Solar Energy 169 (2018) 457–467

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

# A > 3000 suns high concentrator photovoltaic design based on multiple Fresnel lens primaries focusing to one central solar cell

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## ARTICLE INFO

*Keywords:*
Concentrator photovoltaics
Ultrahigh concentrator
Optical loss
Ray trace simulation

## ABSTRACT

A high concentrator photovoltaic design is proposed of 5800x geometrical concentration ratio based on multiple primary Fresnel lenses focusing to one central solar cell. The final stage optic is of a novel design, made of a high refractive index ($n = \sim 1.76$), to accept light from four different directions but very easily manufactured. The high geometrical concentration of 5800x was chosen in anticipation of the losses accompanied due to alignment difficulties. Two scenarios are however simulated, one with state of the art optics (achromatic Fresnel lenses and 98% reflective mirrors) and one of standard, relatively cheap optics. An optical efficiency of ~75% is achieved in simulations if high quality optics are utilised, which gives an optical concentration ratio of just over 4300x. Simulating standard optical constraints with less accurate optics results in an optical efficiency of ~55% which translates to an optical concentration ratio of ~3000x. In this way the quality of the optics can be chosen depending on the trade of between cost and efficiency with room for future advanced optics to be incorporated at a later date. The optical efficiency of each component is simulated as well as experimentally measured to ensure the accuracy of the simulations. A theoretical acceptance angle of 0.4° was achieved in ray trace simulations for this design which is considered good for such a high concentration level. The need for achromatic Fresnel lenses is apparent from this study to reach optimum performance and concentration but even 55% optical efficiency results in a > 3000x concentration not yet experimentally tested. The solar cells irradiance distribution of the design is also presented along with performance and rough cost comparisons to other systems in the literature. The cost of the optics compared to more complex shaped optics is also given.

## 1. Introduction

### 1.1. Prospects and challenges

One trend in concentrator photovoltaic (CPV) technology is towards systems of higher concentration levels (Cristóbal et al., 2012; Shanks et al., 2016c; Vossier et al., 2012). This is due to their ability to increase cell conversion efficiencies and reduce cell size, also reducing the photovoltaic cost contribution to the full system (Gordon et al., 2004; Vallerotto et al., 2016). At present however, cheaper low efficiency solar technology such as flat plate silicon panels often win out over CPV technology despite the higher efficiencies and space conservation achieved by CPV. If an intended Solar Power installation is not restrained by space, then there is little to no motivation to install CPV over flat plate technology due to the consistently cheaper costs of flat plate PV over recent years (Ekins-Daukes, 2017; Morgan, 2017).

The work presented here focuses on a design which is relatively easy and low cost to manufacture. The design method does not prioritise optical efficiency but does incorporate the best and most likely performances due to manufacturing constraints. In this way, the cost and size (space taken up by the system) can be compared in a different manner. For example, a 1000x concentrator system which only works at 50% optical efficiency should perform as well as a perfect 100% efficient 500x design but such high efficiency optics would of course cost far more to manufacture. In which case, the less optically efficient design would be the best choice if there were no space limitations. To illustrate this further, the cost of the design presented here is given and compared to other, more complex shaped optics. This is however only one reason for exploring > 3000x concentration designs.

Multi-junction solar cells are pushing higher and higher efficiency records within relatively short time spans and need equally progressive concentrator optical designs to match. There has already been

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https://doi.org/10.1016/j.solener.2018.05.016
Received 22 November 2017; Received in revised form 26 April 2018; Accepted 5 May 2018
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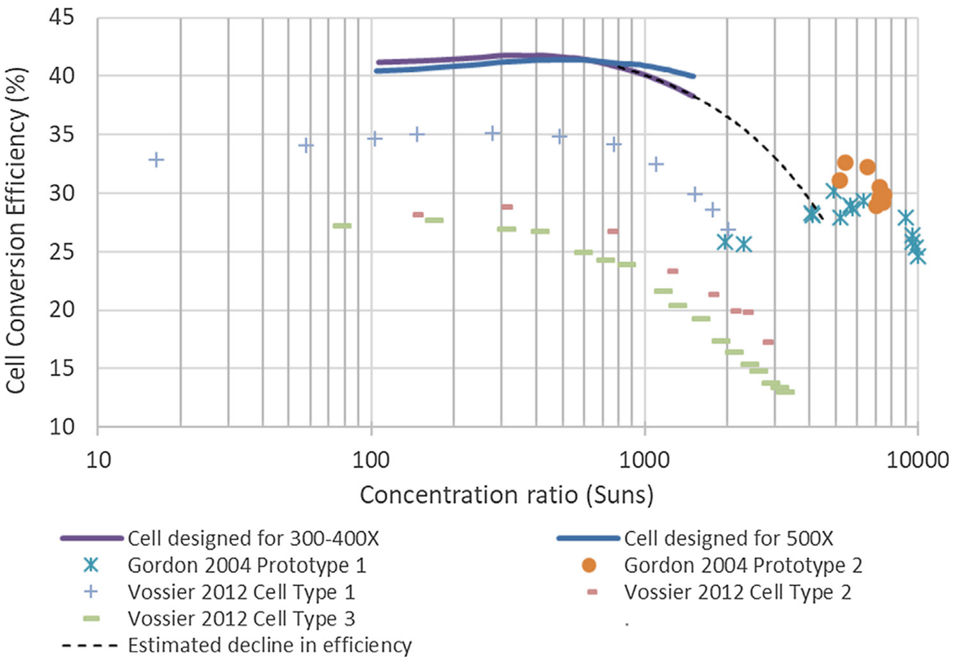

**Fig. 1.** Cell Conversion efficiencies at increased concentration ratios. The data for the Azur Space cells used for the preliminary experimental testing (Section 6) are given (solid lines) as well as a simple extrapolation showing the estimated decline in the efficiency (black dashed line) for the cell to be used. Experimental results from the literature are also shown for different cells and prototypes from Gordon et al. (Gordon et al., 2004) and Vossier et al. (Vossier et al., 2012) for comparison.

promising theoretical and experimental results for the efficiency of solar cells working at higher concentration ratios than which they were designed for as shown by Fig. 1. Although the results from Vossier 2012 are of lower efficiency cells, it is expected from the Azur Space cell data and Gordon 2004's results that a similar efficiency decline is possible for higher efficiency solar cells also.

At present, there lacks any reliable > 3000x CPV system to experimentally test if, in real weather conditions, very high concentration systems could produce more power and be more cost effective despite the lower conversion efficiencies of the cells. The durability of the cell and the optics for example, in varying temperatures and where light exposure will naturally rise and fall depending on cloud cover and day length, are unknown. The maximum temperature reached by concentrated light of > 3000x incident on a solar cell is one of the most important questions to be addressed and required to suitably design cooling mounts and metallization patterns for the solar cells. Literature suggests that as long as the light distribution upon the cell is distributed relatively uniform and there is sufficient cooling (passive or active), then the temperature should be manageable (Braun et al., 2013; Katz et al., 2006). There has already been research into the effect of high temperatures on Fresnel lenses (Hornung et al., 2015, 2010, 2012) and the ability of passive cooling plates to accommodate high concentration ratios up to 4000x (Micheli et al., 2016, 2015). The miniaturisation of solar concentrators in particular is a method which can significantly reduce solar cell temperatures. In which case, the proposed design here could be downscaled and enhanced further but must be proven first.

Although the system is designed for use with a multijunction solar cell, it is anticipated that thermal applications would also be of great interest under such high concentration ratios. Not only for solar-thermal power generation but for other developing thermionic metamaterials which can perform significantly more effectively at high temperatures (Andrade et al., 2014).

The main design constraint for the optics of very high ( > 3000 suns) CPV systems is the difficulty to achieve a high tolerance design which is simultaneously of a high optical efficiency. This is ultimately due to the limits of etendue but are also affected by material availability and manufacturing accuracy (Languy and Habraken, 2013; Shanks et al., 2015; Vallerotto et al., 2016; Winston and Gordon, 2005).

Fresnel lenses as a primary concentrating optic have a relatively good acceptance angle and optical efficiency in comparison to the cassegrain design utilising conic primary reflectors (Shanks et al., 2016c). If used alone, a single medium Fresnel lens is limited in concentration ratio by chromatic aberration to ~1000 suns ((Languy et al., 2013). Achromatic Fresnel lenses made of 2 mediums as described by Languy et al. (Languy et al., 2013) and Guido et al. (Vallerotto et al., 2016) can achieve higher concentration ratios but are still to reach full scale manufacturing. The other option for very high concentrations is to incorporate multiple concentrating optics in a singular system but too many can significantly reduce the optical efficiency and tolerance (due to manufacturing and alignment error). In this paper we present a high concentration design of geometric concentration ratio ~5800x in anticipation of high optical losses and to compare the effects of different quality optics. In this way this study will not only present a new type of > 3000x high concentrator that can be built with current standard optics but also with developing state of the art optics to reach optimal performance. In theory, by deprioritising the optical efficiency it should also be easier to achieve a good acceptance angle for the system.

Another constraint in achieving > 3000x high concentration ratios is fabrication limits, the size of Fresnel lens or conic mirror required would be costly and difficult to manage. To overcome this, we use 4 Fresnel lenses' focusing to 1 central PV cell with the aid of other redirecting and concentrating optics (Fig. 2). A similar method has been adopted by Ferrer-Rodriguez et al. who recently proposed a design consisting of 4 cassegrain style reflectors which were angled to focus onto a central receiver optic and PV cell (Ferrer-Rodriguez et al., 2016). There has also been a design with a similar 4 entrance curved tertiary optic by Zamora et al. (Zamora et al., 2012) but this utilises a dome shaped Fresnel lens which is difficult to manufacture. The curves of the tertiary central optic would also mean a specific mould would need to be developed which has high initial costs. The design presented in this paper maintains a tertiary optic whose conic shape is simply spherical (Figs. 2, 3C and 8A) and which can be made by a common circular drill tip of the appropriate diameter. The uniqueness of this design and the optimisation method is in which the manufacturability of each component is somewhat prioritised more than the optical efficiency of those components.

Minano et al. suggest other designs following the 4 part beam splitting method which can achieve higher CAP values but all of these designs are costly to manufacture either in the primary or in the tertiary optics geometry (Minano et al., 2013). The maximum concentration

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