Solar Energy 136 (2016) 197–209

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Thermo-economic and comparative analyses of two recently proposed optimization approaches for circular heliostat fields: Campo radial-staggered and biomimetic spiral

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ARTICLE INFO

Article history:
Received 18 July 2015
Received in revised form 4 July 2016
Accepted 5 July 2016

Keywords:
Concentrated solar power
Heliostat field collector
Thermo-economic optimization
Campo radial-staggered layout
Biomimetic spiral layout

ABSTRACT

In this paper, comparative analyses between two newly proposed circular heliostat field layout designs, i.e. Campo radial-staggered and biomimetic spiral layouts are carried out. Moreover, different optimization objectives including annual weighted efficiency, annual unweighted efficiency, and levelized cost of energy are considered for field layout optimization. In addition, the effects of different design variables, such as the central tower height, number of heliostats in the field, receiver's dimensions and size of the mirrors on the field thermal and economical capabilities are investigated. Finally, the analysis' results indicate that optimum weighted efficiency for Campo radial-staggered and biomimetic spiral layouts are 61.6% and 61.5%, whereas the optimum levelized cost of energy for both methods are 32.4 US$/MWh.

1. Introduction

Renewable energy, such as solar, wind, and geothermal, can be utilized effectively to abate fossil fuels and natural gases consumptions (Sheu et al., 2015). However, the main advantage of renewable energies over fossil fuel is their less negative environmental impacts. It is reported that activities associated with energy generation using fossil fuels contribute to 61% of greenhouse gases emission (Herzog and Baumert, 2005). Solar energy is one of the favorable solutions to a more environmental friendly power production technology. Heliostat field collector, which is also referred to as the solar tower collector, is the most recent concentrated solar power technology emerging into the industry. In principle, the heliostat field contains a multitude of nearly flat mirrors that direct the sunlight toward the top of the tower where the receiver is located (Slocum et al., 2011).

Heliostat field collectors' mathematical formulation is arguably the most complicated among all solar collectors available in the market. Complexity in design and optimization of heliostat field prompted extensive research in developing different codes including UHC-RCELL (Lipps, 1974; Lipps and Vant-Hull, 1978; Lipps, 1985), DELSOL3 (winDELSOL) (Kistler, 1986), HFLCAL (Schmitz et al., 2006; Schwarzbözl et al., 2009), MIRVAL (Leary and Hankins, 1979), solTRACE, Fiat Lux, OPTEC (Schoffel and Sizmann, 1991), SOLVER from SOLUCAR (Relloso and Domingo, 2006), TONATIUH (Blanco et al., 2005), TieSOL (Izygon et al., 2011), SCT-HGM (Sanchez and Romero, 2006), and HFLD (Yao et al., 2009; Wei et al., 2010). Garcia et al. (2008) categorized the available heliostat field codes into two major clusters. The classification is accomplished based on the codes accuracy in calculating the reflected heat flux on the receiver surface. For example, MIRVAL, solTRACE, and Fiat Lux main objective is to provide a detailed description of the reflected rate of thermal energy from the heliostat field. On the contrary, UHC-RCELL, DELSOL, and HFLCAL accuracy in calculating the solar heat flux on the receiver surface is lower resulting in a faster approximation of the heliostat field performance for the optimization process.

Instantaneous optical efficiency of a heliostat is determined based on Sandia nomenclature such that (Pacheco et al., 2000; Collado, 2009):

$$\eta_{opt,f} = \rho f_{cos}(x,y,t) f_{at}(x,y) f_{sp}(x,y,t) f_{s\&b}(x,y,t) \quad (1.1)$$

As it can be seen, determining instantaneous optical efficiency of a heliostat depends on the time and its location with respect to the tower and neighboring heliostats. A new optimization method is proposed by Collado and Guallar, named Campo (2012, 2013), which systemizes the optimization procedure. This method speeds up the heliostat field optimization process. In heliostat field designs, shading and blocking factor becomes worse as the

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http://dx.doi.org/10.1016/j.solener.2016.07.006
0038-092X/

Nomenclature

Symbols

a, b	control variables for spiral pattern
$\cos\omega$	cosine of the solar incident angle
DM	characteristic diameter of the heliostat [m]
DNI	direct normal radiation [kW/m^2]
$dsep$	additional separation distance between heliostats [m]
E_{net}	annual thermal energy [MWh]
f	factor
i	loan interest rate
$LCOE$	levelized cost of (thermal) energy [US$/MWh]
LH	height of the heliostat [m]
LW	width of the heliostat [m]
n_{opr}	field life time cycle
r_i	polar radius of the i^{th} element of the spiral pattern [m]
r_{ins}	annual insurance rate
Z	capital investment cost [US$]

Abbreviation

CEPCI	chemical engineering plant cost index
TMY	typical meteorological year
UAE	United Arab Emirates

Subscript

ann,uw	annual unweighted
ann,w	annual weighted
at	attenuation
b,ref	reference blocking
cos	cosine
hel	heliostat field
mai	maintenance
min	minimum
opr	operation
opt,f	optical
rec	receiver
s&b	shading & blocking
sp	spillage
Tower	tower and piping

Greek symbols

ΔR	radial increment [m]
ε_T	tower unit vector elevation
η	efficiency
θ_i	polar angle of the i^{th} element of the spiral pattern [rad]
ρ	mirror actual reflectivity

distance between two adjacent heliostat rows is reduced (greater density). In consequence, it is required to place heliostats within the medium range of the tower with relatively lower spillage and attenuation efficiencies. In general, there will be a trade-off between the shading and blocking factor and the other optical efficiency factors. This tradeoff is the main objective of the optimization process.

Most of the introduced codes' field-layouts are based on radially staggered positions of the heliostats in the field as introduced in RCELL. Nonetheless, an innovative heliostat field layout has been proposed by Noone et al. (2012). The authors argue that the transition between the high and low density areas of the field is not continuous in radial-staggered layout. Thus, a new heuristic approach is presented based on the spiral patterns of phyllotaxis discs. This layout is studied by Besarati and Goswami (2014) for design and optimization of a 50 MWth heliostat field in Daggett, California. In another study by Ramos and Ramos (2012), a systematic procedure for the optimization of different aspects of the heliostat field collectors including filed layout, heliostats position, tower height, and receiver's dimensions are presented. Siala and Elayeb (2001) proposed a graphical formulation for a no-blocking heliostat field.

In this paper, thermo-economic and comparative analyses of two recently recommended field layout optimization approaches, i.e. Campo radial-staggered and biomimetic spiral layout, are presented. Furthermore, three different optimization objectives are selected to study their impacts on the optimum field layout and its thermo-economic performance. Finally, the effects of different design variables, such as the central tower height, number of heliostats in the field, receiver's dimensions and size of the mirrors on the field thermal and economical capabilities are investigated.

2. Field layouts

The first heliostat field layout, studied in this research work, is the radial-staggered configuration. In radial-staggered configurations, adjacent circles of mirrors do not share the same azimuth angle resulting in a significant improvement of the blocking factor. Additionally, the distance between two adjacent mirrors increases as they get further away from the tower. Therefore, field density reduces within each zone by moving outward away from the center of the field (tower).

There is another promising heliostat field layout proposed by Noone et al. (2012). A new heuristic is presented based on the spiral patterns of the phyllotaxis discs (Vogel, 1979). It is reported that the new pattern replacing radial-staggered configuration will improve the field optical efficiency and reduce the land area (Besarati and Goswami (2014)). The proposed field layout has the advantage of continuous density function unlike radial-staggered configuration. Moreover, no two heliostat centers within the spiral layout share the same azimuth angle (Noone et al., 2012).

3. Mathematical formulation

3.1. Campo radial-staggered field layout

The densest possible heliostat field layout is fed into the Campo code as its initial field layout to begin the optimization procedure. A comprehensive presentation of the used mathematical formulation to develop the densest possible heliostat field layout is provided by Collado and Guallar (2012).

3.2. Biomimetic spiral field layout

To generate the field with a new pattern of phyllotaxis discs in form of florets on the head of a sunflower, the following formulas are employed (Noone et al., 2012; Besarati and Goswami (2014)):

$$\theta_i = 2\pi i \left(\frac{1+\sqrt{5}}{2}\right)^{-2} \quad (3.1)$$

$$r_i = a i^b \quad (3.2)$$

It should be noted that a and b are the control variables in designing the field layout as their variations can be utilized within the optimization process.