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Energetic and Economic Analysis of a New Concept of Solar Concentrator for Residential Application

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Abstract

Renewable energy penetration is increasing in last years, covering a more and more important role in both electrical and thermal supply. Nowadays, the photovoltaic conversion is a consolidated technology and can be efficiently combined with solar concentration. In this study, a new concept of photovoltaic solar concentrator based on non-conventional mirrors coupled with high efficiency triple-junctions cells is described and discussed. More in details, as for the optical design, deformations are applied to classical spherical mirrors to control solar aberrations and boost efficiency of a receiver consisting in a dense array of cells. The efficiency enhance is obtained by high matching between the collected solar irradiance and the receiver electrical features. The concentrator is able to produce both electrical and thermal energy: the system requires in fact an active cooling circuit to maintain the cells performance. This behavior makes the system suitable for combined heat and power applications with particular reference to high direct irradiance environments. An analytical study, considering a residential utility has been performed in order to understand the energetic and economic performance of the system. In particular, a simulation has been carried out by the use of an in-house-developed calculation code considering a whole year of operation.

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Keywords: Renewable Energy; Solar Concentration; Non Imaging Optics; Combined Heat and Power; Feasibility Study

1. Introduction

Concentrating Photovoltaic (CPV) technology [1] is experiencing a growing interest thanks to the development of multi-junction (MJ) solar cells with continuously improved efficiency. At present, the best reported cell has a record efficiency of 44.4% at direct irradiance concentration of 302 suns [2]. In some of these systems, a large reflective element (the dish) focuses the light over an array of cells densely

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packed in a single receiver element. The whole structure tracks the sun during its daily motion. Commonly, a mosaic of low cost flat mirrors mounted on a parabolic dish frame approximates the concave shape required to concentrate the light. At high concentrations, the cell array experiences a high heat load that reduces their efficiency if not dissipated adequately by an active cooling. Mirrored dish concentrators with diameters ranging from few meters to tens of meters are at the beginning of commercial development working at typical concentration of 500 suns [3].
These dense array systems represent a good perspective to increase the concentration factor towards 1000 suns and beyond. Advantages of the reflective optics are the absence of chromatic aberration thus the better optical efficiency if compared to point focus systems (no refractive elements), lower cell operating temperature and capability to work in cogeneration thanks to the active cooling needed. A significant advantage of concentrator dish systems compared to the other CPV technologies resides in the possibility of move the receiver in case of cleaning, testing or even repair and, as solar cell technology improves, it allows the power station operator to upgrade a concentrator dish PV system to a higher efficiency receiver at very low cost.
The conversion efficiency is the main driver of the CPV technology economic sustainability. In this sense, an important issue is the irradiance distribution over the cells. Non-uniform irradiance on the cells degrades severely the receiver electrical performance thereby reducing its conversion efficiency. The worst illuminated cell produces less current than the others, limiting the current production of the series connected cells. Moreover, the worst illuminated cell experiences an overheating caused by the dissipation of some current produced by the other cells and can eventually break out. The best illumination condition for a dense array receiver is an irradiance pattern as uniform as possible and, at the same time, a light shape that traces the natural rectangular/square shape of the array. Flux uniformity and reshaping are theoretically possible by redesigning the optics of a concentrator [4], by approximating it with an array of flat elements [5] and/or by adding secondary optics (SOs) to tailor the flux delivered by the primary element [6,7], but still few commercial data are presently available on SOs coupled with dense arrays.
In this paper we analyse a dense array concentrator based on a new optical concept (SOLARIS concentrator [1,2,3]) to solve the irradiance mismatch problem. The new design approach led to an innovative single stage multi-dish device without secondary optics but with high irradiance uniformity and high concentration, in which the nominal conversion efficiency of the whole receiver almost equals the performance of the constituting cells. The proposed system has been evaluated with a series of simulations in order to understand its potential as renewable micro Combined Heat and Power (CHP) generator with reference to residential utilities. The electrical and thermal energy production and the maximum sustainable capital cost of the system have been calculated and will be discussed in the next sections of this paper.

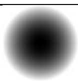
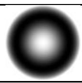
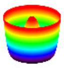
2. The SOLARIS concentrator modeling

Free-form optics for a prescribed irradiance pattern are certainly not new in non-imaging optics, but in solar devices they are mainly used as secondary refractive elements of limited dimensions. The SOLARIS concentrator has been instead conceived as a big primary reflective optics made by several mirrors: specifically, seven mirrors substitute the traditional segmented dish, focusing the light at the same point so that the final illumination pattern impinging on the receiver is the sum of the single incoherent illumination patterns produced. The design guideline is to introduce controlled deformations in originally spherical mirrors in order to degrade the solar image thus obtaining a square spot with prescribed irradiance distribution. The shape optimization aims at maximizing the conversion efficiency.

The system optical/electrical modelling has been carried out with an end-to-end code written in Interactive Data Language IDL® based on analytical models for both optics and receiver. The code includes two main subgroups of routines for individually simulating the optics and the receiver. A third group of procedures calculates the tolerances for the optical/mechanical parameters.

As for the optics, all mirrors have been simulated and designed implementing in the code a well-known analytical model of aberrations based on the Zernike polynomials [8]. Considering a single spherical mirror, a preliminary optical analysis showed that very few deformations associated by coefficients to the Zernike modes, can improve the irradiance uniformity starting from the intrinsically circular solar image (Fig. 1). For a single spherical mirror focusing on axis we identified three main polynomials: the 4^{th}, the 11^{th} and the 14^{th}, acting on the defocused solar image as shown in Table. 1. Then we extended the method to a multi-mirror system, including off-axis mirrors and other polynomials. Ray tracing techniques have been implemented to simulate and optimize simultaneously all the reflective surfaces. Each step of the optical modeling and the results have been further checked with the optical design software Zemax® as reference.

Tab. 1. 2D and 3D representations of the main polynomials involved in the modeling

	Zernike mode		
	4^{th}	**2.1.1. 1 1^{th}**	**2.1.2. 1 4^{th}**
2D			2.1.3. 
3D			

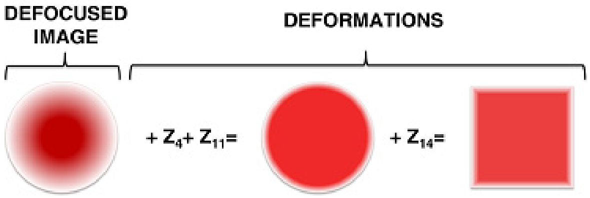


Fig. 1. Effects introduced in the solar image by the indicated polynomials.

The receiver has been analytically designed and numerically simulated using a datasheet of commercially available MJ cells 3C40 produced by AZUR SPACE [9] with 39% nominal efficiency at 500 suns at ambient temperature. The electrical scheme employs series/parallels standard electrical connections. Since the cells include busbars, part of the concentrated light will necessary impinge on the inactive areas: the nominal efficiency thus considering the cell embedded in a dense array will be reduced to around 33%.

The dish has been conceived as a power system suitable for the market of medium residential contexts or small farms, then for a production of around 10 kWe. The diameter of the single mirror has been set to 2.6 m, for a system size of about 7.8 m and a resulting total optical area slightly bigger than 35 m^2. Supposing a direct normal irradiance (DNI) of 1 kW/m^2 (1 sun), the collected power is around 35 kW: with an ideal receiver working at the efficiency of the considered cells, such a system would be able to deliver more than 10 kWe. The detector distance has been set to 4.8 m in order to have a detector distance to total diameter ratio (similar to the focal ratio for imaging systems) of 0.6. In general, small focal ratios are preferred to obtain high concentration and structure compactness despite of the higher aberrations introduced.

3. Nominal performance and irradiance dependence

The concentrator has been optimized for an average concentration of 500 suns. Fig. 2 depicts the mechanical model of the system and a zoom of the focal zone, where the receiver electrical scheme has been superimposed to the irradiance pattern delivered after the optimization. The narrow rectangles in figure are strings of cells series connected. Groups of strings have been then connected in parallel (not shown in figure) to ensure small parallel mismatches and to obtain high voltage and small current in output.

The electric model has ideally no dependence from temperature and spectral variation. Since we deal exclusively with reflective elements no chromatic aberration is introduced, so the last assumption is realistic. The temperature can also be considered reasonably constant as efficient cooling systems have been shown in literature [10, 11].

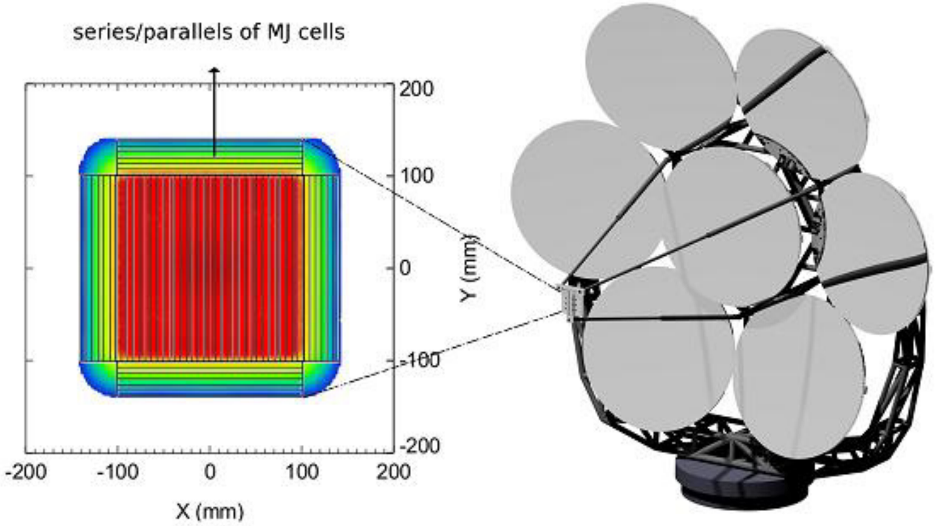


Fig. 2. Mechanical shaded model of the SOLARIS concentrators and zoom of the focal zone showing the irradiance pattern and the receiver scheme

The performance curves of the system are presented in Fig. 3 which shows both the power collected by the concentrator and the light effectively impinging on the array. Further in this figure the electrical and thermal efficiency are plotted as function of the DNI.

It should be observed that at this stage, no model for the bypass diode has been implemented. The mirrors shapes optimized to maximize the efficiency of this receiver gives a uniform irradiance pattern over the 80% of the total power focused (red zone in Fig. 2). With this high matching between light and cells, the receiver shows an effective conversion efficiency, defined as the power produced ratio the total power collected, of 29.4%. The relative efficiency calculated as the ratio between the power produced and the only impinging power on the receiver, is 31.2%.

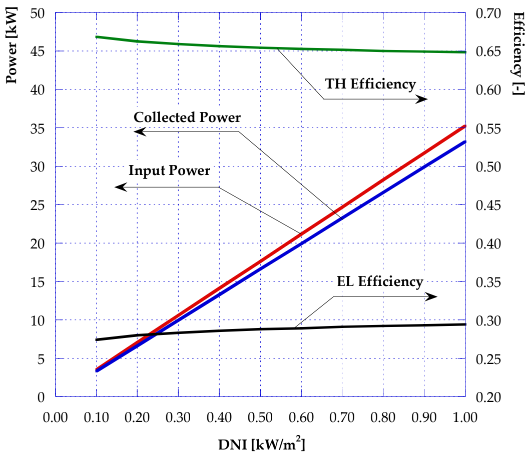


Fig. 3. Collected and input array power of the SOLARIS concentrator and electrical and thermal efficiency as function of DNI at the collector aperture.

This value has to be compared with the nominal performance obtainable for the receiver made with the cells considered (33%) and shows that almost all the cells in the receiver are working approximately at their theoretical maximum.

From Fig. 3 it should be noted that the electrical efficiency drops down from 29.4% to a value equal to about 27% with an irradiance of 0.1 kW/m^2. This evidence clearly highlights that the electrical efficiency trend is quite constant with the change in irradiance. For what regards the thermal efficiency a maximum value close to 65% can be reached (with reference to irradiance equal to 1 kW/m^2). Also this parameter does not show heavy changes with the irradiance variation.

4. Energetic and economic performance evaluation

In order to estimate the performance of the system in Fig. 2 under both the energetic and economic point of view, a parametric analysis has been developed by varying the number of residential utilities served by the solar concentrator. For each of the domestic utilities, the following assumptions have been taken into account: (*i*) yearly required electrical, thermal and cold energy equal respectively to 3200 kWh, 20000 kWh and 3500 kWh (corresponding to about 1000 kWh of electrical energy) [12], and (*ii*) solar radiation according to a latitude equal to 44.51 deg and longitude to 11.35 deg (corresponding to Bologna location) [13]. The performance of the solar concentrator have been calculated on the basis of the curves in Fig. 3. Further a simplified model of an (*i*) electrical storage system and of a (*ii*) thermal storage tank have been included in the calculation in order to minimize the exchange of electrical energy with the grid and the consumption of the fuel for the boiler. In particular for what regards the storage efficiency of electrical energy an average value of 60% was taken into account.
The results of the energetic analysis are presented in Fig. 4 with reference to the electrical and thermal fluxes. For what regards the electrical energy, it can be noted that with a number of served utilities equal to 3, the electrical energy exchanged with the grid can be optimized. It results the total amount of electrical energy sold to the network equal to zero while the purchased energy is less than 2000 kWh. For what regards the thermal energy, with 3 utilities, all the production from the system can be recovered (i.e. the dispersed energy is equal to zero).

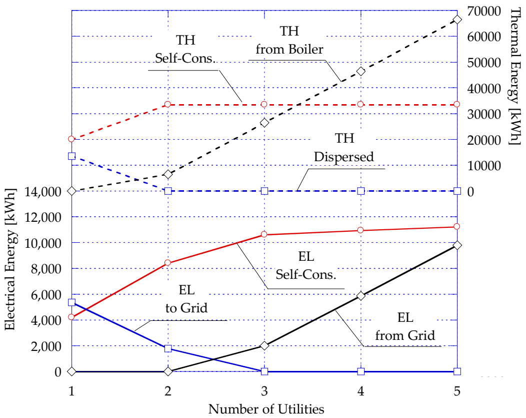


Fig. 4. Electrical and thermal fluxes due to the solar concentrator as function of the number of served utilities

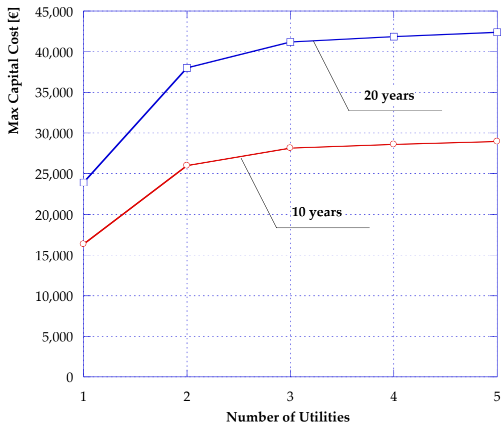


Fig. 5. Solar concentrator maximum sustainable capital cost as function of the number of served utilities

The economic analysis was conducted in order to identify the maximum capital cost that can be paid off in ten or twenty years of operation. More in details, for each of the analyzed cases was estimated the annual savings achievable by the non-purchase of electricity and gas to the boiler. Also the sale of electrical energy to the grid was taken into account. For this analysis, the cost of electrical energy and natural gas where chosen respectively equal to 200 €/MWh and 0.50 €/Sm^3 while the sale price of the electricity is about 70 €/MWh. Finally, the discount rate was assumed equal to 7%. The results of the economic analysis are presented in Fig. 5.

The results show that the capital cost lower than 30˙000 € (10 years) and 45˙000 € (20 years) can be achieved. In particular, with reference to 3 utilities, the maximum sustainable capital cost of the system is equal to about 28˙000 € in case of 10 years of return of the investment. Anyway, it should be taken into account that in many country, such as Italy, the production of electrical energy from renewable source is strongly incentivized. This additional economic advantage can obviously increase, depending on its amount, the values presented in Fig. 5.

Concluding remarks

In this study, a new concept of photovoltaic solar concentrator based on non-conventional mirrors coupled with high efficiency triple-junctions cells has been analysed and discussed. An analytical study considering a residential utility has been performed in order to assess the energetic and economic performance of the system. Results suggest that the proposed system can optimize the electrical and thermal fluxes in case of 3 residential utilities minimizing the exchange of electrical energy with the grid and allowing the total recovery of the produced thermal energy. The economical analysis which has been developed indicates that the maximum sustainable capital cost of the system ranges between 30˙000 € and 45˙000 € depending on the years which are considered for the return of the investment.

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