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Two-stages optimised design of the collector field of solar power tower plants

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ABSTRACT

In solar power tower (SPT) systems, selecting the optimum location of thousands of heliostats and the most profitable tower height and receiver size remains a challenge. Given the complexity of the problem, breaking the optimisation process down into two consecutive steps is suggested here; first, a primary, or energy, optimisation, which is practically independent of the cost models, and then a main, or economic, optimisation. The primary optimisation seeks a heliostat layout supplying the maximum annual incident energy for all the explored combinations of receiver sizes and tower heights. The annual electric output is then calculated as the combination of the incident energy and the simplified (annual averaged) receiver thermal losses and power efficiencies. Finally, the figure of merit of the main optimisation is the levelised cost of electric energy (LCOE) where the capital cost models used for the LCOE calculation are reported by the System Advisor Model (SAM)-NREL and Sandia. This structured optimisation, splitting energy procedures from economic ones, enables the organisation of a rather complex process, and it is not limited to any particular power tower code. Moreover, as the heliostat field layout is already fully optimised before the economic optimisation, the profiles of the LCOE versus the receiver radius for the tower heights explored here are sharp enough to establish optima easily. As an example of the new procedure, we present a full thermo-economic optimisation for the design of the collector field of an actual SPT system (Gemasolar, 20 MWe, radially staggered surrounding field with 2650 heliostats, 15 h of storage). The optimum design found for Gemasolar is reasonably consistent with the scarce open data. Finally, optimum designs are strongly dependent on the receiver cost, the electricity tariff and the assumed maximum receiver surface temperature.

1. Introduction

Solar power tower systems are currently booming, since several new projects at a commercial scale (>100 MWe) have entered the construction phase worldwide (SolarPACES, 2016). At such a scale, the levelised cost of energy (*LCOE*) of power tower systems should definitely be reduced to compete with fossil power plants.

The collector field, with thousands of heliostats or giant mirrors concentrating sunlight onto a receiver atop a tower, is the central building block for solar tower plants (Kolb et al., 2011; Kolb, 2011). However, unfortunately, the optimum design of the collector field of such plants remains a challenge, mainly due to the difficulties in heliostat field layout optimisation, with thousands of mirrors, combined with the simultaneous search for optimum values for the tower height, receiver size, and so on, giving the lowest *LCOE*.

In the open literature, DELSOL3 from Sandia Labs (Kistler, 1986) (originally written in 1986) has become practically a standard (Kolb, 2011; Avila-Marin et al., 2013) in current power tower codes that are able to perform a thermo-economic optimised design of the collector field based on LCOE. The code HFLCAL from German DLR (Schmitz et al., 2006; Schwarzbölz et al., 2009) is also a fully optimised code for solar tower plants but the details about it are rather scarce.

However, DELSOL3 exhibits several drawbacks mainly due to the rather limited computer capacities in the eighties. First, it makes some major simplifications about annual performances, in particular, the division of the whole field into 11 × 11 cells (with numerous heliostats in each one). Consequently, detailed performance factors are usually only calculated for the heliostat in the centre of the cell. Moreover, the optimum layouts were previously found in the 1980s through cost-energy optimisations using the RCELL code (Lipps and Vant-Hull, 1978). Finally, and probably as a result of these simplifications, the *LCOE* minima profiles in DELSOL3 are shallow, see page 118 in Kistler (1986), thus there are no clear selection criteria.

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Nowadays, with the huge calculation power of current personal computers, the question is if a much more detailed performance analysis of the heliostat field (heliostat by heliostat) would provide LCOE profiles sharp enough to establish clear minima. So that, the reliability of such optimised designs would be greatly increased.

Furthermore, the optimisation could be based on an advanced search algorithm such as genetic algorithms. In that case, the tower height, receiver size, and the layout parameters are the design variables and LCOE is the single objective function.

However, a detailed annual performance of thousands of heliostats for a large amount of feasible layouts, with a lot of choices for tower height and receiver size, in addition to the uncertainty of the current cost models, etc., raises major issues with regard to the above search algorithm. In particular, how we could efficiently manage tens of layout options matching them with the LCOE along the optimisation, which would be the range of variation of the design variables and the most convenient variation step, etc. Using the language of genetic algorithms (Obitko, 2016), we could say that the search space (each point in the search space represent one feasible solution) is, by the moment, rather diffuse.

Therefore, in this work, it is suggested to break the optimisation down into two consecutive steps: first, a primary, or energetic, optimisation, which is practically independent of the cost models, and then a main, or economic, optimisation. The primary optimisation would seek a heliostat layout supplying the maximum annual incident energy for all the explored combinations of receiver sizes and tower heights.

It is necessary to highlight that the optimisation decomposition could exhibit some disadvantages. The most important one would be that it is not guaranteed to give an optimal solution of the overall problem.

However, supporting this phased optimisation approach, several detailed layout optimisation codes, which only optimise the heliostat field layout based on receiver size and tower height, have emerged in recent years (Sánchez and Romero, 2006; Wei et al., 2010; Noone et al., 2012; Collado and Guallar, 2013; Besarati and Goswami, 2014; Atif and Al-Sulaiman, 2015). Some of these layout codes published before 2012 (Sánchez and Romero, 2006; Wei et al., 2010; Noone et al., 2012) were reviewed in Collado and Guallar (2013).

This last work is also the layout optimisation, through a smart search, of a surrounding radially staggered heliostat field giving the maximum yearly insolation weighted efficiency, or maximum field efficiency, for a Gemasolar-like 20 MWe plant with 2650 heliostats. The tower optical height and the receiver radius were set to $THT = 130$ m and $RR = 4$ m, respectively. Only two design variables, namely constant radial increments between consecutive rows for the second and third zones, respectively, could define the whole layout of the regular concentric rings generated heliostat field.

Along the same lines, Besarati and Goswami (2014) have recently studied layout optimisation, based on genetic algorithms, of a 50 MWth heliostat field (with a cavity receiver) to provide the maximum field efficiency for Dagget, California, where the shape of the biomimetic spiral pattern-based layout (Noone et al., 2012) is defined by only two design variables. The specific field parameters used along the optimisation were $THT = 115$ m, a receiver aperture width of 13.78 m, and an aperture height of 12 m.

Atif and Al-Sulaiman (2015) have also recently performed a layout optimisation (maximum field efficiency), using differential evolution algorithms, for a regular surrounding radially staggered field with 2940 heliostats located in Dhahran city, Saudi Arabia. Here, the prescribed field parameters are $THT = 130$ m with a receiver diameter $DR = 9.44$ m. The four layout design variables the optimisation determines are an increment of the maximum heliostat footprint, which controls the angular distance between adjacent heliostats in the first ring in each zone, and the three radial spaces between the rows of the heliostats for each of the three zones defined.

Until the knowledge of the authors, LCOE profiles calculated with any of these recent codes have neither published nor even suggested how to use this layout codes to perform a LCOE optimisation of the collector field.

The logic next phase proposed here should be to energetically optimise the layout but now for several sets of design variables (THT, RR) chosen around a reference case. However, all of them need to have the same prescribed number of heliostats N_{hel} to keep the heliostat cost virtually constant so that the whole problem could be effectively broken into two simpler ones. After this primary optimisation, several design collector fields $(THT, RR, \textit{corresponding optimum layout})$, all of them giving a maximum annual energy, would be available prior to their *LCOE* calculations. Finally, the *LCOE* (the levelised cost-net annual energy ratio) of the various design options is the figure of merit of the economic optimisation.

The reference collector field used to check the new procedure is that of Gemasolar (Vázquez et al., 2006; Lata et al., 2006, 2010; Ortega et al., 2006; Burgaleta et al., 2011; Relloso and Lata, 2011), the first solar power tower commercial plant (19.9 MWe, N_{hel} = 2650 heliostats) with molten salt storage (15 h) in the world. The layout code used is *campo* (Collado and Guallar, 2013) although the simple parametric analysis suggested here is not limited to a particular layout code, or even a specific layout pattern, as it is perfectly reproducible by any of the above-commented layout codes.

Finally, the structure of this work is as follows. Section 2 introduces the primary layout optimisation for every set of design variables (THT, RR) checked here, namely 5×5 combinations. The minimum set of variables that reproduce the whole layout is briefly reviewed and how they should be varied along the search is analysed. Some details of the field efficiency are gathered in electronic pdf file Appendix A whereas some comments about the optimal layouts is presented in Appendix B. The energy performances of the twenty-five designs are then available. Section 3 calculates the net annual energy output E_E for those designs. The Sandia (Kistler, 1986) annual energy bookkeeping has been followed, in which the annual receiver thermal losses and the thermodynamic cycle efficiency are assumed to be constant. Section 4 reviews the *LCOE* economic terms and the investment cost models of the main collector field equipment. Section 5 combines the net annual energy E_E with capital cost models to plot the sensitivity of the *LCOE* against various design and cost options searching minima. Finally, Section 6 discusses the main assumptions and advantages of the new proposed optimum search, and provides some conclusions.

2. Primary optimisation of the field layout for every (THT, RR) considered

2.1. Field efficiency

For every (THT, RR) considered, several layout design options for $N_{hel} = 2650$ are tested. The corresponding optimal layout should give a local maximum of the optical (annual averaged) field efficiency η_{field}. The factors that set up the optical efficiency of a heliostat are classically defined in Pacheco et al. (2000), Pacheco (2002) whereas the mathematical models used by *campo* to calculate such factors have been defined elsewhere (Collado and Guallar, 2013, 2012; Collado, 2010; Sassi, 1983). Then, only a brief summary is presented in the electronic Appendix A. *Field efficiency*. As in Collado and Guallar (2013), due to a lack of data, a typical meteorological year (TMY) for PSA (Almería) Meinecke, 1982, which has similar latitude to Gemasolar, is used.