SAND2015-0054J

Reduced Silicon Usage in Flat Photo-Voltaic Panels

WC Sweatt, GN Nielson, & M. Okandan

Sandia National Laboratories, Albuquerque, NM

Abstract:

Silicon usage in fixed, flat-panel photovoltaic systems can be reduced by 60 to 75% with no efficiency loss through use of arrays of mini-concentrators. These concentrators are simple trough-like reflectors that are formed in flat sheets of ~1-mm thick optical plastic. Concentration ratios of 2.55X can be achieved on rooftops and 4.0X on walls while collecting all of the direct sun and scattered skylight. The concentrators are fabricated in optical plastic— preferably polycarbonate for its high refractive index. The panels are typically 1mm thick so the weight of a panel is ~1kg/m^2. In addition to the rooftop, wall and window blind designs, a design is proposed that can be tilted toward the sun position at the equinox. These systems are all designed so they can be mass-produced.

Introduction:

Silicon comprises more than half of the cost of typical flat solar panels[1]. Using mini-concentrators, the amount of silicon needed can be reduced by 2.5X to 4X without reducing the collection efficiency of the panels; including the direct sunlight and the scattered light. Designs are presented for panels facing upward, panels on vertical walls, and panels facing the equinox sun position.

All three designs have close-packed, trough-like reflective concentrators that are built into ~1-mm thick sheets of polycarbonate or other optical plastic. Figure 1 shows the cross-section of a concentrator that can be used on a rooftop. Lines of PV cells are mounted on the front surface with a trough concentrator adjacent to each line. Direct illumination is absorbed on the front surfaces of each line of PV cells, while the adjacent trough collects light and illuminates the back surfaces of the cells. The trough designs for the wall and equinox-mounted panels are similar, and all three designs are theoretically 100% efficient. Note that the relative efficiency will also increase by a small amount due to the concentration.

The concentrating PV systems described here can be a direct replacement for standard flat PV panels. They can be used on the tops and sides of buildings and trucks, and on aircraft wings and bodies. The reduced amount of silicon needed should more than compensate the cost of the optical plastic. We anticipate that these solar panels can be inexpensively mass-produced. The weight of the collectors will be ≤1 kg/m^2 and the outside surfaces are flat for easy cleaning.

Presented here are three similar concentrator designs for rooftops, walls, and tilted, south-facing solar panels:

1.) The roof-top concentrator described above (Fig. 1) collects all of the incident sunlight from a solid angle of Ω_{roof}=2π sr. This includes the direct sun arriving from any direction and all of the scattered light. The concentration is C_{roof}=2.55X, where the front illumination on the PV cells contributes "1X" and the trough contributes "1.55X", summing to C_{roof}=2.55X.

2.) Figure 2 shows the cross-section of a trough-shaped solar concentrator for use in window blinds or on vertical walls. It collects the sunlight incident from any direction above the horizon with a solid angle of $\Omega_{wall}=\pi$ sr. As with the Fig. 1 concept, it collects light on both the front and back of the PV cell yielding a combined concentration factor of C_{wall}=4.0X.

3.) The third design (Fig. 3) is for solar panels mounted normal to the average noonday sun angle. It collects all light arriving from above the winter solstice sun angle ($\Omega_{equinox}\sim 1.6\pi$ sr.) and has a concentration ratio of $C_{equinox}$=3.1X.

Rooftop Concentrators:

Fig. 1 shows the cross-section of the rooftop trough concentrator. This concentrator collects light from the whole sky (2π sr.) and concentrates it by a factor of C_{roof}=2.55X, when the concentrator is formed in polycarbonate with a refractive index of n_d=1.59. The trough concentrator is composed of two mirror sections; a tilted flat reflector to the right and a cylindrical mirror section behind the PV cell. The design is driven by the angle of refraction ($\theta=39^0$) of grazing incidence light arriving from the left[2]. If the flat mirror is tilted by $39^0+1^0=40^0$, then this grazing-incidence light will be reflected back toward the surface of the plastic at 41^0 which is greater than the 39^0 critical angle. Hence the light will be totally internally reflected and thus will remain captured in the plastic until it reaches the cylindrical section. The cylindrical section has a radius equal to the width of the PV cell. Therefore any rays passing below the center of curvature will be imaged onto the PV cell by the cylinder. (A few rays will go directly to the PV.) The cylindrical section has an angular extent of $90^0+40^0=130^0$, so that its slope and that of the flat mirror will be matched where they meet.

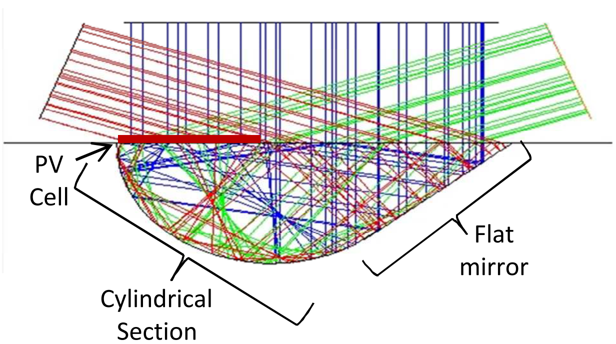

Fig. 1: Roof-top solar concentrator with C=2.55 modelled with ZEMAX[3] optical analysis code

Aside: Three-dimensional concentrators were studied that had the PV cell on the rear. One design was square (Fig. 4) and another was round. These had concentrations of C_{square}=2.2X and C_{round}=2.0X, both of which are less than the C_{roof}=2.55X of the Fig. 1 design. The concentration is lower, largely because these designs only illuminate one side of the PV cell. Also note that the steep sidewalls in these designs would make them hard to build.

Wall-mounted concentrators:

Vertically mounted photovoltaic arrays are particularly useful in the northern latitudes. Consider New York City and Chicago located ~40^0 north of the equator: hence the sun is closer to the horizon than to the zenith during the coldest months of the year. The wall-mounted concentrator design shown if Fig. 2 will collect all light arriving from above the horizon ($\Omega_{wall}=\pi$ sr.). Thus it will collect all of the direct and scattered sunlight available. The concentration for normal incidence is C_{wall}=4.0X when the unit is made of polycarbonate.   If the concentrator were instead made of PMMA plastic the index is lower and the concentration is reduced to C_{PMMA}~3.8X.

The basic two-dimensional shape shown in Fig. 2 appears to be the most efficient design available for a wall mounted concentrator. It is composed of three sections:

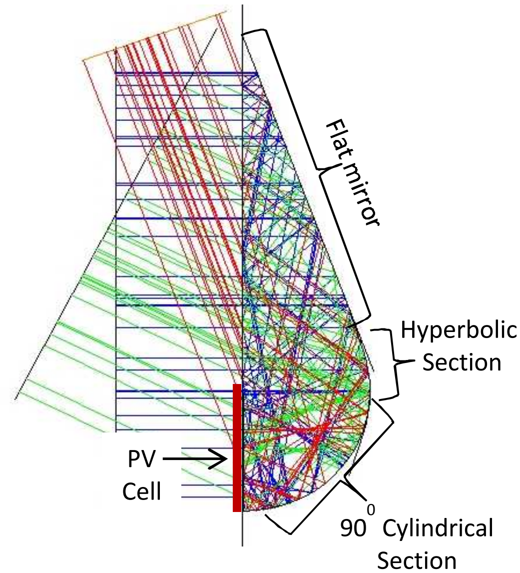

Fig. 2: Wall or window-blind solar concentrator with C=4.0

- The top section of the concentrator contains a tilted flat mirror surface that reflects all light arriving from above the horizon. The mirrored rear surface is tilted by 20^0 so it will capture light incident horizontally. Horizontally incident light will bounce off of the diagonal mirror at 40^0 and will suffer total internal reflection at the plastic/air interface and remain captured in the plastic wedge.   Rays arriving from above the horizon will be reflected down at steeper angles (>40^0) and will also be trapped in the plastic. As with the roof-mounted concentrators, the front-mounted PV cell absorbs light on both surfaces.
- A 90^0 section of a cylindrical mirror located behind the PV cell images all light captured in the plastic onto the PV cell. The flat and cylindrical sections can be connected to one-another directly, but if there is a hyperbolic section between them, the concentration will be slightly larger. As described in the description of the roof design, the center of rotation of the cylindrical section is located at the top edge of the PV cell and the radius is equal to the width of the cell. Any light rays trapped in the 20^0 plastic wedge will reflect off the cylindrical mirror onto the PV cell (or go there directly).
- A hyperbolic section is used to connect the 90^0 cylindrical mirror section to the flat mirror. It is an extension of the cylindrical section, matching slope and curvature at the intersection. This captures any near-normal rays entering the plastic just above the PV cell and images them onto the PV cell. The conic constant of the hyperbola is large (cc ≈ -7), so that it approaches a plane not far from the junction with the cylinder. The hyperbola connects with the 20^0 plane as shown in Fig. 2.

These concentrators can be used on south, east, or west-facing walls or windows.   They could also be used on a flat roof if they were mounted such that the cylindrical sections are on the north end.

This wall concentrator concept could also be used in energy-harvesting window blinds. If one needs to see through the blind, the mirror surface could be a partially transmitting (e.g. T~15%). The partial-reflector could be a metal surface (i.e. Al) or a dielectric multilayer designed to reflect the IR and as much of the visible as prescribed by the customer.

Window blinds, assuming people will be viewing the scenery through them, must not distort the image. Therefore, the front and rear surfaces of the blinds must be parallel to one-another with the tilted, partially-reflecting surface in between (Fig. 2). If the blinds are 1mm thick, then the lines of PV cells will also be 1mm wide (vertically) so they will not clutter the scene for eyes focused at long range.

Tilted, south-facing solar panels:

Solar panels are often held in fixed south-facing mounts that are tilted so the panels' normal vectors point toward the noonday sun at the equinox. Fig. 3 shows a collector for this application with a concentration ratio of $C_{equinox}$=3.1X. It needs to collect the direct sunlight all year round over the range $\Delta\Theta=\pm 26.5^0$ above and below the equinox position. It also captures the scattered sunlight over an angular range from -27^0 to $+90^0$, and being a trough design, it collects light over $\Delta\Theta=\pm 90^0$ in the horizontal direction. In order to capture the light arriving from 26.5^0 below the normal vector, the flat rear reflective face of the plastic must be tilted by ~28^0. The cylinder's radius is again equal to the length of the PV cell. The hyperbolic section connecting the cylinder and the flat mirror preferably has a smaller radius equal to ~0.8 times the radius of the cylinder and a conic constant cc ≈ -3. The smaller radius keeps the mirror's transition zone (from curved to flat) in the shadow of the PV cell as seen from the winter solstice sun position.

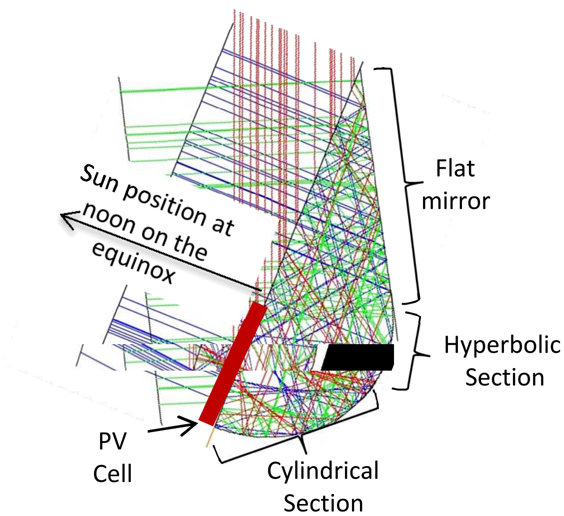

Fig. 3: Concentrator for tilted solar collectors

Proposed fabrication method;

The designs shown in Figs 1, 2, & 3 can be either extruded or molded in a roll-to-roll architecture because the concentrator structures are thin, the trough cross-sections are all two dimensional, and there are no sharp slope changes. The partially reflecting surfaces can be evaporatively (or sputter) coated with a reflective metal or dielectric coating. The PV cells and wiring can be manufactured elsewhere and then attached to the front of the concentrator. A thin (t~50μm) transparent overcoat will protect the electronics from moisture and cleaning. An overcoat this thin will not degrade the performance of the concentrators.

PV cells (Si and III-V materials) have coefficients of thermal expansion (CTE) that are much smaller than that of plastic. Therefore the long, thin PV cells must be composed of a line of small cells. The interconnections between the cells will have to accommodate the plastic/silicon CTE mismatch. SNL has been fabricating sheets of prewired, ~1mm wide crystalline silicon solar cells on flexible substrates[4]. The concentrators described herein could use linear arrays of these (or similar) cells.

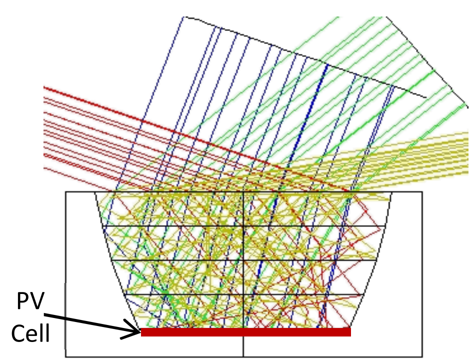

Fig. 4: Alternate concentrator design for rooftop solar collector with lower concentration.

As mentioned above, if one is designing a window blind that people are going to be looking through, the total structure needs to act like a window pane with parallel front and rear surfaces. Therefore, after the concentrator structure is formed, the back must be covered with optical plastic and the rear face needs to be made parallel to the front face. For any other application, the back can be covered with a thermally compatible structural material that will give the unit some rigidity.

Use on trucks and aircraft:

Trucks and aircraft can travel in any direction and a solar collection system for them should operate as efficiently as possible regardless of the vehicle's orientation. This requirement can be met with the roof and wall concentrators described above. An array of the roof concentrators on top of the vehicle will generate electricity from scattered light and from direct sun light any time the sun is up. If there are also arrays of wall concentrators on the sides of the vehicle, they can collect and concentrate light when the sun is low in the sky, and any time the sun is not directly in front of or behind the vehicle. It should also be noted that the side panels will collect half as much scattered light per square meter as will the roof panels.

Panels of these concentrators could be glued to any solid surface making then reasonably robust. The weight of these concentrators is approximately one kilogram per square meter, and less if the panels are thinner than 1mm.

In the direct sun each of these array types should produce ~140w/m^2 using crystalline silicon cells. On a moving vehicle, we would estimate an average power output of ~50w/m^2, assuming there are panels on the top and sides of the vehicle.

Where there is only a limited amount of space that can be covered with PV cells, it would be possible to use higher efficiency solar cells like GaAs, assuming that more power is required from the allotted space than can be generated with crystalline silicon cells.

Summary:

Silicon usage in fixed, flat-panel photovoltaic systems can be reduced by 60 to 75% with no efficiency loss through use of the simple, trough-like solar concentrators described here. Both surfaces of lines of PV cells are illuminated, with the trough-like reflectors illuminating the rear surfaces. The troughs are formed in sheets of optical plastic (i.e. polycarbonate) that are 1mm thick or less so the panels weigh ≤1kg/m^2. Concentration ratios range from 2.55X for roof-mounted panels to 4.0X for wall mounted panels are possible. It also should be noted that these designs are amenable to mass production.

Acknowledgement:

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References:

[1] Fraunhofer Inst. for Solar Energy Sys. *Photovoltaics Report*, Freiburg, 10/24/2014

[2] Smith, W.J, *Modern Optical Engineering 2nd Ed.*, McGraw-Hill, 1990

[3] Zemax Optical Design Code, Radiant Zemax Corporate Offices & Research Center, 22908 NE Alder Crest Drive, Suite 100, Redmond, WA

[4] JL Cruz-Campa, GN Nielson, PJ Resnick, CA Sanchez, M Okandan, T Friedmann, VP Gupta; *Ultrathin flexible crystalline silicon: Microsystems enabled photovoltaics*, PVSC, 2011 37th IEEE