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Enhancing the efficiency of solar concentrators by controlled optical aberrations: Method and photovoltaic application

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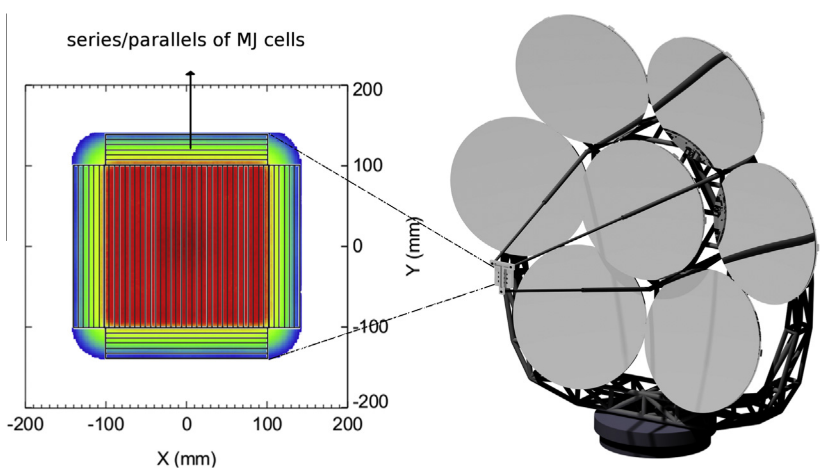
HIGHLIGHTS

- We developed a new optical design method for high performance solar concentrators.
- The method is based on optimizing the optical shapes to match the receiver features.
- A dense array PV concentrator made by few monolithic mirrors was modeled.
- The optimization led to free-form optics focusing high uniform irradiance spots.
- The optimal optics/receiver coupling increases the system conversion efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

We present a general method, based on controlled static aberrations induced in the reflectors, to boost receiver performances in solar concentrators. Imaging mirrors coupled with dense arrays suffer from severe performance degradation since the solar irradiance distribution is bell-shaped: mismatch losses occur in particular when the cells are series connected. The method consists in computing static deformations of the reflecting surfaces that can produce, for an adopted concentration ratio, a light spot matching the receiver features better than conventional reflectors. The surfaces and the deformations have been analytically described employing the Zernike polynomials formalism. The concept here described can be applied to a variety of optical configurations and collecting areas. As an example, we extensively investigated a dense array photovoltaic concentrator, dimensioned for a nominal power of about 10 kWe. The "flat" distribution of light we obtain can exploit the PV device cells close to their efficiency limit. A significant gain is thus obtained, with no need of secondary optics or complex dish segmentation and of special features in the receiver electrical scheme. In the design, based on seven 2.6 m mirrors, we addressed also non-optical aspects as the receiver and the supporting mechanics. Optical and mechanical tolerances are demonstrated not to exceed accurate, but conventional, industrial standards.

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1. Introduction

Concentrating Photovoltaics technology (CPV) is experiencing a growing interest thanks to the development of solar cells with continuously improved efficiency. At present, the best reported cell is a 0.165 cm^2 multi-junction (MJ) cell having a new record of 44.4% confirmed efficiency at direct irradiance concentration of 302 suns (1 sun = 1000 W/m^2) [1]. For both high concentration (HCPV) and low concentration (LCPV) systems the yearly installed capacity increased significantly during the last five years [2]. A simple advantage induced by this technology is that, given the collected energy, the concentration performed by optical devices such as lenses or mirrors allows us to replace the area of photovoltaic material with cheaper optical surfaces. Moreover, high efficiency cells are too expensive to be used in non-concentrating applications. Despite most of the installed systems are point focus lens based as Fresnel [3–6] or micro-dish [7–9] systems, dense array systems have been recently investigated as profitable solutions for lowering the cost per watt-peak supplied [10,11]. In this technology the light is focused using one large reflective element called dish, onto an array of photovoltaic MJ cells densely packed to form a single detector. If compared with lenses, mirrors have the main advantage to not suffer from chromatic aberrations. These systems track the sun in two-axis during its daily motion and usually operate in high concentration mode, i.e. with solar flux up to hundreds times the ambient value. Reflective dish concentrators with diameters ranging from few meters to few tens of meters have been already proposed and are at the beginning of their commercial development working at typical concentrations of 500$\times$ [12–14].

Traditional dish concentrators have paraboloidal shapes. Theoretically, their diameters could reach several tens of meters as the heliostats in central tower plants, the construction of monolithic mirrors being difficult at these scales. The size generally imposes to approximate the profiles with cheap flat reflecting facets mounted on a common frame and reproducing globally the paraboloidal surface. As for the receivers, standard cells have rectangular shapes and the arrays are groups of cells densely packed together mostly in series and parallels connections. The arrays do consequently resemble rectangular shapes too. When a standard imaging mirror that produces a sun image intrinsically circular is coupled with a rectangular detector problems arise. In this condition some cells could be obscured if the spot is smaller than the receiver, or part of the light could be lost if the detector is smaller than the spot, these two effects contributing to a substantial loss in efficiency. Moreover, the given irradiance distribution is bell-shaped in contrast with the requirement of having all the cells under the same illumination. In fact, interconnected cells having identical electrical characteristics and experiencing the same irradiance/temperature conditions produce the same amount of output current and voltage. Mismatch losses occur instead when interconnected cells experience different conditions, in particular for series connections. Still few investigations have been specifically performed on current mismatches in dense array receivers exposed to high concentrations [15–17]. The issue of spatial light uniformity is instead widely known for single cell devices [18–21] and the problem is commonly approached by the introduction of secondary optics (SO) [22–24] working as homogenizers. The presence of an extra secondary optics is rather useful to increase the acceptance angle leading to a relaxation of tracking and alignment tolerances. However, this solution has the disadvantage to increase the system complexity and to add reflection losses, chromatic aberration (if refractive) and mechanical problems as alignment, stability or mounting. A useful review on the state of the art of the nonuniformity problem for single cell receivers has been recently published [25]. Few commercial systems and technical data are available on secondary optics embedded in dense arrays. Some researches faced the uniformity problem from the receiver point of view, developing new electrical connections [26], embedding different cells in the same array [27] or designing new receivers with radial symmetry [28].

Alternative ways of redesigning the primary collector have been poorly investigated but some good results has been obtained by Chong et al. [29]. The proposed planar faceted concentrator coupled to a dense array has been optimized to give a large uniform illumination over the target area with a peak intensity of 391 suns. However, such a concentrator is made by several mirrors to be mounted and aligned before being orientated with the use of line-tilting driving mechanism. Moreover, since the final spot is the overlap of the multiple facets reflections, the size and the uniformity of the final spot is influenced by projection and blocking effects which increase with the distance of the facets from the center of the whole assembly. For this reason, such a mosaic system is not able to both have big collecting area and high concentration ratio without embedding a high number of facets and high focal distances, as reported in similar works [30–32]. In [32] the economical viability is however claimed for a specific configuration of faceted dense array system since a cost for the output power below 2 euro/W has been calculated.

The strategy we suggest in this paper is to boost the spot uniformity by only acting on the primary reflector but using monolithic big surfaces and avoiding the dish faceting into numerous smaller elements. In the proposed method, the shape of the mirrors is analytically described by the Zernike polynomials and its optimization is numerically obtained to give a non-imaging optics able to produce a quasi-square spot, spatially uniform and with prescribed concentration. The free-form primary optics, optimized in this way and validated by a ray tracing software, showed a substantial gain in efficiency without the employ of secondary optics. At the same time, simple electrical schemes for the receiver are required. The concept has been investigated theoretically modeling a CPV application including a conceptual development of non-optical aspects as the design of the receiver and of the supporting mechanics. For the proposed method and the specific CPV system developed, a patent application has been filed in Italy. A preliminary analytical study, considering a residential utility, has been also performed in order to understand the energetic and economic performance of the system [33]. The analysis indicates that the maximum sustainable capital cost of the system ranges between 30,000 euros and 45,000 euros depending on the years which are considered for the return of the investment (10 or 20 years respectively). Further more detailed economical evaluations will be performed during the future constructive phases of the project.

2. Optical concept

From an optical point of view there is no need for an accurate image at the receiver of a solar concentrator. The optical design criteria rather concern with the optimal transfer of light between the source and the target chosen. To solve matching issues in concentrators we thought to reinterpret optical concepts largely used in astronomy, where an accurate image formation is an essential premise for efficient observations. In telescopes, controlled mirrors deformations are introduced by actuators to balance the optical aberrations that degrade the wavefront coming from an observed source [34–36]. What we developed instead is a sort of “reverse” approach of the astrophysical method: the guideline is to apply deformations (active or static) to the mirrors of the solar collectors to introduce aberrations in the wavefront, thus degrading the solar image and, in the case of a CPV dense array system, focusing a squared spot with a prescribed irradiance. The result would be a