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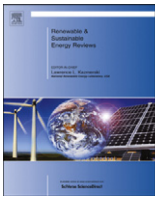

A review of optimized design layouts for solar power tower plants with *campo* code

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ABSTRACT

Solar power tower (SPT) systems are viewed as one of the most promising technologies for producing solar electricity, in which direct solar radiation is reflected and concentrated by a field of giant mirrors (heliostats) onto a receiver placed at the top of a tower. However, the optimized design of a heliostat field is a rather complex problem because the annual performance of a heliostat is a function of not only the instants of time considered and its own position, but also the relative location of neighbouring heliostats, which cause shadows and blockings. A variety of procedures may be found in the open literature, although there is great lack of information on the details of an optimized layout. This review shows that these complex problems have partially led to the expansion of parabolic trough technologies in USA and Spain in spite of their lower thermodynamic efficiencies compared with solar tower power. As a modest support of SPT systems, the authors have presented elsewhere the abilities of a new code called *campo* for fast and accurate calculations of the shadowing and blocking factor for each and every heliostat. This work explores a review of the optimized heliostat field layouts yielded by *campo. Campo* commences the optimization search based on the densest layout, with the worst shadowing and blocking factor, but with good values for the other optical factors, and then progresses towards gradually expanded distributions. The search for maximum annual energy through *campo* results in a clear, steady and reproducible procedure. Finally, as an example of this new procedure, some options of optimized heliostat field layouts are reviewed using as input parameters the scarce open literature data on *Gemasolar*, the first solar power tower commercial plant with molten salt storage in the world.

Contents

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1. Introduction

Among the renewable technologies available for large-scale power production today and for the next few decades, concentrating solar thermal power (CSP) is one with the potential to make major clean energy contributions because of its relatively conventional technology and ease of scale-up [1–6].

Solar power tower (SPT) systems, in which direct solar radiation is focused onto a receiver mounted on top of a tower by means of a field of two-axis tracking heliostats (giant mirrors), are known to be one of the most promising CSP technologies for producing solar electricity in the mid-load power range (≥ 50 MWe) [1–2]. SPT systems have already proved their ability to generate clean electricity in the 20 MWe size in Spain [7], while a 100-MWe SPT plant is under construction in USA [8].

SPT plants are currently competing with parabolic trough systems (PT) to generate clean power (more details about the PT technology can be found in [6]). Both systems are experiencing a major boost in their expansion and size. As we will see later in a review of the development and current status of these technologies, SPT and PT plants of about 300 MWe are expected in future years in USA [9].

This paper is centred on the optimized design procedures of heliostat field layouts in SPT systems in a modest attempt to make the designs of heliostat fields less complex. The current battle of SPT systems against PT technologies requires R&D support in the design, development, and testing of larger receivers, larger heliostats, and larger fields to reduce scale-up risk [1–3]. The need for new tools to scale-up SPT systems is also highlighted by DOE [10]: as the size of the SPT increases, the optical efficiency (the ratio of sunlight capture to incident sunlight) declines. Thus system re-optimization is required.

The heliostat field, the main focus of this study, is the key subsystem in solar power towers because it typically contributes about 50% [11] to the total cost of the plant and results in power losses of 40% [1]. Furthermore, the DLR ECOSTAR study [2] also concludes that innovation potentials with the highest impact on SPT-cost reduction are increases in heliostat size and plant scale (≥ 50 MWe). In view of current and near-future trends in USA [9], this increase in plant scale is already underway.

Clearly, any heliostat field optimization should be based on a fast and accurate calculation of the optical efficiency of a heliostat. Following classic Sandia nomenclature [12], which has also been used by the authors in former works [13,14], the instantaneous optical efficiency of a heliostat η is

$$\eta(x,y,t) = \rho \cos\omega(x,y,t)\ f_{\text{at}}(x,y)\ f_{\text{int}}(x,y,t)\ f_{\text{sb}}(x,y,t,\text{neighbour heliostats}), \tag{1}$$

where ρ is the actual mirror reflectivity, $\cos\omega$ the cosine of the incidence angle between the sun rays and the heliostat normal, f_{at} the atmospheric attenuation factor, f_{int} the intercept factor, i.e., the fraction of the energy spot reflected by the heliostat hitting onto the receiver surface, and finally f_{sb} is the shadowing (of incident sunlight by adjacent heliostats) and blocking (of reflected sunlight by neighbouring mirrors) factor, i.e., the fraction of the heliostat area free from shadowing and blocking, see Fig. 1.

The relation of this efficiency η with energy is immediate. The instantaneous power P_m (kW/m^2-mirror) sent by any heliostat onto the receiver will be

$$P_m(x,y,t) = \eta(x,y,t)\ I_D(t) \tag{2}$$

where I_D (kW/m^2) is the instantaneous normal direct solar intensity for the chosen location and time t.

Notice that, in general, the denser the heliostats in the field, the worse the shadowing and blocking factor and better the other optical factors in Eq. (1). This is the shadowing and blocking-heliostat density trade-off, which has been well-known since the pioneering works of Houston University [15–17].

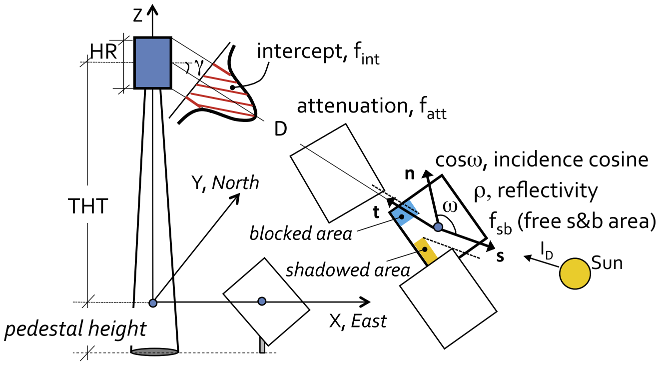

Fig. 1. Nomenclature of optical efficiency in heliostat fields.

However, in view of Eq. (1), the optimized design of heliostat fields in SPT plants is a rather complex problem for two reasons.

First, the instantaneous energy sent by a single heliostat, see Eq. (1), depends not only on its own location in the field and the instant of time considered, but also on the relative position of neighbouring heliostats that may cause shading and/or blocking onto it. This issue has been recently treated in depth by the authors elsewhere [14], in which a new code called *campo*, for the optimized design of heliostat fields, was presented.

Second, the figure of merit in the full optimization process of the collector field is usually the capital cost divided by the annual energy reaching the receiver [15–20]. This annual energy is the sum of the instantaneous energy, see Eqs. (1) and (2), produced by the whole field (there may be thousands of heliostats) along the instants of time (tens) sampled in a typical meteorological year (TMY). Concerning the capital cost, only companies with the capacity to design and construct an SPT system will know, obviously, as this is proprietary information, the accurate costs of the various elements in the collector field although some estimates can be found in [1,11].

Given the complexity of the problem and the expensive computation times, rather different codes with their specific simplifications may be found in the open literature. In [21], Garcia et al. present a general review of the most used codes (published by 2008), and divide the available codes into two categories defined by the calculation procedure for the spillage factor and shadings and blockings, see Eq. (1). MIRVAL [22] and SolTRACE [23] (the latter is free to download at [24]) are typical codes based on Monte Carlo ray-tracing, whereas University of Houston-RCELL [15–17], DELSOL3 (recently winDELSOL) from Sandia Labs [18] and HFLCAL from the German Aerospace Centre (DLR) [19,20] calculate the energy spot sent by a heliostat (and therefore the spillage) through the convolution of various error cones associated with rays reflected from the mirrors. Furthermore, these convolution codes usually calculate the shadowing and blocking factor projecting the outlines of the neighbouring heliostats onto the plane of the analyzed heliostat and then evaluating the heliostat area free from shading and blocking.

An analytical review of the former convolution codes can be found in [14], also including other Monte Carlo codes, such as SCT-HGM [25] (developed within the research project EU SIREC), and the more recent HFLD from the Chinese Academy of Sciences (CAS) [26,27] (published by 2010). More recent convolution codes not included in former reviews, such as CRS4-2 from the Italian CRS [28] and the MIT code [29], will be commented on later.

One conclusion of this former analytical review [14] is that the published codes leave several major questions unanswered concerning the details of the necessary layout optimization process for a