Solar Concentrator for Photo-Voltaic System*

LI Dong-guang
(School of Computer and Information Science, Edith Cowan University, Australia)

Abstract: In standard P-V systems, the high cost and low quantum efficiency of silicon cells has held back widespread adoption of this technology for decades. To generate electrical power from solar energy in a cost effective way, most methods require the concentration of the sunlight in order to increase the efficiency of energy conversion. Most systems use parabolic mirrors to focus sunlight to either a line (trough systems) or a small volume (dishes). One of the reasons solar power still remains little utilised, is the high cost of the collection systems. Light focussing devices using reflection usually take the form of a curved mirror. In contrast, this paper describes the new design of a device consisting of an array of small angled reflecting mirror facets located in a planar form. The three dimensional angle of each facet in the array is a function of its position in the array, and is calculated to be such that for a parallel beam striking the array, each facet will reflect the light in such a way as to form a focal point region.

Key words: solar concentrator; photo-voltaic system; cell calibration
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1 Introduction

The costs of electricity produced by the action of sunlight on solar cells are still much higher than that produced by the burning of fossil fuels[1,2]. The most expensive component in a solar cell (also known as a 'P-V cell') is the silicon material[3]. Although several decades of development have given rise to major increases in efficiency and lower costs, the large areas of silicon required, together with low efficiencies (typically 10 to 15%) have meant that the use of solar cells are only economically viable for certain market segments that do not have access to mains electricity.

Recently, there has been the development of a special type of silicon cell capable of high efficiency operation (up to 25%) at light intensities 10 to 300 times normal sunlight[4]. The use of these cells together with cheaper materials for concentrating sunlight (such as glass/plastic mirrors or lenses) has allowed the development of solar concentrators potentially capable of producing electricity at a lower cost than current flat panels.

As far as we are aware there are only 2 companies currently offering concentrator arrays on the commercial market, Midway and Entech, both in the USA[5,6].

A point of note is that a few percentage points improvement in efficiency of the cells leads to a significantly lower cost per watt. This is because the cost of the supporting infrastructure that relates to each cell also needs to be taken into account. Another way at looking at it is: increasing cell efficiency increases the power output without increasing the costs of anything else.

There is a sizeable need for cheap solar generated electrical energy. The current markets include remote area power, water pumping, and zero emission power generation for grid and industrial uses. The greenhouse protocols recently adopted will also encourage a greater need for such devices.

Additionally, since the solar concentrator can easily be adapted for thermal generation, there is a significant market for heating water or air for industrial applications, such as water distillation, low pressure steam generation, preheating of water for boilers, hot air for fruit drying, etc. By careful choice of technology, a temperature of a few hundred degrees can easily be achieved by such collectors.

The market for flat plate P-V arrays is growing fast. As the price of electricity generated from concentrators becomes lower than the flat plates, then concentrators will certainly take a sizeable fraction of this market—in particular for applications that requiring more than 300—400 watts.

2 Methodology and experiments

A photovoltaic tracking solar concentrator was designed and built using an array of mirrors. The mirror system generates a concentration factor of at least 23 times

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Corresponding author: LI Dong-guang, d.li@ecu.edu.au

onto a line of 26 silicon cells mounted on a heatsink. The entire panel is moved during the day using a 12 Volt electric motor and a double worm drive. Seasonal adjustment is made manually.

A solar tracker was also constructed to control the movement of the array, using 2 photocells. These sensors ensure that the focus remains on the receiver as the sun moves through the sky.

The solar receiver was water—cooled using a circulating pump and a water reservoir.

As in many technologies, the design was defined by the performance of critical components-the solar cells and a mirror design. In this case the solar cells were obtained from a development program being undertaken at the ANU in Canberra.

Several aspects of a mirror design were explored, described here in some detail, before the current design was chosen. These aspects included potential ease of manufacture, expected production cost, efficiency of operation, etc.

The panel was mounted on a pole and connected to a motorised tracking system. A water-cooling system was also connected to the receiver and measurements taken to ascertain the heat absorbed by the water. The electrical power was also measured using a load resistor.

The receiver consists of 26 ANU solar cells mounted on an anodised aluminium rectangular hollow section, 1.6 metres long. The anodising is necessary to offer electrical isolation between the cells, since the silver-plated back face of the cells is an electrical contact. The cells were wired in series with silver tape to give an open circuit voltage of 17 Volts in direct sun. To limit resistance losses on the cells, an additional conductor (a thick layer of solder) was added to the silver top contacts running the length of the cells. A single glass cover plate 3 mm thick was added on top of the cells and sealed with a special silicone sealant, for environmental protection.

When illuminated by the mirrors in direct sun, the scattered light from the receiver is too bright to look at comfortably — visually indicating that the optical efficiency may be improved by using an anti-reflective coating on the cover glass.

A thin film design for a coating that will reflect the I. R. but improve transmission for the visible is currently under consideration. Potentially this could not only improve the transmission of the important wavelengths, but more importantly, reduce the heating effect of the sunlight. In normal flat panel arrays, the cost of coating large areas of glass far outweighs the efficiency benefits. In the concentrator however, the active area is so much smaller, and a cost -benefit analysis may well indicate it is economical.

Since the cells are connected in series, the cell string will need to characterised as a unit. If one cell in the array has a poorer efficiency than the others, then the string output will be limited to the current passed by it. Here lies an important advantage of using a two-dimensional concentrator system as opposed to a linear array; each cell can be physically separated from its neighbours. Therefore not only can each cell be individually characterised in the field, but if they were constructed in a modular form, it would also be possible to individually replace defective cells.

A calibrated test cell was usee to measure the insolation (intensity of the sunlight). At this time of year in ! our current location, a figure of 0.7 kW/m^2 was the maximum intensity recorded, at an ambient temperature of 26 ℃. Using a 1. . 96 ohm load resistance, a current of 6.5 amps was recorded at 12.7 volts. This corresponds to a power of 82 Watts. At the normal solar intensity of 1 kW/m^2 (1 sun) the array would produce 118 Watts of electrical power.

The load resistor was not selected for the maximum power point of the cells, and an increase in power output is likely if an electronic power maximiser was used. The power maximiser varies tie apparent load impedance (by using a capacitor and pulse control circuit) in osder to maximise the power extracted from the cells. This maximum power point will vary with insolation and temperature. Therefore the measurement of power quoted here is somewhat pessimistic.

The cells were measured at the ANU at 30 suns using a flash lamp, and were characterised for a cell temperature of 25 ℃ operation. In practise of course under continuous illumination, the temperature will be significantly higher, and operate at lower efficiency.

Cell efficiency improves with concentration, concentrator cells have efficiencies in the region of 22%—25%, (with some experimental cells achieving 32% efficiency), whilst the best commercially produced flat panel cells are around 15% efficient. A higher concentration factor therefore gives rise to cost improvements both in terms of the potentially lower silicon costs in addition to the higher efficiencies. The trade-off however is the high initial cost of these specialised cells and the importance of efficient and reliable heatsinking. See Figure 1 for cell performance data and Figure 2 for the test cell calibration plots.

2.1 Concentrator Optics

In this research, we use a solar constant of 1 kW/m^2. This intensity (which approximates the midday suns intensity at midsummer) is referred to as 1 sun. Flat panel P—V arrays are generally rated at the electrical power generated for a solar flux of 1 kW/m^2. The uniu of sun here also refers to the multiplication factor (relative measurement) of the concentrator optics.

There are two basic types of concentrators; using either lenses or mirrors.

P-V concentrator systems using Fresnel lenses have recently become commercially Ravailable and are suited for concentration ratios×30 to×300.

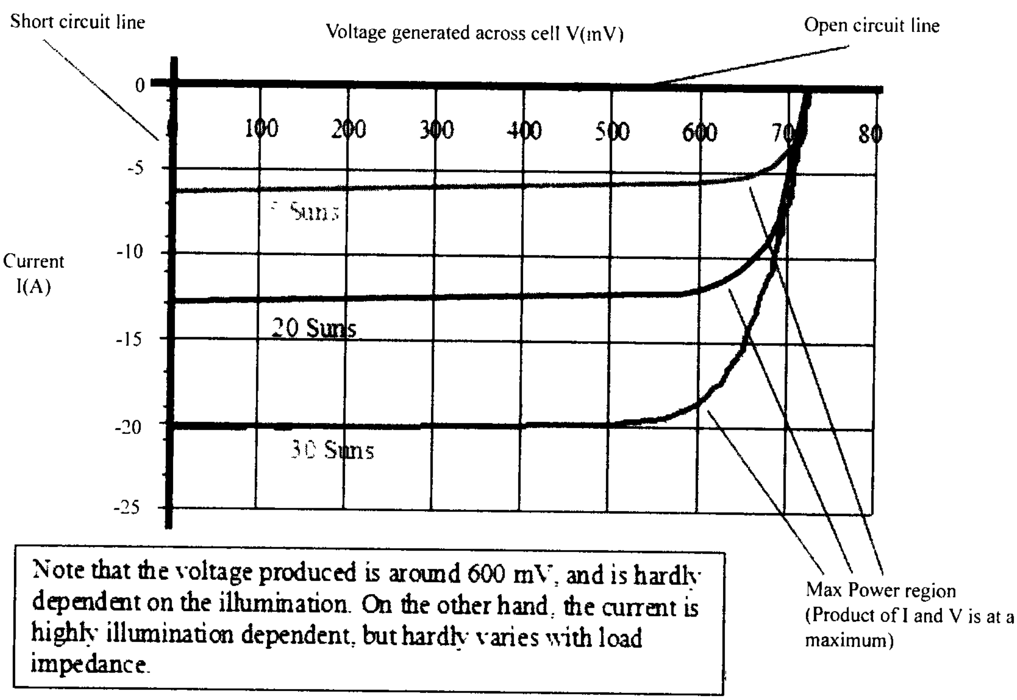

Fig 1　Typical Semiconductor parameters of the ANU Solar cell at 25 ℃

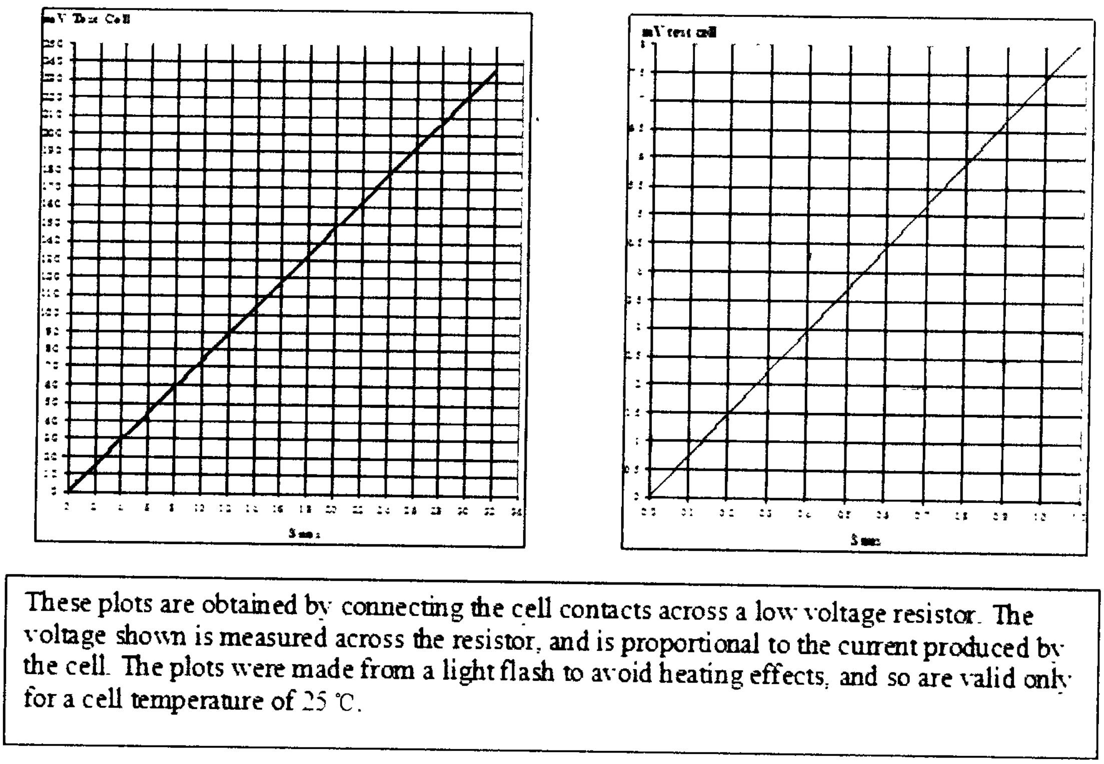

Fig 2　Test cell calibration plots-mV per Sun

We were able to source some special cells made at the ANU in Canberra that were characterised at 30 suns. The cells are being made currently for a 20 Kilowatt demonstration plant being built in Western Australia. This plant uses an array of parabolic mirrored troughs.

Large single sheet curved glass mirrors (with a diameter of two meters or more) are heavy and difficult to fabricate, transport and erect, and vulnerable to impact damage.

The original concept was to make a molded piece of glass or plastic to provide a reflecting surface as in a Fresnel mirror. A Fresnel mirror, shown in Figure 3, consists of a mirrored surface, which has a series of facets. Each facet is angled differently to its neighbours. Together, these facets can reflect light in such a direction as to imitate a curved surface e. g. a parabolic focusing mirror. The important parameters are the size and angle of each facet. See sketch above. By careful design of the facets, one could obtain a parabolic mirror using a flat sheet of material. After the mirror was designed, and costings obtained, it was found to be too expense in small quantity to be manufactured by injection molding.

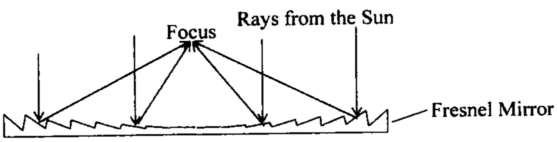

Fig 3 Diagram showing focusing action of a Fresnel Mirror

An alternative concentrator design was explored which allowed the focusing surfaces to also form part of the solar tracker.

The next concentrator option was to use a series of laser cut profiles to hold an array of mirrors at the appropriate angles. A steel bed 2 m× 1.6 m was welded together. A few of the components from the commercial tracker were incorporated into the design to form a tracking platform for the laser cut profiles. 40 mirrors were affixed onto the profiles and focused onto the receiver with little adjustment.

Measurements indicated an optical concentration of 23 was obtained. This was less than the design figure of 30 due to the difficulties maintaining the welded bed in one plane. This gave rise to distortion of the profiles and slight defocusing of the mirrors.

It must be noted that the optical design was not optimized to obtain the highest possible concentration. A design such as that would be best made with a smooth curve parabola designed for a point focus. Such a parabola can have some difficulty in its operation. The intensity distribution may be non-uniform over the cell, producing a hot spot region where the intensity can be considerably higher than in a neighboring region of the cell. This gives rise to a local heating effect, which will reduce the overall efficiency of the cell significantly.

Our design was chosen as a compromise between tolerance of manufacturing variation and concentration factor. In retrospect, the concentration factor could be increased with improved manufacturing techniques.

The mirror length was 40 cm longer (and slightly wider) than the array of solar cells. This allows a tolerance on the seasonal angle variation of the panel. The panel structure also acts as an anchoring point for the receiver mounted 1.5 metres above the mirrors.

2.2 Tracking System

The position of the sun as it moves across the sky can be plotted. This information defines the characteristics required from a tracking system.

When the sun is near the horizon, the sunlight passes through a much thicker layer of atmosphere compared to midday. Much of the suns direct energy is absorbed or scattered at near the horizon, even if there are no obscuring clouds. Therefore there is little advantage in operating the tracker closer than 10 to 15° above the horizon.

Passive trackers (quite popular with flat plate systems) are unsuitable due to their lack of precision and inability to cope with even a light breeze.

The current tracker is a heavily modified version of a single axis commercial tracker obtained from Davy Industries. It uses a 12 V DC motor through a double worm drive to rotate the panel structure during the day. The panel rotates on a pair of 25 mm ball bearings. Seasonal adjustment is by manually adjusting the tilt of the panel.

Using a focal length of 1.5 metres requires an accuracy of tracking of better than 1/4 degree of arc to keep the sun on target. This means moving the mirror every minute or so.

A pair of sensors mounted on either side of the receiver monitors the position of the focus, and a differential signal initiates movement of the motor. This occurs every minute or so, which corresponds to an angular movement of the sun of ? degree of arc. The whole structure is mounted on a single pole and guyed for stability.

2.3 Removal of Heat

The efficiency of the cells drops by around 0.3%/℃. Therefore for efficient electrical operation, the cells must be kept as cool as possible. The maximum cell temperature before damage occurs is in excess of 350 ℃. Therefore high temperatures are not directly going to damage the cells, although other materials in their proximity may suffer.

The current system is water-cooled using a recirculating pump and reservoir. During the day, at a pumping rate of 4.3 litres a minute, the water was warmed by 4 deg C. This corresponds to an absorption rate of 1 kW. No techniques were used to maximise this figure.

Whilst the temperature of the coolant will of course rise during the day, it also cools during the night. In a desert environment, this may be a practical cooling system, especially if the pump continued to operate during the night. This option was chosen primarily for security of operation at this stage of development.

Water-cooling can be utilised in a commercial operation for providing industrial / domestic hot water, as well as in a stand-alone water pumping application in remote areas, where bore water is the coolant.

Water-cooling does have some drawbacks however, in terms of capital and maintenance costs, energy requirements for the pump, moving parts to fail, and corrosion difficulties. Corrosion by normal water may mean that a special coolant and heat exchanger may be required for long—term operation, or the heatsink be made of different materials. These consequences do not preclude the operation of a water-cooled system, and several panels may be served by a single cooling system to amortise costs.

There are however many situations where an air-cooled heatsink is desirable. For lower level concentration (up to say 40 suns) and a well-designed heatsink, a temperature rise of around 35 ℃ can be expected. Even high concentration systems (up to 250 suns) have used a passive air-cooled heatsink. Here the important point to note is that the overall power dissipated is still manageable (less than 100 watts of heat) even though it may be concentrated into a small volume.

3 Conclusions

A solar concentrator was built and tested. It shows promise for a lower cost method of producing electricity from the sun compared to current technologies. Several of the techniques in the design and construction of this system can be refined to make a commercial product in the near future.

The current system comprising of a concentrator array, cooling system, receiver and tracking system, tracks the sun to within 1/4°, and would generate 120 W of electrical power and hot water, when illuminated by 1 sun. This type of technology is suitable for generating many tens of kW from an array of concentrators.

Since this type of panel requires a tracking system, it is not suitable for low power— due to the cost of the tracker. P-V systems gain about a 30% increase in averaged annual power production if they track the sun, compared to being mounted in a fixed direction. We are aiming our commercial development program to produce power in the range 300 to 1, 000 watts from one system.

This research program implemented a means of concentrating sunlight that present some important advantages over the current use of large aperture parabolic mirrors, in terms of cost, ease of manufacturing, transport and commissioning.

References:

[1] STONE Jack L. Photovoltaics: Unlimited Electrical Energy From the Sun [C] //Physics Today, September, 1993.

[2] INAMORI Kazuo. Promoting dissemination of PV power generation system [C] //Japan 21st, p 21, May, 1996.

[3] SIURU Bill. What's new in solar power [J]. Electronics Now, 1998, 69 (8): 53.

[4] TERESKO John. Solar power: Photovoltaics at Georgia Tech [J]. Industry Week, 1997-05-19: 29.

[5] BROWER Michael. Cool Energy: Renewable Solutions to Environmental Problems [M]. Union of Concerned Scientists, MIT Press, 1992.

[6] FLAVIN Christopher, LENSSEN Nicholas. Power Surge: Guide to the Coming Energy Revolution [M]. Worldwatch Institute, W W Norton and Co., 1994.