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Strategy and criteria to optically design a solar concentration plant

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ABSTRACT

The objective of this work is to individuate the best strategy to determine the layout of a thermodynamic plant based on the concentration of solar flux by means of a large number of mirrors. Many software tools exist, both dedicated software and more general optical software. This analysis shows the advantages derived from the use of a general non-sequential optical software, proposing criteria and procedures in order to establish dedicated optical merit figures, which are suggested and evaluated from the point of view of their effectiveness to achieve a favorable layout design. Particular attention is devoted to merit figures that estimate the optical efficiency, a key quantity for all the CSP plants that can be defined in different ways. The description includes examples of application, discussion of results and various proposed alternatives for the merit figure.

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1. Introduction

Recently the sector of production of renewable energy is experiencing a great development of systems based on the concentration of solar flux by means of a large number of mirrors. These Concentrated Solar Power (CSP) plants are thermodynamic solar energy installations that are mainly composed of a field of heliostats, which concentrate the sunlight on a receiver, often placed on a tower.

In order to maximize the system efficiency, the utilization of suitable optical design software to structure the mirror field and the receiver is indispensable. At present for CSP systems it is possible to utilize different codes and software tools in order to evaluate the optical performances of the mirror field [1] and to simulate the flux distribution on the inner surfaces of cavity or receiver, which is practically impossible to get by real measurements (for example, see Qiang Yu et al. in [2]). They permit to obtain several merit figures, many of them introduced and employed in literature, in order to evaluate the performance of a whole renewable energy plant: as example, [3] proposes "net energy" and "gross carbon emission (CO2eq)" as merit figures in order to compare different sources for electricity generation, while [4] utilizes "embodied energy", devoted to total cost evaluation (it considers only commercial energy) and "emergy", that is the amount of energy involved in a transformation process. Scholars

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introduced different merit figures to evaluate costs and advantages of the sources for energy generation (in particular, to compare their results in terms of efficiency, costs, sustainability and environmental protection), but very often they are general figures that do not specifically characterize the optical configuration of the heliostat field. In effect, problems and methods related to the heliostat plant realization suggested to use appropriate merit figures to characterize the CSP optical system and to guide the design process, as it was done for other solar systems or components. Kumar, in [5], estimates the design parameters for a box-type solar cooker introducing two merit figures related to heat losses and water heating capability; Sansoni et al., in [6], investigate the image uniformity separating the contributions of different regions of a prismatic lens, while in [7] carefully analyze the performance of a simulated trough collector, assessing by ray-tracing received light and acceptance angle. All these papers evidence the necessity of introducing some merit figures specific for the actual case. From this point of view, the utilization of a generic optical design software permits more flexibility to individuate the actual best merit figures and to assess the performances concerning flux distribution and system collection efficiency with respect to dedicated software (see [1] for a review of specific codes for solar flux calculation). Obviously, the utilization of a generic optical design software requires the development of customized methods and design tools, as studied by Sansoni et al. in [8], but it permits to choose the best evaluation tools. Very interesting is the work of Segal et al., in [9–11], where the optimization is focused on the maximization of the energy at the entrance of the receiver system in a tower-reflector system. It is essential to highlight that the traditional merit figures for optical systems are quite useless, because solar divergence and component tolerances very often generate a beam enlargement wider with respect to the optical aberrations. Moreover, the optical aberrations exist only if the solar field is composed of non-flat mirrors: in this case the actual most important aberration, the astigmatism, can be significantly reduced if a suitable plant layout is utilized; coma and spherical aberration, for large solar plants, are often unimportant [12,13]. For this reason the best choice is a non-sequential optical design software (like ASAP, LighTools, TracePro), from which it is possible to obtain more useful information with respect to a traditional (sequential) one. Basically, optical design software tools can be split into two categories: traditional software, where the user decides the order in which the rays hit the surfaces; lighting simulation software, where the rays hit the surfaces in a "natural" order, depending on their optical path (more similar to the physical reality). A sequential software permits to calculate the aberration values, while the non-sequential ones focus on radiometric and photometric quantities: the most useful of them, for the analysis of the performances of a mirror field, are the irradiance maps that show both "how much" (scalar quantities, i.e. the total flux on the surface) and "how" (imaging maps, i.e. the flux distribution) of the ray tracing.

The present paper is dedicated to summarize the merit figures utilized for the design of CSP plants using a generic optical design software, separating the subsystems [9] and focusing on methods and tools to evaluate the optical performance of a heliostat field in order to choose the best plant configuration.

2. Field of heliostats

The first phase of the optical design of a CSP plant is to define the field of mirrors, thus a set of parameters that permit to evaluate and classify it, from an optical point of view, must be outlined. Defined the plant location [14], the positions where the heliostats have to be placed are determined by the mirror size and the acceptability of a shadowing degree and a blocking grade in various day hours/seasons. The degree of shadowing is how much a mirror's shadow can cover the mirror behind; the grade of blocking defines how many rays from a heliostat to the receiver are blocked by the rear surface of other mirrors. Many tools and procedures developed by means of a non-sequential optical software can be utilized in this phase in several ways: shadowing and blocking phenomena can be evaluated in different day hours or seasons in order to establish a convenient trade-off between land occupation and CSP plant efficiency; the land occupation is computable also by a reverse ray-tracing from the receiver toward the mirror field, measuring the flux not intercepted by the heliostats. Many authors studied the influence of these parameters on the final optical efficiency of a CSP system [15–19], but the real difficulty is to find a useful merit figure to compare different mirror fields or the same heliostat field in different hours of the day or seasons. In fact the actual input flux depends on the system configuration: it varies with the cosine factor and the mirror shadowing factor. Thus the efficiency (output flux / input flux) based on the actual input flux is not very useful to compare different layouts of the same field (for example with towers of different height), because an increase of the shadowing (that is a decrease of the input flux) and a proportionally identical decrease of the output flux lead paradoxically to the same efficiency. Jafrancesco et al., in [20], defined a new merit figure that describes the field collection efficiency: it is the ratio between a variable *field output flux* (quantity of radiation reflected by the mirror field towards the receiver) and a constant *field input flux*, defined as the product between the DNI and the total reflecting surface, where the DNI is the *Direct Normal Insolation*. Substantially this is a conventional definition of mirror field efficiency, where the actual input flux is replaced by the so-defined *field input flux*, and it is always less than 1. This definition could be useful to compare different fields layouts (setting the actual sun position), but it does not take into account the cosine factor (that is the angle between the normal to the mirror surface and the sun rays). In effect, it has to be highlighted that it is mandatory to individuate the "critical parameters" concerning the realization of a CSP plant, as the area of the mirroring surface or the land occupation. If the last one is the major concern, it seems preferable to use as input flux the product of DNI and area utilized by the CSP plant[1] (obviously only to compare CSP plants with different mirroring surface, because for the same plant the merit figure introduced in [20] is equivalent); moreover, the averaged cosine factor can be evaluated and considered in the formulas in order to estimate the flux that hits the mirroring surface without blocking.

Regarding two-dimensional (2-D) and three-dimensional (3-D) maps that represent the distribution of the parameters of interest (e.g. irradiance, shadowing, output flux, …), they are the output of a software simulation and act both as qualitative figure and as "parameters set". So from them it is possible to obtain various merit figures; in fact a quantitative measurement of the performance requires the passage from a 2-D or a 3-D map to unidimensional parameters (just because there is no ordering among the 2-D or 3-D maps, thus it is impossible a quantitative comparison between two configurations of CSP plant). However, the qualitative analysis of the performance is very useful in order to warn the designer about some weaknesses or faults in the CSP layout that are very difficult to be obtained from consolidated data: they typically are lack of irradiance or efficiency of a part of

[1] Please note that it would be possible to define a more general merit figure too: the ratio between the averaged (annual) output flux from the mirror field and the area of CSP plant; it would seem to permit for comparison among CSP plants in different locations, which is really very difficult due to the design priority change (land occupation, area of the mirroring surface, limits to tower height, etc.).