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Surpassing the 2D limit: a 600x high-concentration PV collector based on a parabolic trough with tracking secondary optics

Thomas Cooper[a], Gianluca Ambrosetti[b], Andrea Pedretti[b], Aldo Steinfeld[a,c,]*

[a]Department of Mechanical and Process Engeineering, ETH Zurich, 8092 Zurich, Switzerland
[b]Airlight Energy Holding SA, 6710 Biasca, Switzerland
[c]Solar Technology Laboratory, Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland

Abstract

We report on the design and performance of a novel 600x high-concentration photovoltaic (HCPV) collector. The design is unique in that it diverges from the predominant HCPV approach of a 3D concentrator mounted on a 2-axis tracker. We consider minimization of the cost per m^2 of collecting aperture to be the most important aspect in achieving cost-competitiveness. Accordingly, we borrow from the knowledge of the more mature CSP industry which has shown the parabolic trough to be an effective and economical method to concentrate sunlight. To further leverage the advantages of scalability of trough geometries, the primary concentrator utilizes a construction based on inflated metalized polymer membranes as reflectors supported on modular concrete structures. With this design, aperture widths surpassing 10 m and trough lengths exceeding 200 m are possible. At a trough length of 200 m, the rated power of one collector is 500 kWp. To augment the concentration into the realm of HCPV, where use of high-efficiency triple-junction concentrator cells becomes economically viable, a novel secondary concentrating stage is employed, consisting of an array of tracking non-imaging concentrators arranged along the focal line of the primary. This two-stage line-to-point focus system allows for concentrations of over 600x, considerably surpassing the 2D limit of ~200x inherent to trough-like geometries, while maintaining the advantages of a one-axis tracking trough primary concentrator. A full-scale prototype of the system has been constructed in Biasca, Switzerland. Year-round solar-to-electrical efficiency is expected to exceed 25%.

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* Corresponding author. Tel.: +41-44-6327929; fax: +41-44-6321065.
E-mail address: aldo.steinfeld@ethz.ch.

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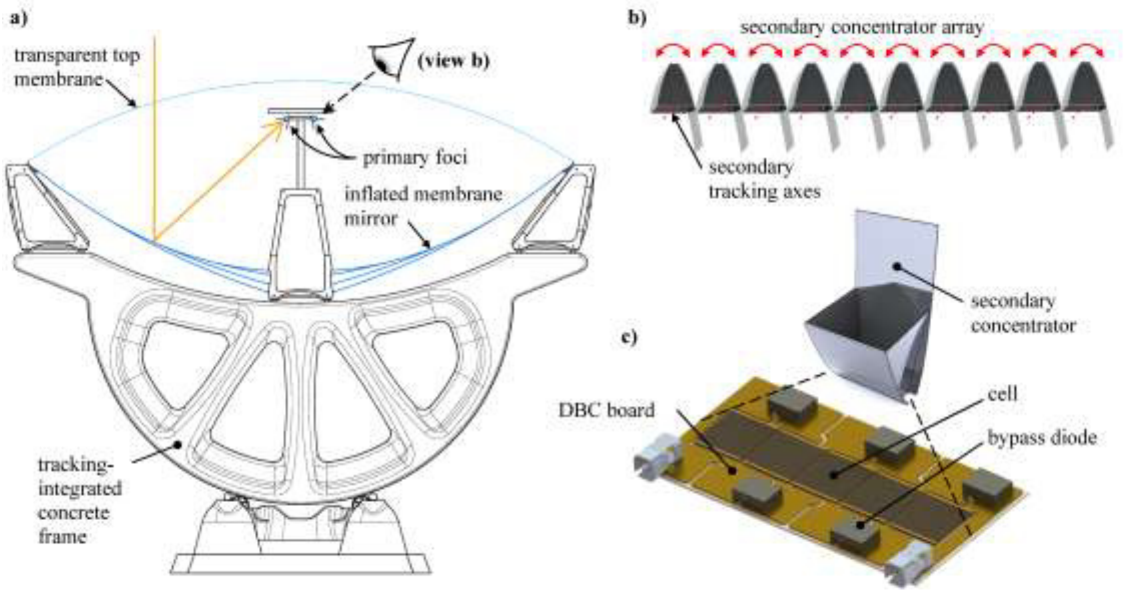

Fig. 1. Schematic of the line-to-point focus HCPV collector: (a) inflated parabolic trough primary concentrator; (b) array of tracking non-imaging secondary concentrators arranged along the focal line of the primary; (c) close-up of secondary concentrator and receiver consisting of 5 1-cm^2 triple-junction concentrator cells placed at the exit of each secondary [3].

1. Introduction

Concentrating photovoltaic (CPV) collectors share the common goal of aiming to reduce the cost per W_p of generated electricity, by replacing expensive cell area with less-expensive concentrator area. To this end, reduction of the cost per m^2 of the primary concentrator is of paramount importance. Recently, focus has been placed on high-concentration photovoltaics (HCPV), with geometrical concentration ratios, C_g, exceeding 500x, enabling the economic use of expensive but highly-efficient triple-junction solar cells, which have demonstrated efficiencies approaching 44% [1]. For HCPV, reduction of primary concentrator cost is of particular relevance, since the primary concentrator represents the largest part of the overall system cost. The optical design of conventional HCPV collectors follow two main concepts: 1) a parquet of small-aperture lens or mirror concentrators each coupled to a single cell; or 2) a large-aperture point focus concentrator coupled to a dense-array receiver. Both require 3D concentrator structures and two-axis tracking.

Here we propose an alternative HCPV collector which does not fit into any of these two conventional concepts. Instead, we borrow from the more mature concentrating solar thermal power (CSP) industry which has shown one-axis tracking troughs to be an economical and highly-scalable method to concentrate sunlight. Due to their 2D extruded geometry, construction of troughs is simpler, and the primary goal of having a low-cost primary concentrator can be readily achieved on large scale. However, having a 2D geometry implies that the primary concentration is limited by the 2D limit of $1/\sin\theta_{sun} \approx$ 215x. To overcome this limit, and bring the system into the realm of HCPV, a novel secondary concentrator stage, coupled to the primary concentrator, has been developed. The so-called line-to-point focus system is comprised of a line-focus trough primary concentrator, and an array of non-imaging secondary concentrators arranged along the focal line of the primary. In order for the secondary concentrators to be able to achieve a high-concentration for any sun position, they are allowed to individually track on secondary tracking axes which are perpendicular to the primary concentrator tracking axis. This line-to-point focus configuration allows for C_g > 600x to be easily achieved while maintaining the benefits of a one-axis tracking primary concentrator. Since the length-scale of the secondary stage is on the order of $1/C_g$ of the length-scale of the primary, more exotic designs and materials may be utilized for the secondary stage without greatly affecting the overall cost of the system. A schematic of the system is given in Fig. 1.

2. Design

2.1. Primary concentrator

As shown in Fig. 1 (a), a two-wing configuration is utilized for the primary concentrator geometry. Each wing of the concentrator assumes the geometry of an off-axis parabolic trough and focuses sunlight to one of two tilted focal planes near the plane of symmetry of the concentrator. The two-wing design allows for improved system compactness for a given rim angle Φ of the primary concentrator. Unlike conventional parabolic trough concentrators, which use back-silvered glass or aluminum sheet mirrors, this system utilizes a metalized polymer foil as the reflector [2]. A chamber is formed by the metalized foil on the bottom, and a highly transparent fluoropolymer foil on the top. The chamber is inflated with an over pressure of a few millibar causing the bottom foil to stretch into a curved shape. The precise shape of the mirror membrane is controlled by three support membranes underneath the mirror foil. By adjusting the differential pressure across the support membranes, a profile very closely approximating a parabola is obtained on the upper reflective membrane [2]. The inflated mirror is mounted on a rigid concrete frame which forms the primary tracking function.

The clear aperture width of each wing of the primary concentrator is ~5 m, yielding an overall collecting aperture width of ~10 m, which is significantly larger than that of conventional parabolic trough designs. The secondary concentrating stage is placed at the focal plane of each wing. The width of the secondary inlet is 0.07 m, yielding a primary concentration of:

$$C_{\mathrm{g},1} = \frac{w_{\mathrm{primary}}}{w_{\mathrm{secondary}}} \approx 71\mathrm{x} \tag{1}$$

2.2. Secondary concentrator

The secondary stage consists of an array of non-imaging concentrators arranged along the focal line of the primary as shown in Fig. 1 (b). Each secondary concentrator is allowed to track on an axis perpendicular to the primary axis in order to face the direction of the reflected solar beam at any solar position. The secondary concentrator is an asymmetrically truncated $\theta_{\mathrm{in}}/\theta_{\mathrm{out}}$ transformer crossed with a truncated hyperbolic (trumpet) concentrator. The precise design parameters of the secondary concentrators have been determined by optimizing for maximum year-round performance as predicted by Monte Carlo ray-tracing. The geometric concentration of the second stage is:

$$C_{g,2} = \frac{A_{\mathrm{secondary,in}}}{A_{\mathrm{secondary,out}}} \approx 8.5\mathrm{x} \tag{2}$$

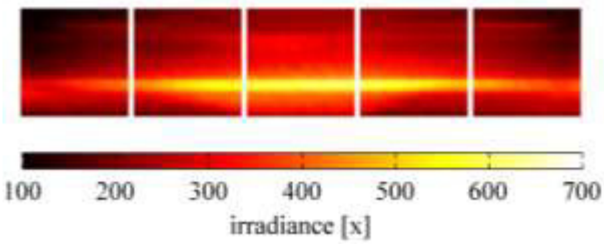

Fig. 2. Irradiance distribution on the 5-cell receiver for a solar incidence angle of 50° as simulated by Monte Carlo ray-tracing [3].

The total concentration of the system is:

$$C_{\text{g,total}} = C_{\text{g,1}} \cdot C_{\text{g,2}} \approx 605\text{x} \tag{3}$$

2.3. Receiver

The receiver comprises a linear array of 5 1-cm^2 3J concentrator cells at the exit of each secondary concentrator as shown in Fig. 1 (c). The linear (semi-dense) array configuration allows for a relatively large-area receiver while mitigating the main drawbacks of a 2D (dense) array [3]. In the linear array configuration, cells may be placed very near to each other with the bus-bars running in parallel along the length of the array, thus minimizing gap losses and allowing flexible placement of the cell interconnects and external electronics (e.g. bypass diodes).

3. Simulation

3.1. Optical

Simulation of the optical performance of the system was performed by Monte Carlo ray-tracing using the in-house VeGaS code [4]. Figure 3 shows the resulting simulated flux distribution on the 5 by 1 cm cell receiver for a solar incidence angle of 50° on the primary aperture. The simulation predicts an overall optical efficiency of 78% for the collector [3].

3.2. Electrical

The optical simulation provides the flux distribution on the receiver which serves as the input to an electrical simulation used to predict the minimodule output for different operating conditions. An equivalent circuit model of the minimodule was developed in Simulink® and validated vis-à-vis indoor measurements using concentrated radiation from a flash solar simulator [3].

It was originally envisioned to connect the 5 cells in a series string, thus achieving a higher voltage and lower current from each array, which is beneficial for reducing Ohmic losses. However, it was found that the serial arrangement could lead to significant losses resulting from the mismatch of irradiance from one cell to the next in the linear array as evidenced by Fig. 2. By changing to a parallel arrangement, these mismatch losses could be almost entirely eliminated [3]. The comparison between the performance of a serial and parallel array is summarized in Fig. 3. Based on the electrical and optical simulations, a year-round solar-to-electricity efficiency surpassing 25% is predicted.

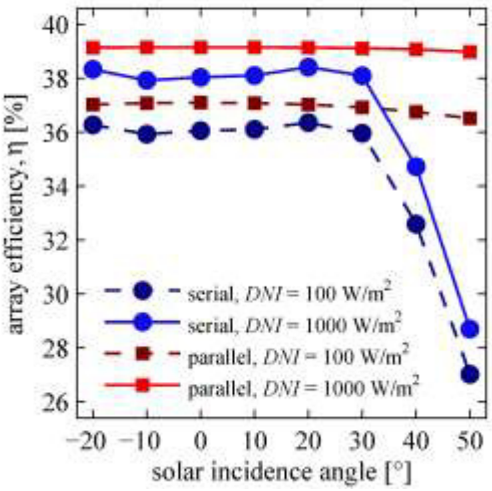

Fig. 3. Efficiency of the 5-cell array as a function of the solar incidence angle for serial and parallel cell connections. Results are shown for a low and high direct normal irradiance (*DNI*). The parallel arrangement mitigates the effects of irradiance mismatch resulting from cell-to-cell non-uniformity [3].

4. Experimental

Based on the positive performance predictions of the simulations, a full-scale prototype of the inflated trough primary concentrator has been constructed in Biasca, Switzerland. A photograph of the 42 m long prototype is shown in Fig. 4. At the center of the trough is placed an array of 5 secondary concentrators and cell receivers. Results of the experiments indicate performances approaching those predicted by simulation, where any limitations are the result of the limitations of the prototype rather than of system design.

Fig. 4. Photographs of a full-scale 42 m long prototype of the inflated trough concentrator in Biasca, Switzerland. An array of 5 secondary concentrators was placed in the center of the trough [2].

5. Conclusions

An HCPV collector with a geometric concentration over 600x has been developed based on an inflated trough primary concentrator with tracking secondary optics. The novel line-to-point focus system allows the 2D limit of concentration to be surpassed, while still maintaining the advantages of having a one-axis tracking trough primary. The performance of the system was determined by optical and electrical simulations based on Monte Carlo ray-tracing and equivalent circuit modeling respectively. The simulations predict a year-round solar-to-electricity efficiency surpassing 25%. A full-scale prototype of the system has been constructed in Biasca, Switzerland, serving as a proof of concept of the design.

Acknowledgements

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