

Original article

A novel approach to determine the non-dimensional heliostat field boundary for solar tower plants



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ARTICLE INFO

Article history:

Received 26 April 2016

Revised 27 June 2016

Accepted 8 August 2016

Keywords:

Solar tower

Heliostat field boundary

Packing density

Energy contours

ABSTRACT

Solar tower technology has gained considerable momentum over the past decade. In a solar tower plant, the power collected by the heliostat field is strongly coupled to the height of the tower and its location with respect to the field. This paper provides a methodology to fix the boundary of the field (non-dimensionalised with respect to the tower height). While developing this methodology, it was realised that one needs to have an estimation of the nominal variation of packing density with non-dimensional distance of the heliostat from the tower base. Packing density is fixed during the design of the field. A nominal variation of packing density was obtained by studying three existing plants which use radial staggered field patterns. This packing density data was used to arrive at contours of equal annual energy per unit land area (e_l). This approach was then evaluated qualitatively and verified quantitatively with non-dimensional solar fields of existing plants. Based on these comparisons, it is suggested that for preliminary analysis, a seed value of $e_l = 0.16$ MWh/m² may be used as a nominal value to set the field boundary. The significance of coupling of the solar field boundary with tower height is also discussed.

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Introduction

A solar tower uses a large number of heliostats or mirrors to reflect solar energy incident on them, onto a receiver that is located at the top of a tower. The concentrated solar energy that falls on the receiver is transferred to a Heat Transfer Fluid (HTF) which passes through the receiver. The thermal energy of the HTF is then transferred to a working fluid in the power block, by means of a heat exchanger, thereby generating electricity. Fig. 1 shows the schematic diagram of a solar tower plant.

The goal of the present study is to define a rational methodology to fix the boundary of the solar field of a Concentrated Solar Power (CSP) plant using solar tower technology. The objective is to obtain a non-dimensional radial field boundary as a function of azimuth, taking into account the latitude of the location, hourly DNI data as well as packing density. This is required in order to develop a method for the preliminary design of a solar tower plant that is analogous to that which was done for the design of a para-

bolic trough plant (of given capacity, thermal storage hours and hybridisation) [1].

Though there are a number of articles dealing with solar tower plants, they all deal with either characterisation and performance studies of existing plants [2–5], detailed design of heliostat field, given the heliostat and tower details, and optimisation [6–8] also using proposed spiral layouts [9] or detailed flux distribution on a receiver [10,11]. Analyses of ray tracing methods for simulation, shadowing and blocking due to adjacent heliostats and analyses of heliostat images have been performed [12–14]. Reviews of the various components in this technology as well as existing plants (in operation and under construction) have been performed [15,16]. However, information in open literature on the method to be followed for preliminary optimum design of a solar tower plant is very scarce. A chapter in [17] provides empirical guidance in the preliminary sizing and specification of the heliostat field. However, it does not provide a method for fixing the solar field boundary in order to carry out the preliminary design of solar tower plant analogous to what is developed for a parabolic trough plant [1], where the design is optimised to get maximum solar to electric conversion efficiency (η_{s-e}). This paper attempts to develop a systematic method to fix the solar field boundary necessary for preliminary design of a solar tower plant.

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Nomenclature

$A_{\text{heliostat}}$	area of heliostat, m^2	r_{n-1}	radial distance from base of tower to the $(n-1)$ th row of heliostats, m
DNI_i	hourly direct normal irradiance at the location for the i^{th} hour, W/m^2	r_n	radial distance from base of tower to the n th row of heliostats, m
N_f	number of points inside the field boundary	r_{n+1}	radial distance from base of tower to the $(n+1)$ th row of heliostats, m
MA_n	total mirror area of n th row, m^2	r/h	non-dimensionalised radial distance of point $(x/h, y/h)$ from the tower
LA_n	total land area of n th row, m^2	$(\frac{r}{h})_{\min}$	minimum non-dimensional distance from tower
PD_p	packing density at point p , ratio of the mirror area to land area.	x/h	non-dimensionalised x coordinate of point in field w.r.t tower height
$P_{s,d}$	design solar power of plant, W	y/h	non-dimensionalised y coordinate of point in field w.r.t tower height
SM	solar multiple	$\Delta\theta$	angle subtended by farthest two heliostats of a row, radians
d_x/h	non-dimensionalised grid spacing in x direction	$\Delta\phi$	circumferential angle between heliostat centres, radians
d_y/h	non-dimensionalised grid spacing in y direction	ϕ	latitude of the location, degrees
e_l	annual reflected energy per unit land area (taking into account cosine effect and packing density), Wh/m^2	θ_i	angle of incidence of the sun for hour i
e_m	annual reflected energy per unit mirror area of field (taking into account only cosine effect), Wh/m^2	$\theta_{i,p}$	angle of incidence of the sun for hour i and point p
h	height of the tower, m	η_m	efficiency of the heliostat
$h[1]$	height of the tower at solar multiple = 1, m	η_{s-e}	solar to electric conversion efficiency
i	number of the hour (varies from 1 to 8760)		
n_n	number of heliostats in n th row		
p	point in the field		
r	radial distance from base of tower to point in field, m		

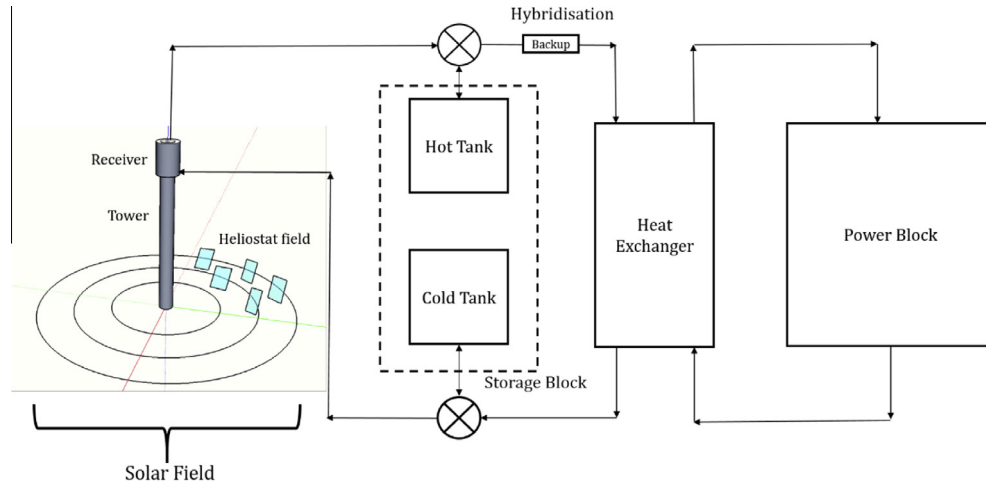


Fig. 1. Schematic of Solar Tower Plant.

Section “Need for coupling of tower height and solar field boundary” discusses the need for coupling between the solar field boundary and the tower height (i.e. height at which the receiver is located) in non-dimensional terms. Section “Assumptions of methodology” discusses the assumptions on which the methodology is based. Section “Rationale for choosing equi-energy contours per unit land area” deals with the rationale for choosing contours of equal energy per unit land area (e_l) to guide the choice of non-dimensional solar field boundary. The results of the method, applied to four typical locations, are given in Section “Results of application of methodology to typical locations” to show that equal e_l contours qualitatively exhibit the expected variation of the non-dimensionalised radial distance of a heliostat from the tower base (r/h) with azimuth, with respect to changes in latitude and Direct Normal Irradiation (DNI). Section “Choice of the field boundary” deals with the choice of field boundary. Concluding remarks are made in Section “Conclusion”.

Need for coupling of tower height and solar field boundary

In solar tower technology, the complexities involved in estimating the energy obtained from the field are listed as follows:

- The cosine effect of each heliostat is different and depends on r/h , azimuth position and time of the day.
- The shadowing and blocking effects vary for every heliostat. These effects depend on the heliostats r/h and azimuth position as well as the spacing of neighbouring heliostats. Therefore, in assessing the power and energy that can be collected by any heliostat, a nominal packing density effect has to be considered.

It is clear that the two effects listed depend on r/h and azimuth angle of the heliostat.

For a given tower height to choose the corresponding surround solar field, in order to avoid the process of choosing the boundary

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