WILL WE HAVE A 20%-EFFICIENT (PTC) PHOTOVOLTAIC SYSTEM?

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ABSTRACT: This paper discusses the importance of solar cell efficiency to reduce the overall cost of electricity produced by photovoltaics. A large-scale demonstration of a concentrator PV system in White Cliffs, Australia is presented. The concentrator system, based on reflective dish and Point-Contact silicon solar cells, has a PTC efficiency of 20.02%.
Keywords: High-efficiency - 1: Concentrators - 2: PV system - 3

1. INTRODUCTION

There is a very common practice within the photovoltaic community, from both industry and research, to price every component of a photovoltaic system in terms of dollar per peak power ($/W$_p$). This practice is generally used throughout the whole value chain, from bulk starting material (for example silicon feedstock in the case of silicon technologies) to system pricing. Since every developer is usually focussing on only one element of the value chain, this practice may not end up to the most economical PV system. At the end, what really counts is the cost of energy ($/kWh). For example, a research team developing a new process for solar cell manufacturing may choose or not choose a particular technology based only on the additional cost of this particular technology and the additional power produced by the solar cell under Standard Rating Conditions (SRC). If the ratio of those is greater than the current cost of manufacturing solar cells, the idea may be abandoned. If this research team had a larger view, they would realize that the increase in efficiency has a tremendous effect on the whole value chain. This is particularly true and well known for concentrator systems where the cost of solar cells is a very small portion of the whole system cost and, therefore, the cell efficiency has a great impact on the cost of the produced solar electricity. It is also very true for flat-plate systems because a large part of the overall system cost is proportional to the area of the system. The realization of this leverage, that the solar cell efficiency has to reduce the cost of PV systems, is possible if the PV industry becomes fully vertically integrated or if collaborative design and implementation is increased across the whole PV value chain.

The purpose of this paper is to present the reasons why efficiency is a very important parameter in the final cost calculation of PV solar electricity, to analyse the potential of the different commercially available PV technologies, and to present the first large-scale demonstration of a cost-effective PV system to reach 20% efficiency under PVUSA Testing Conditions (PTC).

2. PV SYSTEM COST

Although we have the habit to price each element of a PV system in terms of dollar per peak power, the largest part of the cost is actually more proportional to the system area and less proportional to the peak power. Table 1 A-B shows a non-exhaustive list of the components of a PV system and their cost relationship to the area of the system or the peak power.

Table 1-A: Components of the cost of a PV system that are more proportional to the area than the peak power of the system (Not all the components apply to all PV technologies.)

Component of a PV System	**Cost is more proportional to area**
Bulk Starting Material	- silicon feedstock - gases - chemicals - substrates
Wafer	- ingot pulling or casting - slicing - etching
Solar Cell Manufacturing	- labour - film deposition - screen printing - diffusion - anneal - etching - testing
Module	- tabbing and stringing - laser scribing - glass, EVA, Tedlar - lamination - frame, junction box - testing - packaging
Installation	- shipping - mounting structure - labour - field wiring
Maintenance	- cleaning

Table 1-B: Components of the cost of a PV system that are more proportional to the peak power than the area of the system

Component of a PV	**Cost is more proportional to**

System	peak power
Balance of System	- inverter, controller - battery - breaker
Monitoring	- monitoring equipment

In order to illustrate how much leverage the efficiency has over the overall system cost, let's take the following example. A typical residential roof-top grid-connected PV system without backup batteries costs between US$8 and US$12 per peak Watt. The cost of solar cell manufacturing, excluding the starting material and the lamination, represents only 20% of the total module cost [7] and around 7% of the total cost of the PV system. On the other side, the inverter, breakers and controller also represent less than 10% of the whole system cost. There is also a fix cost for every installation, about 10% for a typical roof-top system. Therefore, all the other components represent more than 73% of the PV system cost and their cost is proportional to the area of the system. Assuming that the efficiency of the system is mostly determined by the solar cell manufacturing technology, an increase of the solar cell efficiency by 50% would reduce the system area by a factor equal to 1.5, and would be economically profitable even if the technology to produce it is up to 4.4 times more expensive.

This type of reasoning is well understood by a fully vertically integrated PV company or if collaborative design and implementation across the value chain is achieved within the PV industry.

3. TEMPERATURE COEFFICIENT

There is another fundamental reason why efficiency is important for reducing the cost of solar electricity. All existing commercially available flat-plate PV modules are rated under Standard Rating Conditions (SRC), i.e. 1000 W/m^2, AM1.5G and 25°C cell temperature. These are laboratory-type conditions and are quite unrealistic. In order to calculate the amount of energy that the PV system will produce over one typical year, one need to use a complete performance model that includes, among others, temperature coefficients, spectral coefficients, and wind coefficients, as the one developed by D. King [4]. A much more realistic rating is the one used by PVUSA. In the PVUSA Testing Conditions (PTC), the PV modules or systems are tested under real conditions: AM1.5G, 1000 W/m^2, 20°C ambient temperature and 1 m/sec wind speed. The modules with the best thermal management design and the cells with the lowest temperature coefficient will be the ones with the smallest difference between the SRC and the PTC ratings. Also, the cells with the highest efficiency have the lowest temperature coefficient.

It is well known that the efficiency temperature coefficient of a solar cell is mostly impacted by the voltage reduction when the temperature of the junction increases, but this voltage temperature coefficient is not a constant. It decreases as the voltage of the cell increases. In fact, it is almost proportional to the difference between the voltage of the cell and the bandgap of the material. In Voc condition, we know that:

$$V_{oc} = kT/q \ . \ \ln \{ I_{sc} / I_o + 1 \} \quad (1)$$

where I_o is the saturation current of the cell which is proportional to the square of the intrinsic carrier density, n_i^2. Also, it is well known that:

$$n_i^2 \sim T^3 \ . \exp (- E_g / k.T) \quad (2)$$

The derivative of V_{oc} with respect to temperature then becomes:

$$dV_{oc} / dT = - \{ (E_g/q - V_{oc}) + 3 \ kT/q \} / T \quad (3)$$

The dominant part of this equation is ($E_g/q - V_{oc}$), and we can see that the voltage temperature coefficient is smaller for high-efficiency solar cells with large open-circuit voltages than for low-efficiency cells. For example, a typical flat-plate silicon solar cell would have a voltage temperature coefficient between –2.2 and –2.6 mV/°C, whereas a 22% efficiency silicon solar cell has a temperature coefficient between –1.6 and –1.8 mV/°C, and a concentrator silicon solar cell has a temperature coefficient between –1.28 and –1.34 mV/°C depending on the concentration ratio.

4. MODULE EFFICIENCY

Although the record efficiency for a laboratory silicon solar cell has reached 24.7 % (crystalline FZ Silicon solar cell fabricated by UNSW and measured at one sun with a designated aperture) [1], the efficiency of commercially available flat plate PV modules is still in the range of 5% to 12% (measured under PVUSA Testing Conditions, PTC) [4]. Flat plate PV modules over 20% efficient have been demonstrated [1-2,6]. However, the fabrication cost of these modules is far beyond what is acceptable for terrestrial application. Only concentrator modules have so far demonstrated promising results to attain 170 W/m^2 or 20% PTC efficiency at reasonable cost [3]. Of course comparing efficiencies of flat-plate and concentrator systems is difficult. In first approximation, and if both modules are placed on 2-axis trackers, we could say that a 20% efficient concentrator system would be equivalent to a 17% flat plate system due to the difference between direct (850 W/m^2) and global (1000 W/m^2) irradiance.

Table 2 summarizes the record SRC efficiencies for most of the commercially available PV technologies, measured sometimes on very small cells or with designated aperture or even uncut from the wafer to avoid edge recombination. The data for record SRC efficiencies for cells and modules are from the "Solar Cell Efficiency Tables" [1]. The right column gives the best PTC efficiencies for commercial PV modules and the data are extracted from the Sandia I-V Tracer program and their most recent database [4]. The PTC efficiency of the Concentrator III-V module was reported by M. O'Neill et al. [5] and corresponds to a prototype module with linear-focus Fresnel lens and multijunction III-V cells. Finally, the PTC efficiency of the concentrator silicon module is from this work and corresponds to a 19.75 m^2 concentrator dish with a dense-array receiver made of silicon solar cells.

One has to note that the PTC efficiencies reported in Table 2 are for the entire module area and includes the losses due to packing density, frame and other non-active area of the modules, which could represent up to 30% of the module. Figures 1, 2 and 3 present the PTC efficiency of several PV modules as a function of the module area, for mono-crystalline silicon, multi-crystalline silicon and thin film respectively

Table 2: Record laboratory cell efficiency of different technologies measured at Standard Rating Conditions (SRC, AM1.5, 1000 W/m^2, 25C cell temperature) and best commercially available, cost-effective, module efficiency measured at PVUSA Testing Conditions (PTC, AM1.5, 1000 W/m2, 20C ambient temperature, 1 m/sec wind speed)

Technology	Record SRC Cell Efficiency	Record SRC Module Efficiency	Best PTC Module Efficiency
Mono-Crystalline Si	24.7 %	22.7 %	11.7 %
Multi-Crystalline Si	19.8 %	15.3 %	11.2 %
Silicon Film	16.6 %	-	7.23 %
a-Si	12.7 %	10.4 %	5.88 %
CIS	18.2 %	12.1 %	8.27 %
CdTe	16.0 %	10.7 %	6.65 %
Conc. Si	28.3 %	N/A	20.0 %
Conc. III-V	32.4 %	N/A	25 %

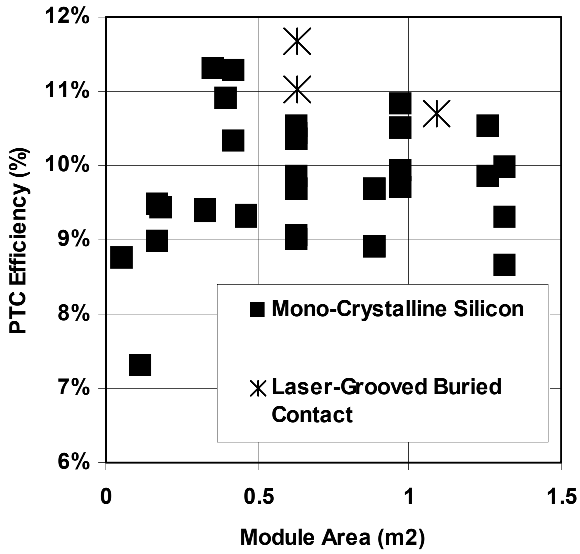

Figure 1: PTC efficiency of commercial PV modules with mono-crystalline silicon technology

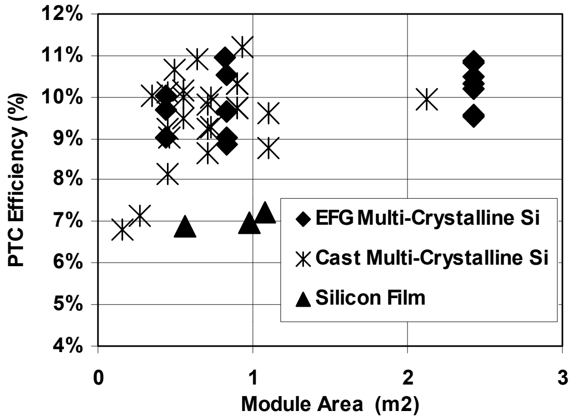

Figure 2: PTC efficiency of commercial PV modules with multi-crystalline silicon technology

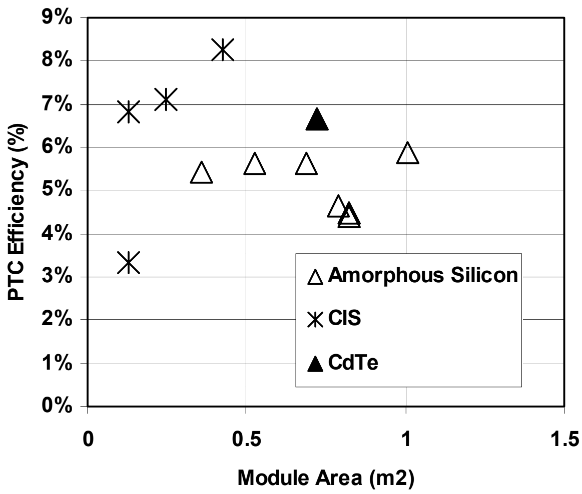

Figure 3: PTC efficiency of commercial PV modules with thin-film technology

5. HIGH-EFFICIENCY CONCENTRATOR SYSTEMS

5.1 Description of the concentrator PV system

Solar Systems Pty Ltd. has developed concentrator photovoltaic systems since 1990. The concentrator PV system is designed around a parabolic reflective dish, concentrating sunlight about 340 times (250X optical concentration) onto a photovoltaic receiver. The 24 x 24 cm receiver is composed of a dense array of 16 PV modules (6 x 6 cm) assembled by Solar Systems using dense-array cells fabricated by SunPower Corporation.

The first large-scale proof of concept is a power plant operated by Solar Systems in White Cliffs, NSW, Australia. The power plant is composed of 14 parabolic concentrators, of almost 20 m^2 in area, that have been refurbished from a previous solar thermal experiment. In 1998, the reflective surface of the dishes and the old thermal receivers were replaced with new mirrors and photovoltaic receivers. The picture in Figure 4 shows a partial view of the entire power plant.

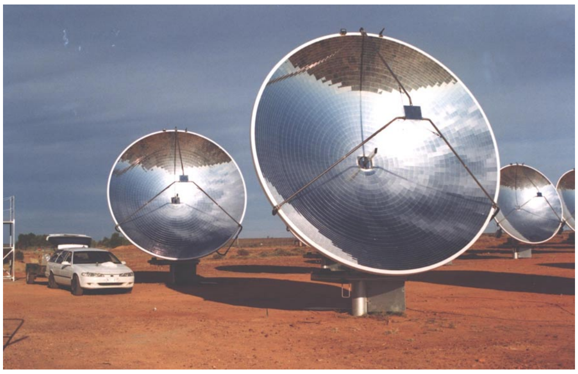

Figure 4: Partial view of the 14-dish photovoltaic power plant at White Cliffs, NSW, Australia, operated by Solar Systems. The result data presented in this paper are from the dish in front of this picture.

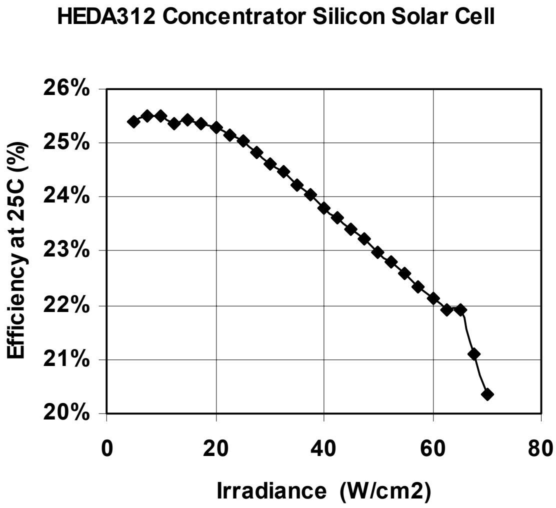

Figure 5: Efficiency of HEDA312 concentrator silicon solar cell for dense-array application vs. irradiance

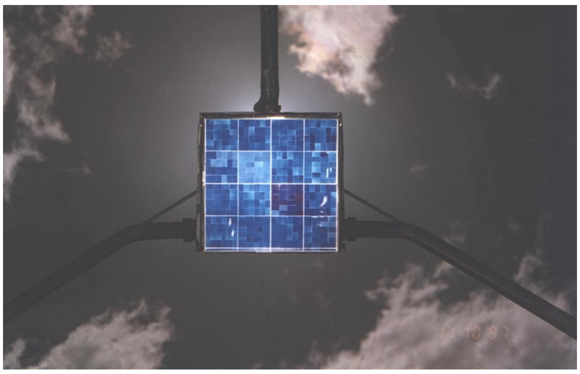

Figure 6: Photovoltaic dense-array receiver assembled by Solar Systems, composed of 384 series-connected silicon backside contact (Point-Contact) HEDA312 solar cells from SunPower Corporation.

The silicon solar cells used on the receivers are HEDA312, Point-Contact solar cells from SunPower. The cells are 1.0 x 1.5 cm and are specially designed for dense array application. A typical HEDA312 solar cell efficiency at 25°C is presented in Figure 5. The PV modules are built by laminating the solar cells onto a 6 x 6 cm ceramic substrate forming a dense array of 24 series-connected cells. The ceramic substrate is attached on a water cold plate for active cooling of the dense array. The solar cells are then protected by a thin AR-coated cover glass that is attached to the solar cell surface with RTV silicone.

The PV receiver of each dish is composed of 16 modules, each with 24 solar cells, forming a total of 384 series-connected solar cells. A picture of a receiver while in operation is shown in Figures 6 and 7.

5.2 Results

The following data (Table 3) has been taken from Dish No. 2 of the White Cliffs power plant on April 5, 2001 at 10:40 AM. The conditions were very similar to PVUSA Testing Conditions (PTC), i.e. 850 W/m^2, 20°C ambient temperature and 1 m/sec wind speed. In this case, the wind speed is not relevant because the receiver is actively water cooled, with the water being pumped from a very large water reservoir with an almost constant temperature.

The overall DC electrical efficiency is 20.02 % under conditions that are very similar to PTC, and without accounting for the parasitic power losses. Table 4 gives the value of the different parasitic power losses per dish. Taking into account the parasitic power losses, the overall system efficiency (DC) is 19.32 %. We believe that this is the first large-scale demonstration of a cost-effective photovoltaic system with a PTC efficiency greater than 20%.

5.3 Incident Power Density on Receiver

The total thermal power P_{Th} on the receiver is calculated from the water temperature difference ΔT_W between inlet and outlet of the cold plate manifold.

$$P_{Th} = \Delta T_W \,.\, Q_W \,.\, H_w = 9{,}098.7 \text{ W} \quad (4)$$

where Q_W is the cooling water flow rate in the receiver and H_w is the specific heat of water (4.186 J/g.K).

The total incident power density P_{in} impinging on the receiver can be calculated from the total thermal power P_{Th} and the total output electrical power P_{out} as follows:

$$P_{in} = (P_{out} + P_{Th}) / \{(1 - R) \,.\, A_R\} \quad (5)$$

$$= 25.26 \text{ W/cm}^2$$

where R is the integrated reflectance from the cover glass surface and from the solar cell (front and back surface), and A_R is the receiver area (576 cm^2). The reflectance of the receiver was calculated to be 13.78 %, from thermal reflection measurement (11.4%) and from simulations of radiation losses at high angle of incidence (2.7%). The incident power on the receiver is 14,552 W.

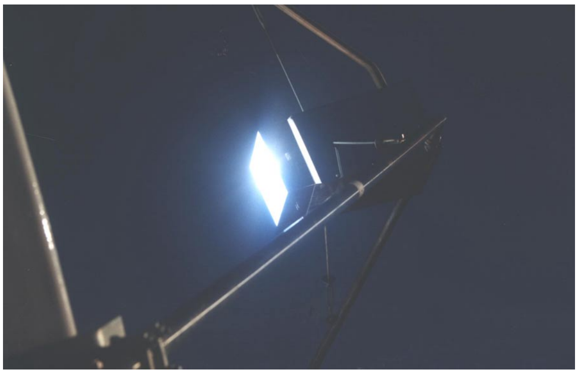

Figure 7: Photovoltaic receiver of Dish #2 while in operation. The incident power density is 25.3 W/cm^2 in average. One can notice the "flux modifier" in front of the solar cells.

Table 3: Measurement data from Dish No. 2

Data	**Symbol**	**Value**	**Accuracy**
Ambient Temperature	T_A	19.7°C	± 1.0°C
Direct Normal Irradiation	DNI	872 W/m^2	± 3 % Class 1 Pyroheliometer
Water Flow Rate	Q_W	33.44 lpm	± 5.0 %
Dish Area	A_D	19.75 m^2	
Receiver Area	A_R	576 cm^2	
Delta Temperature (In-Out)	ΔT_W	3.9°C	± 0.1°C
DC Power Output	P_{out}	3,448 W	± 2.0 %
DC system efficiency	η_{DC}	**20.02 %**	**± 5.0 %**

Table 4: Parasitic power loss per dish

Power Loss	**Value**	**Accuracy**
Control Electronics	30 W	± 5 W
Water Pumping	86 W	± 1.5 %
Tracking Motors		
Azimuth	1.28 W	± 2 %
Elevation	3.52 W	± 2 %
TOTAL	**120.8 W**	**± 10 W**

5.4 Receiver Electrical Efficiency

The efficiency of the receiver, i.e. the efficiency of the 384 series-connected solar cells, at operating temperature is calculated as follows:

$$\eta_R = P_{out} \ / \ (P_{in} \ . \ A_R) \qquad (6)$$

$$= 23.7\ \%$$

The average cell temperature, calculated from the water temperature and the temperature drop across the ceramic substrate and the cold plate, is 38.52°C.

For comparison to the outdoor efficiency results, we also have measured efficiencies at cell and module level. For this receiver, the typical cell efficiency, measured at SunPower with a flash testing system, was 25% at 25 W/cm^2 and 25°C. Considering a relative temperature coefficient of -0.003/°C, the typical cell efficiency would be 24.0% at 25 W/cm^2 and 38.5°C. One should note that these reported cell efficiencies are for non-encapsulated solar cells. Since the anti-reflection coating is optimised for an RTV encapsulant, we have to expect that the efficiency of encapsulated solar cells with AR coated cover glass will be higher than the efficiency of non-encapsulated solar cells, due to a better match of the refractive indexes and a better light trapping.

Before mounting the modules in the receiver, indoor flash testing (at Solar Systems) of the least efficient module showed an efficiency of 26.5% at 25.0 W/cm^2 and 21°C. Considering a relative temperature coefficient of -0.0038/°C, this module efficiency would be 24.7% at 25 W/cm^2 and 39°C.

Comparing the module efficiency (24.7%) to the receiver efficiency (23.7%) allows calculating the power losses, mostly due to light non-uniformity. There is an estimated relative loss of 4.1% in power due to light non-uniformity. This is very good considering, for example, that the cell efficiency varies from 25.3% at 10 W/cm^2 to 23% at 50 W/cm^2.

5.5 Solar Cell Temperature

The temperature of the solar cells has been calculated from the average module temperature, T_{mod} = 27.4°C, measured with thermocouples attached to the backside of the ceramic substrates, and from the variation of open-circuit voltage of the array with the incident power density. A previously measured open-circuit voltage temperature coefficient of –1.3 mV/°C per cell, or –500 mV/°C for the array, allowed us to determine the U-factor and to derive the average cell temperature by the following formula:

$$T_{cell} = T_{mod} + P_{in} \ / \ \text{U-factor} \qquad (7)$$

where the U-factor has been measured to be 2.216 W/cm^2.K.

5.6 Concentrator Optical Efficiency

The concentrator optical efficiency is calculated from the ratio of the incident power on the receiver and the incident power on the dish:

$$\eta_{opt} = (P_{in} \ . \ A_R) \ / \ (DNI \ . \ A_D) \qquad (8)$$

$$= 84.4\%$$

The optical efficiency of the dish calculated from several previous tests has shown to be around 86%. This value is only 2% relatively higher than this particular test value of 84.4%. The difference is probably due to the 5% accuracy in the water flow rate measurement.

The results of the performance calculations are summarized in table 5.

Table 5: Summary of the performance and operating conditions of the PV concentrator system at 872 W/m^2.

Parameter	**Symbol**	**Value**	**Accuracy**
Dish Optical	η_{opt}	84.4 %	± 5.0 %

Efficiency			
DC System Efficiency	η_{DC}	20.02 %	± 5.0 %
System Efficiency with Parasitic	η_{DC*}	19.32 %	± 5.0 %
Receiver Efficiency	η_R	23.7 %	± 5.0 %
Module Efficiency	η_{mod}	24.7 %	± 5.0 %
Cell Efficiency	η_{cell}	24.0 %	± 5.0 %
Average Cell Temperature	T_{cell}	38.52°C	± 2.0°C
Average Module Temperature	T_{mod}	27.4°C	± 5.0 %
Inc. Power Density	P_{in}	25.26 W/cm^2	± 5.0 %
Inc. Power on Dish	$P_{in} . A_D$	17,222 W	± 3.0 %
Inc. Power on Receiver	$P_{in} . A_R$	14,552 W	± 5.0 %
Total Thermal Power	P_{Th}	9,098.7 W	± 5.0 %
DC Electrical Power	P_{out}	3,448 W	± 2.0 %

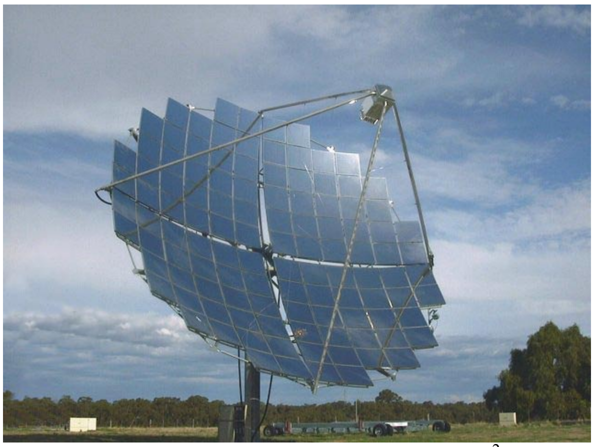

Figure 8: Solar Systems large-area (130 m^2), high-efficiency concentrator PV system with 24 kW rated power.

5.7 Recent Concentrator Development

The power plant at White Cliffs is the first large-scale demonstration of high-efficiency PV concentrator systems. It is an excellent proof of concept. Solar Systems has recently developed a larger concentrator PV system that will be soon deployed in the Australian outback. The concentrator has a projected aperture of 130 m^2 and concentrates the sunlight onto a 48 x 48 cm receiver with a 560X concentration ratio (50 W/cm^2). The DC power output of this new concentrator system is 24 kW. Figure 8 shows a picture of the large area concentrator system.

6. CONCLUSIONS

Most of the components in the cost of a PV system are proportional to the area of the system and the solar cell processing cost represents a small portion of the overall system cost. Therefore, the cell efficiency has a large impact on the cost of energy produced by photovoltaics. Not only the use of high-efficiency solar cells allows reducing the PV system area, but also higher efficiency cells have a lower efficiency temperature coefficient and make PV modules with higher PTC efficiency.

The efficiency of commercially available flat plate PV modules is still in the range of 5% to 12% (measured under PVUSA Testing Conditions) far behind the record efficiencies of laboratory cells. Only concentrator PV systems have, so far, demonstrated high-efficiency, above 20%, or 170 W/m^2 for comparison with flat-plate, under PVUSA Testing Conditions, in a cost-effective way.

We also reported the performances of a concentrator PV system, based on reflective parabolic dish and silicon Point-Contact solar cells, in a large-scale demonstration in White Cliffs, Australia. The concentrator system has an overall efficiency of 20.02% under testing conditions that are very similar to PTC. We believe this the first time that a cost-effective concentrator PV system with such high efficiency has been demonstrated.

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