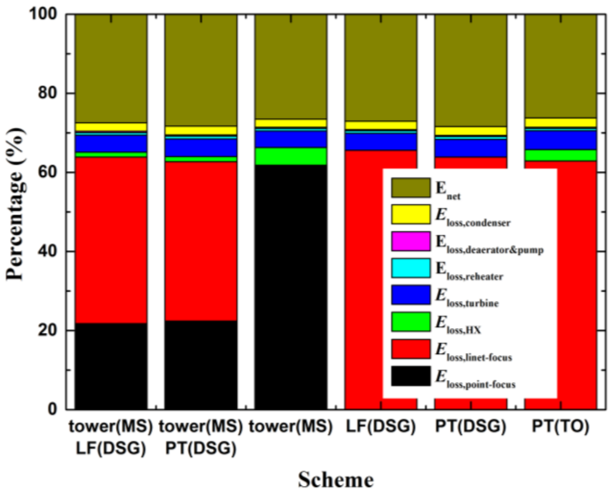


Fig. 3. Proportional exergy balances of a 50 MWe CSP plant with different schemes for solar field

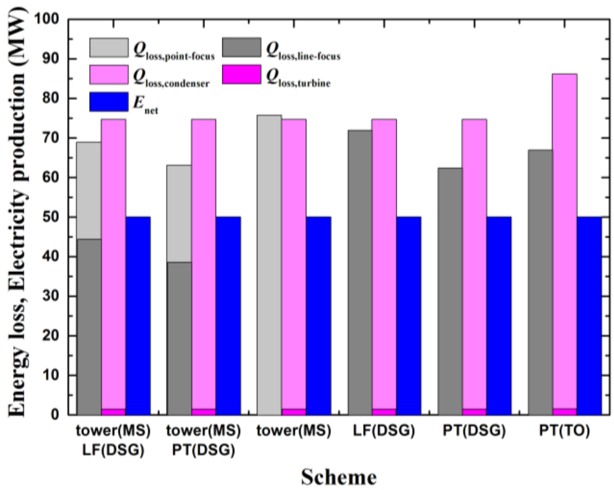


Fig. 4. Componential energy balances of a 50 MWe CSP plant with different schemes for solar field

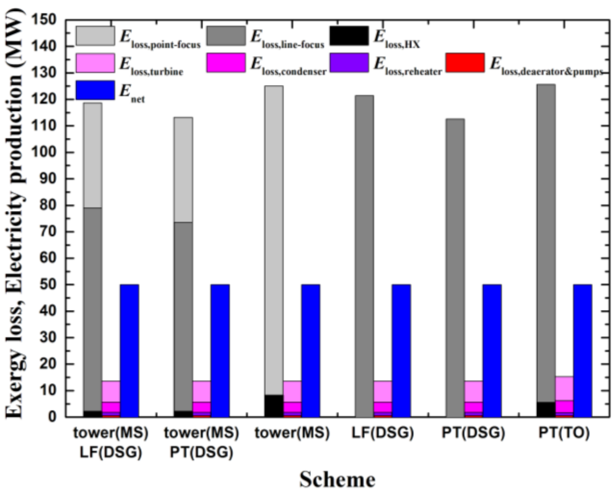


Fig. 5. Componential exergy balances of a 50 MWe CSP plant with different schemes for solar field

The annual performance and economic analysis of different scheme cases are listed in Table 5. The annual performance is based on the conditions of *DNI*=2791 kWh m^{-2} and operation time=2791 hours in Gaggett, CA, US (34º51' N, 116º49' W). Different from the design point performance (lowest total efficiency in the PT (TO) case as 23.4%), the lowest annual total efficiency is found in the LF (DSG) case as 10.7%, followed by the tower (MS)+LF (DSG) case as 12.7%. The reason is that the cosine loss of LF is larger than PT, especially in winter. The tower (MS) and PT (TO) cases have the same annul total efficiency of 14.0%. The tower (MS)+PT (DSG) case shows the highest total efficiency of 15.9%, followed by the PT (DSG) case at 15.6%. Note that the total efficiency of tower (MS) deceases with upscaling. The orders of annual net electricity production for different generally follow those of the total efficiency but it is also effected by the solar field aperture area. For example, it is seen that the tower (MS)+PT (DSG) case gives the largest electricity production but the PT (TO) case produces more electricity than the tower (MS) case though they both have the same total efficiency. The capacity factor is widely used to evaluate the annual performance of power plant, which is calculated as:

$$\text{capacity factor} = \left.\frac{\text{actual electricity production}}{\text{potential electricity production at full capacity}}\right|_{\text{annual}}, \qquad (12)$$

The results show that the tower (MS)+PT (DSG) case gives the highest capacity factor of 25% while the LF (DSG) case gives the lowest of 17%.

The economic analysis has been carried out with the major costs and charges taken into account, e.g. the capital cost, the annual O&M cost, the interest rate and the insurance cost. The results exhibit the distinct advantage of LF technology in low-cost solar field. This advantage greatly makes up the low electricity production, which finally leads to the lowest capital costs. Note that the entries of hybrid scheme cases are calculated by aperture-area-weighted average of single scheme cases. According to Eq. (11), the LCOEs of different cases are calculated and compared. The tower (MS)+LF (DSG) and PT (TO) cases equally give the lowest LCOE of 0.188 \$ kWh^{-1}, followed by the tower (MS)+PT (DSG) and LF (DSG) cases (equally 0.193 \$ kWh^{-1}), the PT (DSG) case (0.201 \$ kWh^{-1}) and the Tower (MS) case (0.203 \$ kWh^{-1}).

To clearly compare the cases in all aspects, the efficiency, electricity production, capital cost, annual O&M cost and LCOE of different cases are normalized in histogram (see Fig. 6). It is found that the tower (MS)+PT (DSG) and PT (DSG) cases show advantage in high efficiency; the tower (MS)+LF (DSG) and LF (DSG) cases show advantage in low cost; the PT (TO) case does not have outstanding advantage but with good balance due to high maturity and industrialization.

Table 5. Assessment of a 50 MWe CSP plant with different schemes for solar field

	Tower+LF (MS+DSG)	Tower+PT (MS+DSG)	Tower (MS)	LF (DSG)	PT (DSG)	PT (TO)
Annual performance						
Location	Daggett, CA, US (34º51' N, 116º49' W)					
DNI [19] / kWh m^{-2}	2791					
Operation time /hour	3550	3550	3550	3550	3550	3550
Point-focus solar field efficiency / %	47.6	47.6	42.1	-	-	-
Line-focus solar field efficiency / %	32.0	47.6	-	32.0	47.6	48.3
Overall solar field efficiency / %	37.8	47.6	42.1	32.0	47.6	48.3
Net power block efficiency / %	33.7	33.7	33.7	33.7	33.7	30.1
Auxiliary efficiency / %	87.7	107.1	98.7	99.5	97.5	96.6
Total efficiency / %	**12.7**	**15.9**	**14.0**	**10.7**	**15.6**	**14.0**
Net electricity production / GWh	88.2	107.7	101.6	75.8	107.3	104.9
Capacity factor / %	20	25	23	17	24	24
Economic analysis						
Spec. S.F. cost / \$ m_{aper}^{-2}	225	330	298	182	350	277
Spec. P.B. cost [13][1] / \$ kW^{-1}	770	770	770	770	770	895
Indirect cost and contingencies [13] / % plant cost	31					
Average spec. land cost [17][1] / \$ m^{-2}	8.9	8.9	8.9	8.9	8.9	8.9
Point-focus land area multiplier [3] / -	5.9	5.9	7.6	-	-	-
Line-focus land area multiplier [3] / -	2.0	3.4	-	2.0	3.4	3.5
Land area multiplier [3] / -	3.5	4.4	7.6	2.0	3.4	3.5
Capital Cost / \$ kW^{-1}	3046	3813	3966	2646	3889	3719
Annual O&M Cost [13] / \$ kWh^{-1}	0.037	0.038	0.032	0.040	0.042	0.033
Useful life and amortisation period / year	30					
Interest rate / %	4.2					
Annual insurance cost [17] / %	1					
Surcharge for engineering, EPC, project management and risk [17] / %	20					
Total plant availability [17] / %	96					
LCOE [17] / \$ kWh^{-1}	**0.188**	**0.193**	**0.203**	**0.193**	**0.201**	**0.188**

[1]EUR to USD exchange rate is chosen as 1:1.273
S.F.: solar field
P.B.: Power block

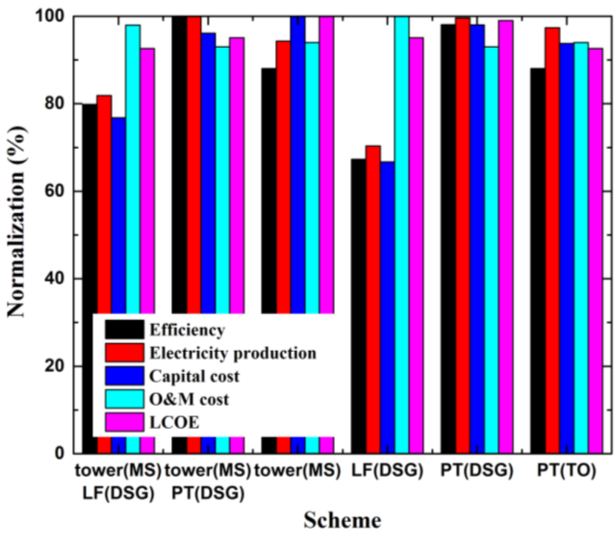


Fig. 6. Normalized comparison of a 50 MWe CSP plant with different schemes for solar field

4. Conclusions

In the present work, the point-/line-focus hybrid scheme for concentrating solar power (CSP) plant is proposed and compared with currently single scheme cases. The assessment of performance shows that the tower (MS)+PT (DSG) and PT (DSG) cases have advantage in high efficiency. The assessment of economics shows that the tower (MS)+LF (DSG) and LF (DSG) cases have advantage in low cost. The PT (TO) case shows good balance due to high maturity and industrialization. Based on a 30-year lifetime economic analysis, the tower (MS)+LF (DSG) and PT (TO) cases equally give the lowest LCOE of 0.188 \$ kWh^{-1}. However, considering the potential improvement, environmental effects and further industrialization, the promising DSG-based CSP technology has high probability to substitute the current solutions at low cost. On the other hand, the advantage of the hybrid scheme, which is benefit from the high concentration ratio of point-focus technology and low cost of line-focus technologies, has been clearly demonstrated and validated for large-scale CSP plants.

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