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Novel nonimaging solar concentrator for portable solar systems for developing countries

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***Abstract*—Portable solar chargers have been gaining popularity as a new technology to help increase electrification in rural areas in developing countries. It is a fast developing industry aiming to produce a low-cost solution for the application of off-grid solar lighting and charging of small devices to be used by the poorest and most vulnerable of society. Solar concentrators are proposed as an add-on to help further reduce costs, to increase light-output hours and to reduce charging time. So far, no suitable concentrator designs have been proposed. This paper presents a novel concept for the design of a static nonimaging concentrator, suitable for portable solar systems for developing countries. The novel concentrator design is compared with existing concentrators and its suitability for portable solar chargers, as well as its potential for further improvement, are highlighted.**

***Index Terms*— concentrated portable solar systems; rural electrification; solar chargers; solar power**

NOMENCLARURE

Symbols:

A	Entrance aperture width
a	Exit aperture width
a^2	Exit aperture area
C_g	Geometrical concentration ratio
C_{opt}	Optical concentration ratio
h	Concentrator height
θ_a	Half-acceptance angles
η_{opt_max}	Maximum optical efficiency

Abbreviations:

CCPC	Crossed compound parabolic concentrator
SEH	Square elliptical hyperboloid
TIR	Total internal reflection

INTRODUCTION

Nearly 1,200 million people worldwide lack access to electricity [1]. One of the fist and main application of electricity is lighting. Non-electrification has an impact on people's every-day lives, including limits to learning when it gets dark, a short productive day and high expenditures on lighting [2].

In Sub-Saharan Africa over 630 million live in off-grid communities [1], where the alternatives to clean electrical lighting are kerosene lamps and candles for the one who can afford it, while most commonly switchgrass is burned. These alternatives have associated health hazards such as poisoning from kerosene fumes, eye irritation and an increased risk of fires and burns. Furthermore, the introduction of small electrical devices like mobile phones leads to an increasing gap between electricity supply and demand [3].

Due to the remoteness of the affected communities, an increase in electrification rate through grid supply is technologically and financially challenging [4]. Off-grid solar chargers have been gaining popularity and the technology is under continuous development aiming to achieve lower cost, faster battery charge and more electricity generation to prolong light hours at a high light intensity. From a detailed analysis on the improvement of individual parts of the solar chargers it has been concluded, that solar concentrators can help to achieve these goals. The following section gives an overview of existing concentrated solar technologies.

EXISTING TECHNOLOGIES

A solar concentrator is a device which focuses light from a larger onto a smaller area, thus increasing the irradiance on the solar cell and consequently its electrical output [5], [6]. From a comparison of different types of solar concentrators [5], [7]–[13] it has been concluded that low concentration, static, nonimaging concentrators manufactured from a dielectric material are best suited, since they do not require tracking or cooling, are easy to operate and maintain and have the ability to capture diffuse light [9]. For a concentrator design to be suitable for portable solar systems for developing countries, it must comply with the following:

(i) same light acceptance angle on all vertical planes for easy use
(ii) sufficiently high concentration ratio to enable savings in photovoltaic material
(iii) minimum height and volume to reduce weight and manufacturing cost
(iv) design needs to be suitable for a concentrator array to be produced from a single mould to minimize manufacturing and assembly costs

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Yet, nonimaging concentrators have not been used for portable solar systems. From designs which have been proposed for concentrated building integrated solar systems, the most suitable designs which could also be used for portable solar systems are the three dimensional crossed compound parabolic concentrator (3D CCPC) and the square elliptical hyperboloid (SEH) concentrator, both proposed by Sellami [14], and the three dimensional refractive lens proposed by Saitoh and Yoshioka [15] (Table 1). The characteristics are defined as follows:

C_{opt}	Optical concentration ratio: ratio between the number of rays reaching the cell with the concentrator and the number of rays reaching the cell without the concentrator.
θ_a	Half acceptance angles: range of angles of incidence within which the optical concentration ratio remains within 90% of the optical concentration ratio at 0º.
h	Concentrator height
a^2	Exit aperture area

TABLE I. CHARACTERISTICS OF THE 3D CCPC, THE SEH CONCENTRRATOR AND THE 3D REFRACTIVE LENS

	3D CCP concentrator [14]	***SEH*** ^{a} ***concentrator*** [14]	***3D refractive lens*** [16]
C_{opt}	3.43	1.6	2.00
θ_a **(º)**	± 30	± 60	± 30 / ± 45
h **(mm)**	16.16	10	14
a^2 **(mm²)**	100	100	150

a. SEH concentrator with a height to aperture ratio of 1 to 1 and a geometrical concentration ratio of 4

PROPOSED DESIGN

The 3D refractive lens uses only refraction for light concentration, thus the side profile does not have an optical function. The SEH concentrator on the other hand uses refraction at the entrance aperture and reflection at the side profile. However, as it has been stated by Winston, Minano and Benitez [9], that the family of trumpet concentrators needs to have a lens to be suitable for infinite sources. The proposed design for portable solar systems combines the entrance surface of the 3D refractive lens with the hyperbolic profile of the SEH concentrator.

A. Design procedure

The entrance aperture of the concentrator is designed point by point using an iterative algorithm defining the slope at each step, in order for all parallel rays, incident at the specified acceptance angle to be focused in point ± *a/2* (Figure 1). This method guarantees that all rays incident within the acceptance angle reach the exit aperture [15].

Input parameters:	θ_a half-acceptance angles a exit aperture width
Output parameters:	h concentrator height A entrance aperture width

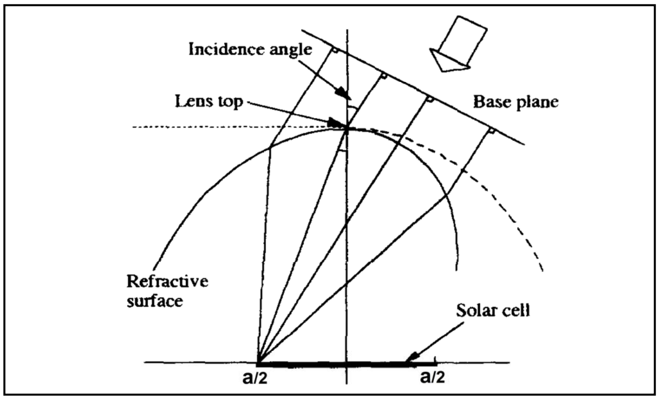

Figure 1. Design principle of the 3D refractive lens, adapted from [16]

Concentrators deigned only by this method achieve concentration ratios of around 2x. In order to increase the concentration ratio, the exit aperture is reduced. A hyperbolic profile is used to reflect extreme rays towards the exit aperture by total internal reflection (TIR) which would otherwise be focused in ± *a/2*. The input parameters of the hyperbolic profile design are the output parameters from the entrance aperture design *h, A* and the input parameter *a*, which is defined as 10 mm to create a concentrator for a 100 mm² solar cell.

It needs to be noted that the larger the acceptance angle of the lens, the smaller the resulting height but also the smaller the geometrical concentration ratio [15]. In order to generate a concentrator with a small height, large acceptance angles were chosen for the design procedure of three concentrators A, B and C.

Concentrator A: 40º entrance aperture acceptance angle
Concentrator B: 50º entrance aperture acceptance angle
Concentrator C: 60º entrance aperture acceptance angle

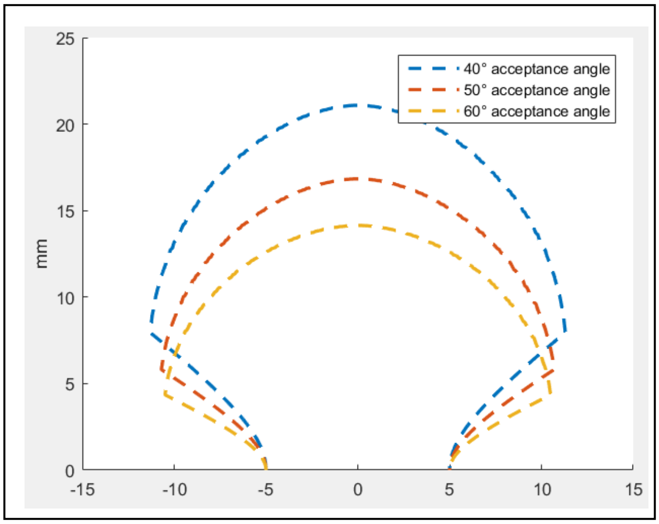

Figure 2. From heighest to lowest: side view of Concentrators A, B, C

RAY TRACING ANALYSIS AND RESULTS

Concentrators A, B and C were tested using ray tracing in ZEMAX OpticStudio. A light source was set to emit 1 million rays at a power of 1000 W. The concentrators were placed at a 350 mm distance from the light source as well as a thin layer of index matching gel and a 100 mm^2 detector to replicate conditions for the experimental analysis.

B. Optical characteristics of the proposed designs

The properties of concentrators A, B and C (Table 2) are compared in terms of geometrical concentration ratio C_g, optical concentration ratio C_{opt}, maximum optical efficiency η_{opt_max}, half acceptance angles θ_a, height h and exit aperture area a^2. The design goal is a minimum height, a maximum optical concentration ratio, and a maximum acceptance angle. C_g and η_{opt_max} are defined as follows:

C_g: ratio between the area of the entrance aperture and the area of the exit aperture

η_{opt_max}: ratio between C_{opt} and the maximum C_g

TABLE II. CHARACTERISTICS OF CONCENTRATORS A, B, C

	Concentrator A	*Concentrator B*	*Concentrator C*
C_g	4.01	3.60	3.46
C_{opt}	3.94	3.49	3.14
η_{opt_max} (%)	100	97	94
θ_a (°)	± 28	± 32	± 35
h (mm)	21	16.8	14.1
a^2 (mm^2)	100	100	100

Concentrator A provides the highest optical concentration ratio but has the smallest acceptance angle and the largest height. A further disadvantage is the non-uniformity of irradiance distribution at the exit aperture at 0º (Figure 3). This is due to its stronger entrance aperture bent (Figure 2). Thus, the larger the acceptance angle of the entrance aperture, the more uniform is the irradiance distribution on the receiver and the lower is the risk of hotspots on the solar cell.

Increased irradiance uniformity is therefore achieved with concentrator C (Figure 5) with further advantages being a larger field of view (Figure 6) and a reduced height. However, the rays are concentrated onto a larger area than the 100 mm^2 exit aperture area. Thus, the side rays for which the condition for TIR at the side profile is not fulfilled are lost, leading to a reduced optical concentration ratio.

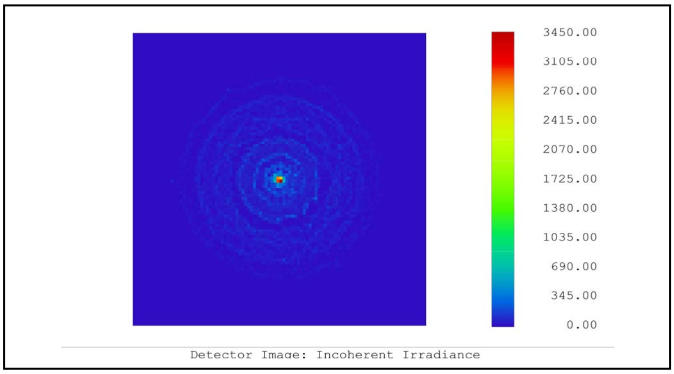

Figure 3. Irradiance distribution with concentrator A at 0º

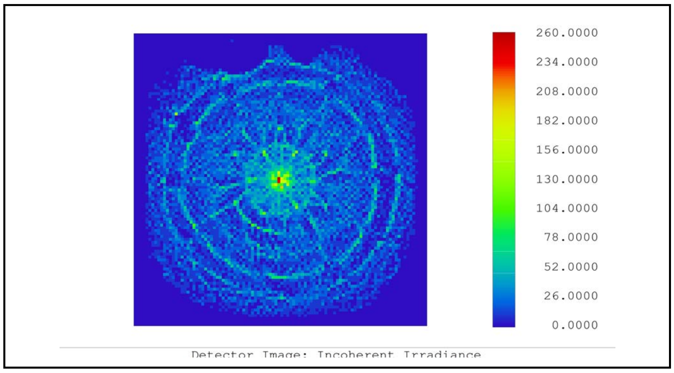

Figure 4. Irradiance distribution with concentrator B at 0º

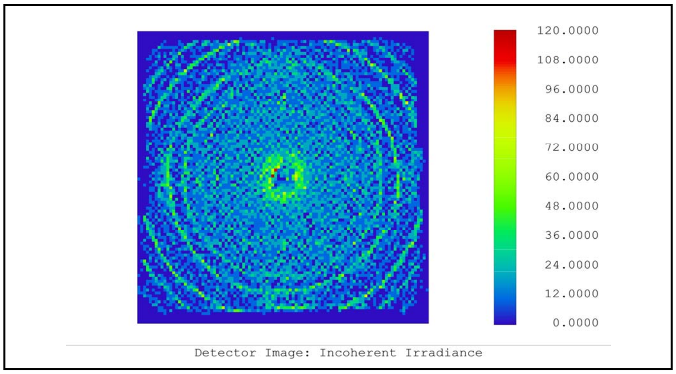

Figure 5. Irradiance distribution with concentrator C at 0º

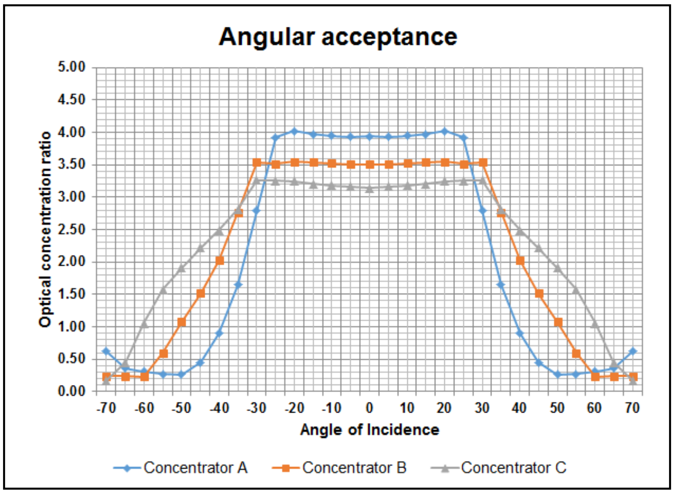

Figure 6. Angular acceptance of Concentrators A, B, C

C. Comparison of concentrator B with the 3D CCPC

Concentrator B and the 3D CCPC have a similar height, and optical concentration ratio. However, the 3D CCPC has an ideal field of view, meaning that it does not accept light outside the acceptance angle. Concentrator B on the other hand redirects light rays to the solar cell beyond an angle of incidence of 70º. For portable solar systems it is very important that the concentrator does not stop generating electricity outside the acceptance angle since this would be a significant disadvantage compared to a flat solar cell.

D. Comparison of concentrator C with the SEH concentrator

Due to the similar side profile, concentrator C and the SEH concentrator have a similar field of view. However, the optical concentration ratio of the SEH remains around 1.6x for acceptance angles ± 60º (Table 1) while the optical concentration ratio of concentration C remains around 3.2x within ± 35º and above 2 within ± 50º (Figure 6). For the concentrator design to be a financially viable solution, the optical concentration ratio and the acceptance angle need to be maximised.

DISCUSSION AND FUTURE WORK

The presented design concept is a promising alternative to already existing designs of static nonimaging concentrators due to its potential to generate designs which combine the following advantages:

(i) the same light acceptance angle on all vertical planes
(ii) an optical concentration ratio above 3
(iii) a reduced height

The input parameters of the side profile strongly influence the optical properties of the design due to the changing slope of the side profile and its condition for TIR for particular rays. The three proposed designs shall be further optimised to improve the optical concentration ratio and the acceptance angle by conducting a numerical optimisation of the input parameters of the hyperbolic profile. Once an optimum design has been achieved, a prototype shall be manufactured and tested experimentally.

CONCLUSION

The implementation of concentrators in portable solar systems allows a reduction of photovoltaic material used, enables faster battery charge and has the potential to reduce the cost of the overall system. Yet, no suitable concentrator deigns for portable solar systems have been proposed. This paper showed a novel design method which combines a free form entrance aperture and a hyperbolic side profile. It has been shown that this design method provides concentrators which combine the advantages of small height, a large field of view with an increased optical concentration ratio. The performance of the proposed concentrators shall be further improved using numerical optimisation in order to produce a new alternative for the improvement of the solar chargers and consequently to help increase the electrification in rural areas in developing countries.

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