INCREASED ENERGY COLLECTION USING ANTI-REFLECTIVE COATED GLASS

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ABSTRACT: The authors have previously reported that Anti-reflective (AR) coated glass results in a 2.4 to 3% increase in output power for crystalline silicon PV modules [1]. Because it impacts the front surface reflection, the AR coating can change the angle of incidence behavior of the PV module, thereby influencing the energy collected from the module. Individual AR coated modules have been tested at the BP Solar Homebush, Australia site and at a third party site in Germany. In all cases the AR coated modules produced 4 to 5% more energy than the controls. In order to better characterize the energy gain, two large arrays (each 41.5 kW), identical except for the type of glass used, have been installed at a site in Germany. The array with AR coated glass is producing 4% more energy than the array with standard glass. The largest difference in performance occurs at low light levels.
Keywords: Antireflection Coating, Optical Properties, c-Si

1 INTRODUCTION

The use of an anti-reflective coating on the outer glass surface can increase the coupling of light into a photovoltaic (PV) module and therefore increase its conversion efficiency. While AR coated glass has been available for years, in the past these coatings were unable to survive long term exposure outdoors. Recent advances in glass coating technology have improved the ability of the coatings to survive the outdoor environment.

Previous work demonstrated module efficiency gains under standard test conditions (1000 W/m^2 at normal incidence, AM1.5G spectrum, 25° C) of 2.4 to 3% when utilizing dip coated AR glass [1]. Sample modules were then deployed outdoors in Germany and Australia as part of BP Solar's continuing outdoor test program [2]. The measured increase in energy was typically 4 to 6% (depending upon the time frame and location) versus the measured STC power gain of 2.5 to 3.0%.

In order to further evaluate the performance of AR coated glass a larger size pilot run was conducted. The AR and control modules built in the pilot run have been installed in two otherwise identical 41.5 kW systems in Germany. The performance of the two systems has been monitored since April 1, 2005 to determine the energy production of each over an extended period of time.

2 INITIAL LABORATORY EXPERIMENTS

2.1 Approach

In the initial laboratory experiment full sized modules, with 72 (12.5 by 12.5 cm) cells, were fabricated using the dip coated AR glass along with controls using standard low iron glass. Every effort was made to uniformly mix the cells into the modules. All three different types of silicon cells produced by BP Solar (screen print multicrystalline, screen print monocrystalline and Saturn, laser grooved buried contact monocrystalline) were utilized in the experiment.

2.2 STC Results

The electrical results are given in Table 1. Power gains of 2.5 to 3% were measured. The increased efficiency is mainly due to increased short circuit current. Outdoor measurements at normal incidence verified the power improvement from the AR glass.

Cell Type	Glass Type	Voc (V)	Isc (A)	Pmax (W)
Screen Print Multi-Si	Control	43.4	4.96	156.3
3160	AR	43.5	5.10	160.5
3160	Δ	0.2%	2.8%	2.7%
LGBC Mono-Si	Control	43.9	5.52	180.4
7180	AR	44.0	5.62	184.9
7180	Δ	0.2%	1.8%	2.5%
Screen Print Mono-Si	AR	44.2	5.54	180.1
4175	Δ			3.0%

Table 1: Laboratory results for AR coated glass

2.3 Environmental testing

Modules made using the dip coated AR glass have been subjected to BP Solar's extended version of the IEC 61215 [3] test sequence. The test sequence included exposure to 500 thermal cycles from -40 °C to +85 °C, 1250 hours of damp heat at 85 °C at 85% relative humidity and a combined leg of UV/50 thermal cycles and 10 humidity freeze cycles. The modules made with the AR coated glass successfully passed the qualification tests without any visual evidence of degradation of the coatings or power loss from the modules.

2.4 Outdoor Testing

Several of the AR coated glass modules along with standard glass control modules were installed outdoors at several test sites around the world to determine if the AR coatings translate to increased energy collection. Figure 1 shows a plot of dc power gain versus time for both BP-3160 multicrystalline and BP-7180 Saturn monocrystalline modules installed at ISET in Germany. In all cases the modules with AR coated glass produce at least 4% more power than the control modules made with the same efficiency cells but with standard glass.

All of the laboratory AR coated modules monitored outdoors, have yielded an increase in energy of typically 4 to 5% (depending upon the time frame and location) versus the measured STC power gain of 2.5 to 3.0% that was shown in Table 1. Based on these results a larger size pilot run was conducted.

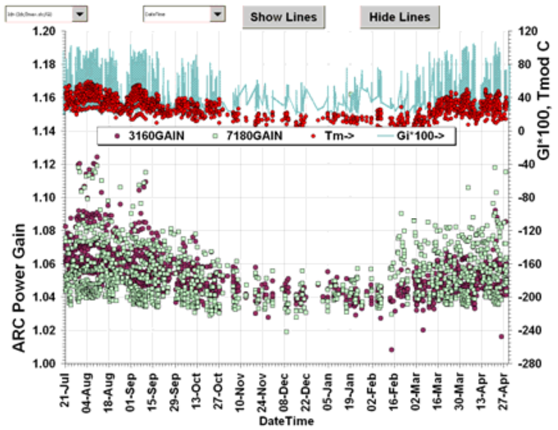

Figure 1: DC Power gain versus time (July-04 to April-05) for AR coated glass in Germany for irradiances > 200 W/m^2

3 PILOT RUN

In order to further evaluate the performance of AR coated glass, a pilot run was conducted building modules with 72 mono-crystalline silicon Saturn cells. The pilot run was designed to:

- Provide improved statistics to determine the STC flash test power increase;
- Determine what precautions are necessary in handling AR coated glass through the production line; and
- To provide modules for the larger outdoor test designed to determine the energy gain from the AR coating.

The pilot run included 231 AR coated glass modules and 231 control modules made with standard low iron glass. The modules were processed alternately (one AR and then one standard) in order to eliminate variability in the results.

The modules built in the pilot run have been installed in two otherwise identical 41.5 kW systems in Germany. The performance of the two systems is being monitored to determine the energy production of each over an extended period of time.

The results of the pilot run are given in Table 2. In this case the power improvement for the AR coated glass was 2.4% dominated by increased short circuit current as would be expected for AR coated glass.

Glass Type	Voc (V)	Isc (A)	Pmax (W)
Standard	44.1	5.42	179.5
AR	44.2	5.54	183.8
Δ	0.2%	2.2%	2.4%

Table 2: Cell results from the AR glass pilot run

Figure 2 shows the distribution of module powers obtained during the pilot run. There is little overlap between the two distributions with the AR coating shifting all modules to higher power by approximately the same amount.

The pilot run modules have been installed on the roof of a building in Assamstadt, Germany. The two arrays are tilted at 20°, oriented almost due south and suffer no shading. Each array has 7 x SB5000 inverters with 11 x 3 modules feeding each inverter. A picture of a part of the two arrays is shown in Figure 3. The difference in reflection can be seen in the picture.

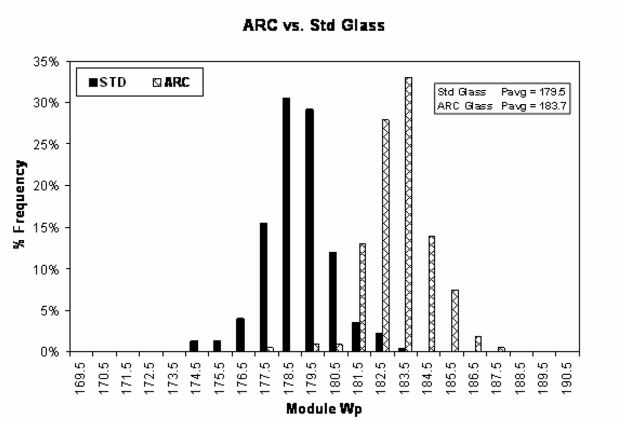

Figure 2: Distribution of module power from pilot run

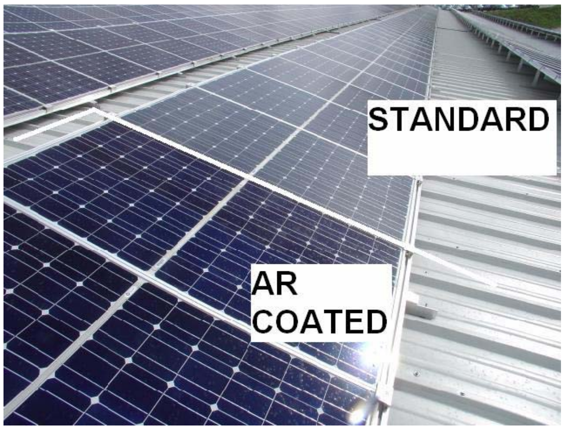

Figure 3: Picture of test arrays. Two darker modules in foreground have AR glass. Remainder of the row has standard glass.

The Sunny Boy Control system takes measurements very 5 minutes of the following variables:

1. Date and time
2. Tilted Plane Irradiance from reference cell
3. Ambient Temperature
4. Module Temperature (one)
5. Wind Speed from anemometer
6. DC string voltage (66 substrings)
7. DC Power (66 substrings)
8. AC Power (22 strings)

From the data set we calculate Vdm (=Vdc/Vmax.stc), PF (DC Performance Factor), PR (AC Performance Ratio), YA (dc yield), and YF (ac yield) as functions of date/time, irradiance and temperature. Most of the important parameters used to evaluate system performance are given in Table 3. (See also IEC 61724)

Every day each array yields a set of DC curves as shown in Figure 4 for the 231 standard glass modules compared with 231 AR coated glass modules. From these two curves we can see that during the middle of the day the normalized current I_{DN} is much higher for the AR array (1.1 for AR versus 1.04 for non-AR). In addition the DC yield peaks at a higher value for the AR array (0.84 versus 0.81).

Sym	Name	Units	Range	Definition
G_I	Plane of Array Irradiance	kW/m^2	0~1.4	
T_{AM}	Ambient Temperature	C	40~100	
T_M	Module Temperature	C	40~100	
YR	Insolation	kWh/m^2	0~1.4/h	$=\Sigma_t(G_I)$
V_{DM}	Normalized DC voltage		0~1.4	$=V_{DC}/V_{MAX}$
I_{DN}	Normalized DC current		0~1.4	$=I_{DC}/I_{MAX}/G_I$
YA	DC Yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{DC})/P_{MAX}$
YF	AC Yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{AC})/P_{MAX}$
PF	Performance Factor (DC)		0~1.4	=YA/YR
PR	Performance Ratio (AC)		0~1.4	=YF/YR

Table 3: Important normalized parameters

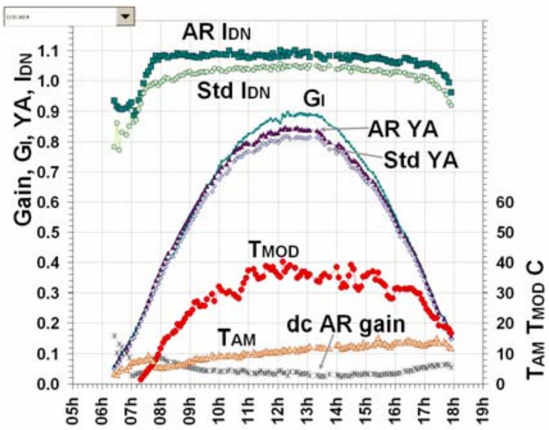

Figure 4: Daily DC performance of 231 module AR array and 231 module standard array.

A similar set of curves can be generated for the AC performance parameters. Figure 5 shows the output of 14 Sunny Boy inverters each of which is hooked to three strings of 11 modules. The difference in these curves is not as easy to see as the DC curves, but close examination shows that for the AR coated glass modules the Performance Ratio is 3 to 8% higher all day and that the AC Yield YF peaks at a higher value.

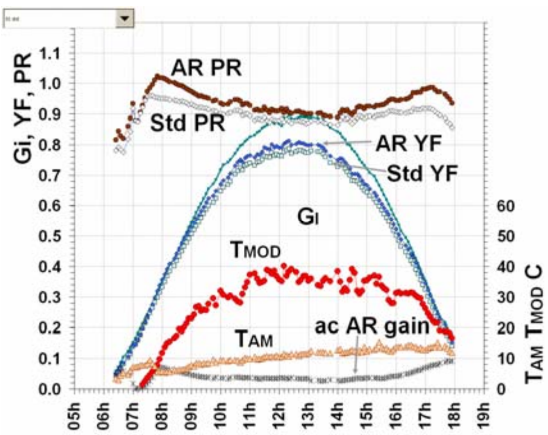

Figure 5: Daily AC performance of 231 module AR array and 231 module standard array.

By comparing the output of each of the strings over time we can determine how much additional energy the AR coated strings produce. Figure 6 shows the AC yield and performance ratio for each of the 14 inverter (each with 3 strings) for 1-Apr to 25-May, 2005. Clearly the inverters with AR coated modules produced more energy during this time period. Summing the results for the whole time period, the array with AR coated modules produced 4.2% more energy than the array with the standard glass modules. This 4.2% gain should be compared to the 2.4% power increase measured at STC on the simulator (See Table 2). So the AR coating must be more effective at reducing the amount of reflected light under conditions other than those used for the STC tests.

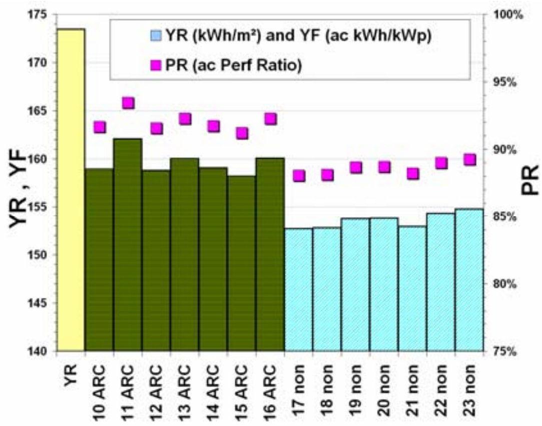

Figure 6: Insolation YR, AC Yield and Performance Ratio for each string for 1 April to 25 May, 2005.

Figure 7 is a plot of AC Power Gain = [PR AR coated strings/PR standard strings] plotted as a function of plane of array irradiance using all of the data from April 1 to May 10, 2005. There is clearly a large amount of scatter in the data particularly at low irradiance levels. The scatter appears to be due to the fact that low irradiances can result from either cloudy conditions during the middle of the day or from sunny conditions at high angles of incidence during morning and evening. To verify this, Figure 8 was plotted for the same variables, but using only data from the two hours before and after solar noon. The scatter is dramatically reduced and two distinct clumps of cloudy and clear data can be seen.

From Figure 8 it is clear that the AR coated strings resulted in a higher AC Power. At high irradiances the ac power gain is around 3%, slightly higher than the 2.4% measured on a simulator (which is only normal incidence radiation, outdoors there is always some diffuse radiation and the direct component is almost always at non normal incidence). At lower irradiances the power gain increases to more than 5%. The tilted plane clearness index is calculated as the ratio of Global tilted plane radiation divided by the extraterrestrial beam radiation that would impinge on the array plane, allowing for the angle between the array and the solar position plus the $1/r^2$ dependence on beam radiation with the earth-sun distance.

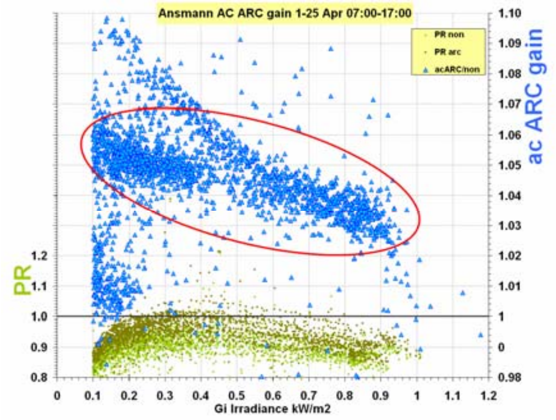

Figure 7: AC Power gain for AR coated glass versus plane of array irradiance using all data from April 1 to May 10, 2005.

Figure 9 shows the difference between AR coating gain at low clearness (i.e. cloudy) and high clearness (i.e. sunny) conditions. At low clearness the Irradiance doesn't rise above 0.5kW/m^2 and the AR gain is quite flat at 5%. At high clearness the gain falls from about 7% at low irradiance (i.e. early morning or late afternoon) and falls to around 3% at highest irradiance (i.e. a bright noon).
Lowest clearness and Intermediate clearness show more scatter. Most of the highest clearness points are near where the angle of incidence (AOI) is nearly normal. This data clearly shows that the AR coated glass produces a greater efficiency gain for higher incidence angles for both diffuse and direct light.

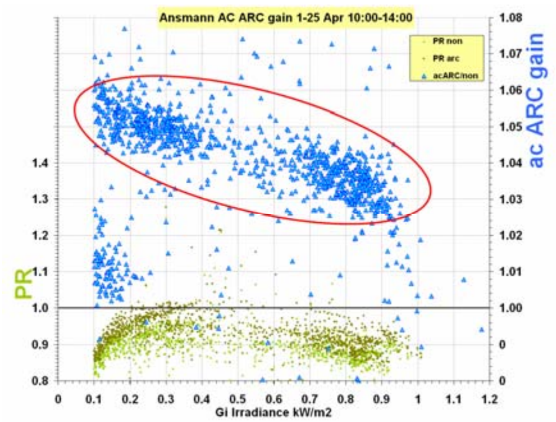

Figure 8: AC Power gain for AR coated glass versus plane of array irradiance using the data from for 2 hours before and after noon from April 1 to May 10, 2005.

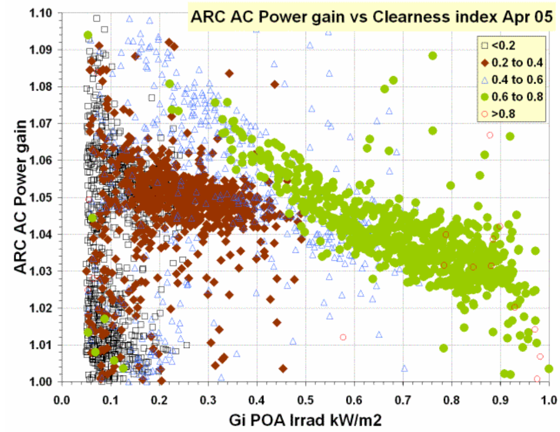

Figure 9: AR coated glass power gain versus clearness index.

4 SUMMARY

Dip coated AR glass resulted in significant (2.4 to 3%) increases in STC power output. Outdoors these modules are producing in excess of 4% more energy. The difference in performance is due to the coating reducing the amount of reflected light at non normal incidence.

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