

REACHING GRID PARITY USING BP SOLAR CRYSTALLINE SILICON TECHNOLOGY*

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ABSTRACT

This paper reports on BP Solar's DOE sponsored Technology Pathways Partnership. The paper presents the goals, the technical approach and progress for two years. The overall goals of the program are to reach grid parity for residential and commercial markets and to increase production volumes. This program is addressing all aspects of the PV product chain including:

- Solar grade silicon (SGS) development;
- Implementation of Mono²™ technology (single crystal quality at multi cost);
- Wafering thinner wafers using thinner wire;
- Optimized cell process for thin Mono²™ to achieve a cell efficiency of 18 % in 2010;
- Lower module material costs and products designed for integration into specific roof types;
- Automation and process control for handling hundreds of cells per minute and;
- Inverters designed with the capability to dispatch batteries.

Specific accomplishments reported on in this paper include:

- A manufacturing trial of Mono²™ technology from casting through module production;
- Product development for a utility scale module;
- Development of ThermoCool™ encapsulant to reduce module operating temperatures;
- Work with Dow Corning to qualify a silicone based encapsulation system and;
- Evaluation of measured versus modeled module and array performance

INTRODUCTION

This paper is a report on the first two phases of BP Solar's DOE sponsored Solar America Initiative, Technology Pathways Partnership. The overall goal of the program is to reach grid parity for residential and commercial markets and to increase production volumes [1, 2]. To meet this goal, our objectives are to substantially reduce, 1) module cost to 67% of the 2006 cost by 2010 and to 50 % of the 2006 costs by 2015; and 2) system costs to 60 % of the 2006 cost

by 2010 and to 36 % of the 2006 costs by 2015. These are projected to result in levelized cost of electricity (LCOE) of 8 to 10 ¢/kWh for residential systems and 6 to 8 ¢/kWh for commercial systems by 2015. Key components of the program include:

- Silicon: Development of a purification process for solar grade silicon to lower the cost and increase the availability of silicon feedstock for the PV industry.
- Casting: Implementation of Mono²™ technology (single crystal quality at multi crystal cost);
- Wafering: Thinner wafers down to 160 µm in 2010; using thinner wire, improved slurry, slurry recycling, and automated demounting and singulation of wafers.
- Cell Process: Optimize design and processing for ultra-thin Mono²™ wafers to achieve a cell efficiency of 18 % in 2010.
- Module: Lower material costs, products designed for integration into specific roof types, increased energy collection and improved safety.
- Automation and process control to transition from hundreds of cells per hour to hundreds of cells per minute.
- Higher efficiency, increased reliability inverters that can charge and discharge storage batteries from a standard high voltage array.
- Improved low cost systems monitoring with the ability to remotely dispatch energy from the storage system.
- Reduced indirect costs through organized deployment channels and integrated solutions.

This paper will discuss results from several key areas of the program.

TECHNICAL RESULTS

Mono²™ Production Trial

BP Solar has developed a new technique for casting silicon ingots with extremely low defect densities (Mono²™ silicon) [3]. A production demonstration of the Mono²™ process was conducted as part of the TPP Program in order to validate the processing and to determine the expected performance. Fifty-five 240kg ingots were produced using four different cast-

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ing conditions. Procedures were created and operators trained before-hand to allow operation's personnel to perform all production aspects of the trial. A total of 650,000 wafers were cut, processed into solar cells and fabricated into modules resulting in approximately 1.4 megawatts of Mono²™ product.

Some important results of this trial were:

- Casting yields for Mono²™ were slightly lower than yields for multi-crystalline ingots, indicating the need for process improvements.
- Wafering yields for Mono²™ were identical to the wafering yields for multicrystalline.
- Cell and module yields were equivalent to standard production yields of multicrystalline.
- There was a small but measureable decrease in cell efficiency after multiple uses of the seed.
- Cell efficiencies averaged ~ 2 % higher than multicrystalline controls.
- The 7,643 modules averaged 14.3 % with the best modules exhibiting ~15.6 % total area efficiency.
- For the best process conditions the top end of the cell and module efficiency distributions overlapped with the co-processed monocrystalline silicon cells and modules.

The Mono²™ process shows great promise for producing monocrystalline quality at multicrystalline costs. Future work is necessary to improve the seed reprocess procedure, to improve the overall material uniformity, and to scale the process to larger ingots.

Utility Module

BP Solar's project also investigated various ways to increase the energy output of the solar module. In addition to optical losses, which were addressed by the optimization of the glass anti-reflection coating, electrical losses in the module were modeled and ways to reduce specific elements were determined. The section below describes the resistive component analysis and subsequent selection of the interconnect bus bar as a major element in the module I²R loss. The second part of this section highlights the production data on approximately 1MW of BP Solar's 1m by 2m Utility scale module that utilizes the optimized resistance design for ½ size, 156mm multicrystalline cells.

The total series resistance loss in a PV module is made up of numerous elements. These elements are shown in Figure 1. The sum of these components represents the total series resistance of the module. Minimizing these components will reduce overall series resistance and increase fill factor, therefore, increasing the power of a module.

The magnitude of these losses is directly proportional to the square of the current (from Ohms law; Power_{loss} = I²R). For this reason, resistive losses in a module made with 125mm cells are lower than losses

in one made with 156mm cells. This is due to the higher current in the 156mm case. At BP Solar, we have investigated methods to utilize the larger cell format yet reduce the electrical losses within the module. Moreover, a module has been designed where the cell size is optimized to reduce these losses and boost performance as well as increase shade tolerance over a traditional assembly. This has been achieved by sectioning the cells into two halves, reducing interconnect losses, and recombining the current at the cables. In reducing cell current by reducing cell size, the I²R losses in the front tab and tab extension are also reduced. This leads to an improved fill factor. We call this the reduced or optimized series resistance design.

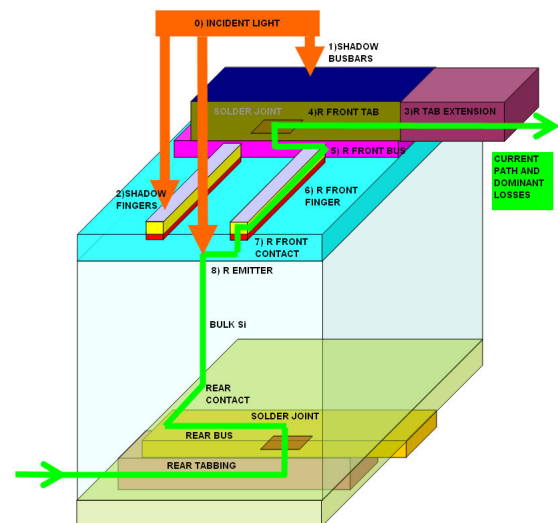


Figure 1: Resistive elements of an encapsulated cell

By reducing series resistance, the performance of the module increases in the following ways:

- Better performance at high light levels.
- Improved encapsulated STC cell efficiency by up to 0.5 % absolute.
- Better power density in the field.
- Twice the shade tolerance of a standard module due to a higher level of by-pass diode protection. This is enabled by leveraging BP Solar's intellectual property, the Integra Bus™.

The next section describes the product performance of the BP Solar BP3280T module that incorporates the reduced series resistance design. The production data comes from modules built in BP Solar's joint venture assembly factory during May 2010. The production data in Table 1 shows the average data for 3,410, 2m² modules (0.955MW nominal power) of three different cell efficiency bins ranging from 15.6 % to 16.4 %. BP Solar used a primary reference module calibrated by ESTI-JRC in Italy. The maximum

module power reported was 297.8W. This relates to 17 % encapsulated cell efficiency and a STC module efficiency of 14.9 %. The distribution of module powers is shown in Figure 2.

Table 1 illustrates the performance comparison within the production distribution for the standard full 156mm x 156mm multi-crystalline cell design and the optimized series resistance (1/2 cell) design using the same starting cell efficiencies. In this case, we chose a cell efficiency of 15.8 % to 16.0 %. The standard module design had an STC power 9W lower than the optimized resistance Utility module design. The parameter that produced the improved performance was fill factor. The average fill factor for the optimized design was 0.766 (per module) versus 0.729 for the standard configuration. This is 5 % relative increase in fill factor. Voc for the two sets was identical, 44.3V, but Isc was 1.6 % lower for the optimized design. The lower Isc may be due to measurement error as the two groups were measured at different times with different reference modules. This gave a net gain of 3.2 % in module efficiency for the optimized design over the standard design.

Standard Utility Module				
Cell bin 15.8%/16.0%	Power (W)	FF	Voc (V)	Isc (A)
Average	278.3	0.729	44.3	8.61
Standard Deviation	1.0	0.003	0.1	0.02
Low Resistance 1/2 cell Utility Module				
Cell bin 15.8%/16.0%	Power (W)	FF	Voc (V)	Isc (A)
Average	287.3	0.766	44.3	8.47
Standard Deviation	2.0	0.006	0.2	0.05
Percentage Difference	3.2%	5.1%	-0.1%	-1.6%

Table 1: BP Solar BP3280T utility scale module comparison data (ESTI – JRC primary reference)

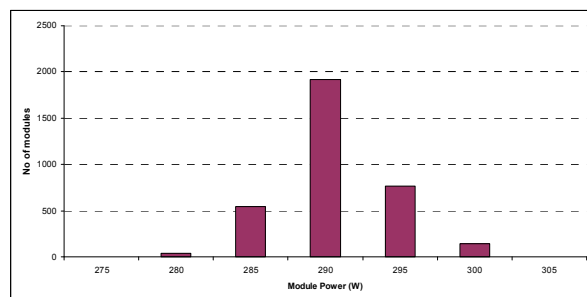


Figure 2: Production data (module power) for 3,410 utility scale modules with reduced resistance loss.

Silicone Encapsulation

BP Solar has been evaluating the use of a silicone encapsulation system in collaboration with Dow Corning Corporation. The new Dow Corning system has the potential to reduce process time, improve module efficiency because of higher light transmission, and to reduce long term degradation of module performance. Efforts under the TPP program include module qualification and certification as well

as quantification of improved energy collection in the field.

Standard BP Solar multicrystalline silicon cell matrices have been encapsulated by Dow Corning using the new silicone system. Resultant modules were then subjected to the BP Solar internal qualification sequence that includes:

- 500 thermal cycles from -40 °C to +85 °C,
- 1250 hours of damp heat at 85 °C and 85 % relative humidity
- 1000 mechanical load cycles, 50 thermal cycles and 10 humidity freeze cycles.

The silicone encapsulated modules passed all of these tests with minimum power loss as shown in Table 2. The percentage changes in this table are based on initial module measurements after the stabilization procedure (IEC 61215 outdoor exposure totaling 5kWh).

Samples	After 1000 Hr DH	After 1250 Hr DH
Damp Heat A	-0.8%	-0.9%
Damp Heat B	-0.8%	-1.5%
	After 200 TC	After 500 TC
Therm. Cycle A	-0.9%	-1.1%
Therm. Cycle B	-0.8%	-0.8%
	After MC/ 50TC	After MC/50TC/10HF
TC/HF A	-0.7%	-0.6%
TC/HF B	-1.0%	-0.1%

Table 2: Percent Power Loss of Silicone Encapsulated Modules after Qualification Testing

The initial wet insulation resistance of the silicone modules (measured at 1,000VDC) was 4 to 10 times higher than the wet insulation resistance measured for the standard EVA based modules. The wet insulation resistance of the silicone modules changed more during the damp heat test but still had approximately 1.5 times the insulation resistance after 1,250 hours of damp heat.

At this writing, BP Solar modules with Dow Corning silicone encapsulation are under external evaluation for third party certification to IEC 61215, IEC 61730 and UL 1703. All of the IEC tests have been successfully completed except for the TC50/HF10 sequence after UV preconditioning, which is in progress. All of the UL tests have been successfully completed. The silicone/back sheet structure received a partial discharge maximum permissible system voltage rating of approximately 1,300 volts for 225 µm of silicone encapsulant and a rating of almost 1,600 volts for 300 µm of silicone encapsulant. This test was performed as defined in IEC 60664-1.

A pilot run was conducted to produce 5 kilowatts of silicone encapsulated modules for a demonstration array. In order to have a baseline with which to

compare the results, BP Solar built 30 EVA laminated modules along with 30 matrices that were fabricated into silicone modules by Dow Corning using the same cell efficiencies. The silicone modules averaged 173.7W versus the EVA controls at 173.1W. Both arrays were installed at the Dow Corning site in Freeland, Michigan. They are being monitored separately to evaluate the energy performance of silicone versus EVA encapsulation. The results for the first 5 months of operation are shown in Table 3. The silicone modules produced approximately 0.5 % more energy during this time period.

EVA Total kWh	Silicone Total kWh	Difference kWh	Difference %
1976	1986	10	0.51

Table 3: Energy Collection from EVA and Silicone Arrays in Freeland, MI (Nov, 2009 to April, 2010)

Figure 3 shows three modules (one EVA control and two equivalent modules made with Dow Corning silicone encapsulant) deployed outdoors at BP Solar, Frederick where the maximum power point is measured every minute. From this data the specific energy yield was determined. Figure 3 shows the specific energy difference for the two groups. The differences (0.5 % and 0.7 %) are very similar to the energy yield difference seen on the large array at Freeland, Michigan.

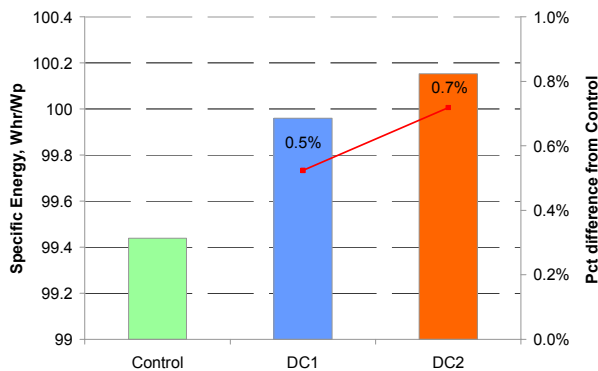


Figure 3: Specific Energy difference for an EVA module control vs. two equivalent modules made with Dow Corning silicone encapsulant

ThermoCool™

Solar modules convert a fraction of the incoming solar energy into electricity. A high percentage of the light that is absorbed by the modules will be converted to heat and therefore increase the cell temperature. For crystalline silicon products high cell temperature decreases the module energy output by ~0.5 % for every 1 °C increase in temperature. At BP Solar, we have successfully formulated EVA encapsulant with improved thermal properties. This

high thermal conductivity will lower the module temperature and increase the module energy output.

The potential increase in thermal conductivity achieved by adding two thermally conductive fillers to the EVA has been modeled. Modeling is based on equations 1 through 3 shown below. The results are shown in Figure 4.

$$\frac{K_c}{K_m} = \frac{1 + AB\phi}{1 - \phi B\phi} \quad (1)$$

$$B = \frac{\left(\frac{K_f}{K_m}\right) - 1}{\left(\frac{K_f}{K_m}\right) + A} \quad (2)$$

$$\phi = 1 + \frac{(1 - \phi_{\max})\phi}{\phi_{\max}^2} \quad (3)$$

Where:

K_m : thermal conductivity of encapsulant matrix

K_f : thermal conductivity of filler

$\phi_{\max}$: maximum packing factor

A: filler geometry factor=1.5

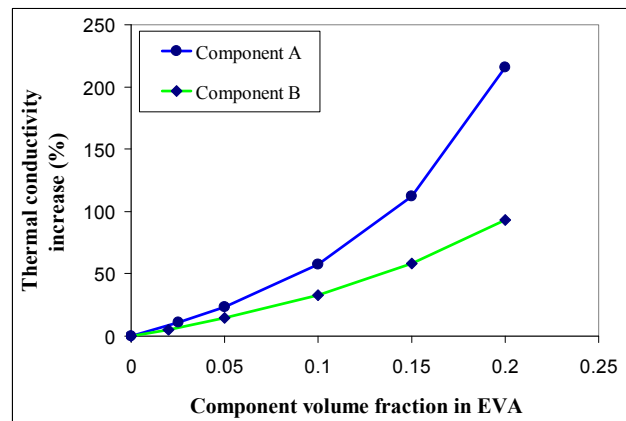


Figure 4: Thermal conductivity increase vs. filler component volume fraction

Based on Figure 4, at 5 % volume loading level, filler A should be able to increase the thermal conductivity of the EVA by 20 %. At 10 % volume loading level, a 57 % increase in thermal conductivity of the EVA should be achievable. Using the Fourier heat transfer law, the relationship between the temperatures of a cell encapsulated with standard EVA (old) and that of a cell encapsulated with improved EVA (new) is given by equations 4 - 6:

$$T_{old} - T_{environment} = \frac{Q}{\sum R_{old}} \quad (4)$$

$$T_{new} - T_{environment} = \frac{Q}{\sum R_{new}} \quad (5)$$

$$T_{new} = T_{environment} + \frac{\sum R_{old}}{\sum R_{new}} (T_{old} - T_{environment}) \quad (6)$$

Where Q is the heat to be removed from the cell and R is the total thermal resistance.

Based on the above analyses, a 25 % increase in EVA thermal conductivity would reduce the cell operating temperature by 5 °C with an irradiance of 1000 Wm⁻² at AM1.5 and provide a 2.5 % gain in module power at operating temperature. Figure 5 shows the outdoor performance for one day of a module made with high thermal conductivity EVA. The result is consistent with the modeling results.

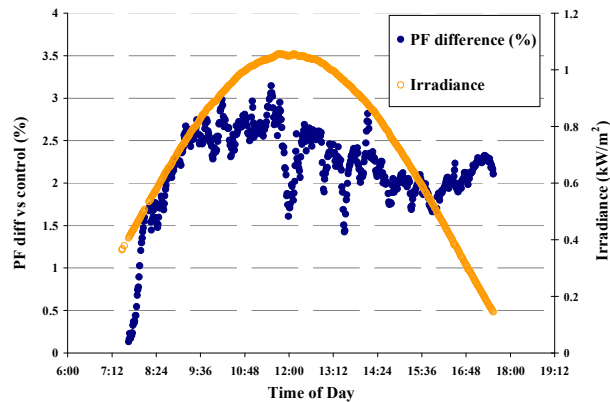


Figure 5: Irradiance and change in performance factor, PF (W/Wp/irradiance) between New EVA and Old EVA throughout the day

Several different high thermal conductivity EVA formulations were utilized during a month long test of energy collection. The results are shown in Figure 6. The module with the best formulation produced 2.2 % more energy than the module with standard EVA. This experiment was performed during the autumn, higher energy gains are expected during times of higher irradiance with higher ambient temperature.

System Modeling versus Measured Results

In order to evaluate module energy performance, BP Solar has set up three outdoor test facilities, one at the Frederick, MD factory, one at Fraunhofer IWES, Kassel Germany, and one at Arizona State University. All three sites are fully functional, providing energy data on a variety of module types.

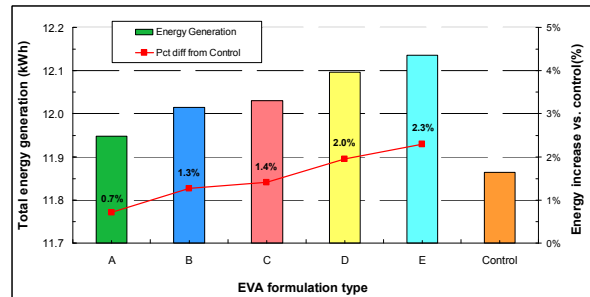


Figure 6: Improved Energy Collection from ThermoCool Modules

Both the trend toward ever larger PV power projects and the drive towards grid parity emphasize the need for accurate prediction of PV energy production. PVSyst® [4], a popular PV modeling software published by the University of Geneva, is used by many systems integrators and has recently been adopted by BP Solar as the basic modeling tool in planning PV projects.

Thin film PV modules can have unusual low-light performance that is very different from that of crystalline silicon. In our tests the low light level performance of one type of commercially available thin film module was not constant, but changed significantly within the first year of operation. Change was not observed near 1 Sun but dramatic changes were observed at irradiances less than 0.6 Sun. Figure 7 and 8 compares the measured data for the sample during two periods in the first year of operation. The initial very good low light level performance disappeared after about 5 months in the field.

The single-diode model used in PVSyst to predict the performance of PV modules is very sensitive to the shunt resistance (Rsh) and the series resistance (Rser) parameters associated with the module. By comparing the model predictions with measured data these parameters have to be manipulated to allow PVSyst to accurately model the complex performance of PV modules. Figure 7 and 8 overlay the PVSyst predicted performance with two sets of Rsh and Rser values selected for a best fit of the measured data. Table 4 shows the Rsh and Rser setting used to produce the fitted data.

It can be seen that shunt values used in PVSyst had to be reduced by a factor of 3 and greater to fit the Performance Factor (W/Wp/irradiance) profile of the light stabilized thin film module.

The fit of the PVSyst data to the measured data could be improved if Rsh was a variable with irradiance. This could be achieved with a 2 diode model approach. In the current version PVSyst can only model constant Rsh or rising Rsh (the default) at low irradiance.

The PVSyst study does help us to understand the changes that are occurring in the thin film modules during long term outdoor exposure. However, the original model inputs only represent the initial “out of the box” module performance and not the stabilized performance which would contribute to the majority of the product energy generation during its lifetime in the field.

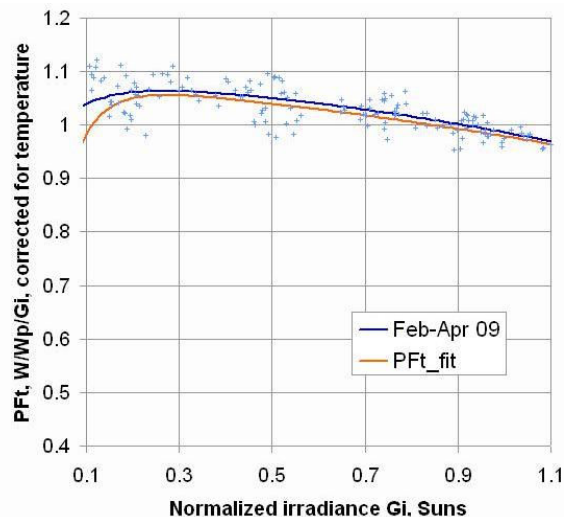


Figure 7: Performance Ratio for Thin Film Module for Period Feb – Apr, 2009 (Blue is Measured – Orange is Modeled)

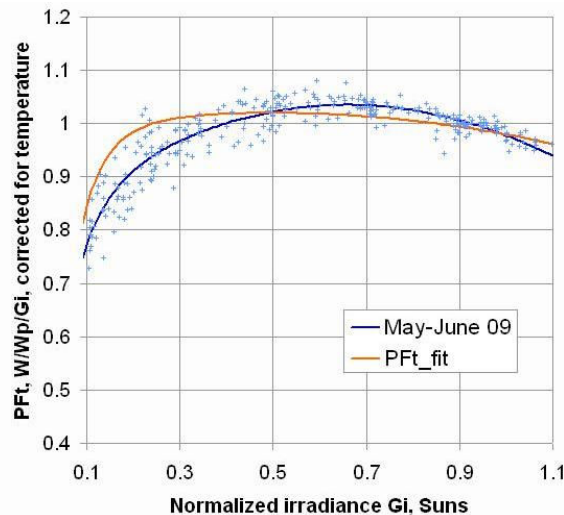


Figure 8: Performance Ratio for Thin Film Module for Period May – June, 2009 (Blue is Measured – Orange is Modeled)

Parameter	Feb-Apr 2009	May-June 2009
Rsh (Ω)	12,000	4,250
Rsh @ Gi =0 (Ω)	40,000	4,250
Shunt Exponential Factor	5.5	1.0
Rser (Ω)	6.8	6.8

Table 4: Parameters used in PVSyst for best match to measured data.

SUMMARY

BP Solar’s program is addressing all costs associated with producing and installing residential and commercial PV systems. The program’s Stage Gates for Phases 1 and 2 were all met.

In this paper, the BP Solar technical team has described some the key attributes in the PV value chain that can be optimized to maximize performance and significantly reduce leveled cost of electricity.

ACKNOWLEDGEMENT

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