4% HIGHER ENERGY CONVERSION FROM BP 7180 MODULES

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ABSTRACT

BP Solar have previously studied [1,2] Anti-reflective (AR) coated glass from several different manufacturers under extensive accelerated environmental testing and found a 2.4 to 3.0% increase in output power at STC (Standard Test conditions) for both BP Saturn 7-Series (Saturn mono-) and BP Poly 3-Series (multi-) crystalline silicon PV modules [3].

The AR coating changes the front surface reflection in a manner which is both Angle of Incidence (AOI) and wavelength dependent and thus the outdoor gain will depend on the prevailing meteorological conditions.

Pairs of modules were monitored at ISET[4], Germany and Homebush, Australia to prove >4% energy gain over a year. Subsequently two 41.5 kWp nominal arrays identical except for the type of glass used were installed in April 2005 in Germany and monitored for 13 months (shown in figure 1).

At high irradiances near noon the AC power gain of the installed system is around 3%, rising to 5% under diffuse light and >8% on a bright early morning / late afternoon.

In total the array with AR coated glass has produced an average of 4% more energy than the array with standard glass over the 13 months of monitoring.

Keywords: Modelling, Energy Rating, Anti reflection

Figure 1: Panoramic view of the 83kWp AR vs Control test arrays in Germany

1 INTRODUCTION

Anti-reflective coatings on the outer glass surface can increase the coupling of light into a photovoltaic (PV) module and therefore increase its conversion efficiency.

AR and control modules have been installed in two otherwise identical 41.5 kWp nominal systems in Germany shown in figure 1. The performance of the two systems was monitored continuously from April 2005 to April 2006 by activ solar energietechnik GmbH [5] to determine the energy production of each over an extended period of time.

A model was developed to predict the AR gain under different weather conditions including solar to module angle of incidence and direct:diffuse ratios.

2 ANTI REFLECTIVE COATINGS

ARC on glass can be produced by surface coatings, surface etching or surface texturization.

The outer layer of a solar module whether it be glass, plastic or resin will partially reflect incident light due to the difference in refractive index n between the covering (n2 glass ~ 1.56) and air (n1 ~ 1.003). This reflection is both wavelength and angle of incidence dependent.

For near normal incidence

$$R = [(n1 - n2)/(n1 + n2)]^2 \qquad \text{<1>}$$

where the refractive indices will be somewhat wavelength dependent, this gives R=4.7% for the values above. This reflection increases at incident angles away from normal.

In optical devices such as telescopes and camera lenses thin film AR coatings are often applied to minimise this loss. Optimum performance is obtained from quarter wavelength coatings with a refractive index n = (n1 * n2)$^{1/2}$ as then the reflected wave will be half a wavelength out of phase with the input and will destructively interfere.

However in solar modules not only are they designed to capture light from a wide range of wavelengths (typically 300 to 1200 nm for c-Si, usually less for thin films) but most of the incident light comes also from non normal incidence meaning the effective film thickness will appear higher by 1/cos(angle of incidence).

On bright days much of the light comes directly from the sun (the direct beam radiation Bn is defined as the irradiance coming from the angle of the centre of the sun ± 2.5°) but there is also light scattered from clouds, atmospheric particles and the surroundings which make up the diffuse component D (i.e. radiation not coming directly from the angle of the sun).

At the site two important irradiance values that can be measured with horizontal sensors are

- Global horizontal irradiance Gh (figure 2 left)
- Diffuse horizontal irradiance Dh (figure 2 right where the sun's image on the detector is shaded)
-

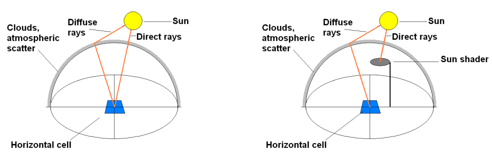

Figure 2 (left): Measuring Gh Global horizontal irradiance capturing direct and diffuse rays.
(right): Measuring Dh diffuse horizontal radiance by using a tracked shader to stop the direct rays hitting the cell.

By definition
Bh (Beam horizontal irradiance) = Gh – Dh <2>
and
Bn (Beam normal irradiance) =
Bh / sin (Zenith angle) <3>

The beam fraction BF is defined as the proportion of beam/global radiation incident on the horizontal plane as
BF = Bh / Gh <4>

This can be as low as 0.1 for a very overcast measurement or as high as 0.8 for a very bright one (some authors instead refer to the Diffuse fraction DF = 1 – BF).

A model has been developed to study the ARC gain from a single thin film coating on a substrate, the input screen is shown in figure 3 where the refractive indices and thickness of the film and glass are entered, then the beam fraction and angle of incidence to be studied are chosen.

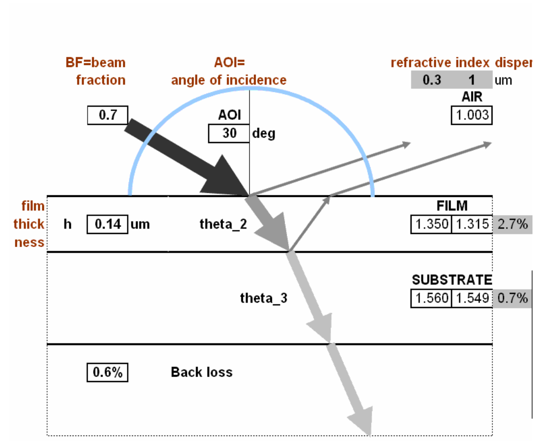

Figure 3: Input screen for the single layer ARC model

Figure 4 gives the modelled reflection loss versus incidence angle at AM1.5 from a control sample and one with an AR coating. It can be seen that near normal reflectivity has been reduced from around 4.5 to 1.9%, the reflectance rising rapidly as the Angle of Incidence increases.

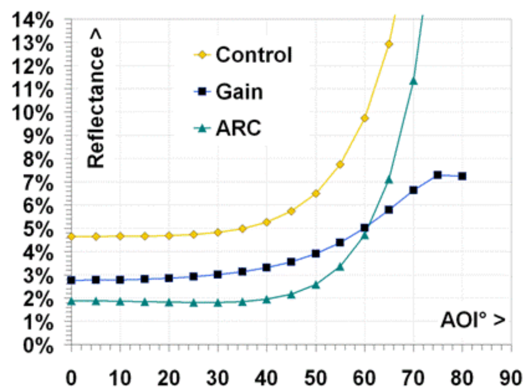

Figure 4: Reflection loss predicted by model for AR and control glass versus Angle of incidence.

Figure 5 illustrates the measured transmission loss at normal incidence from a control sample and one with an AR coating vs wavelength and includes the AM1.5 spectrum. In this example there was approximately a 5% gain over the useful wavelengths (approximately 0.35 to 1.1um for c-Si).Note that a transmission measurement may give a slightly different AR Gain as the glass-cell interface is not present.

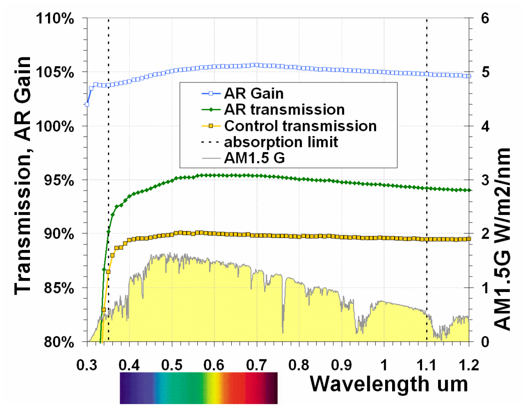

Figure 5: Transmission loss and Transmission Gain for ARC vs Control modules against AM1.5G spectrum.

As solar modules receive light from different angles (Beam + Diffuse) the model analyses the expected gain as functions of Beam Fraction (Beam/Global) and Solar Angle of incidence. The model shows in Figure 6 around 5% under totally diffuse conditions (BF=0), around 2.5% under the flashed simulator conditions (BF=1 and AOI=0°) and >8% under grazing angles of incidence for high beam fractions (although rarely will there be much irradiant energy at beam fractions >0.7 and AOI >60°).

While it might appear beneficial to have higher AOI values (perhaps by tilting the modules away from the sun) then the total incident radiation would fall so it is better to align the modules optimally for maximum irradiance and then have a slightly lower AR gain added to this high value.

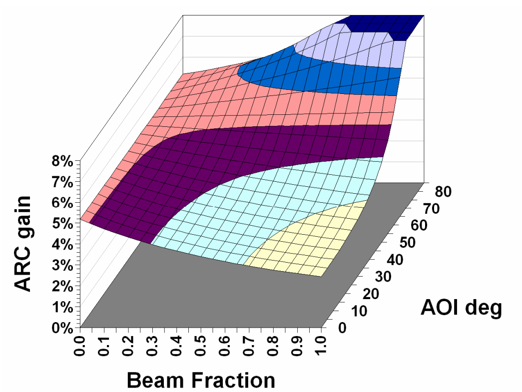

Figure 6: Predicted AR gain vs Beam Fraction and Angle of Incidence.

3 INITIAL TEST MODULES

3.1 Approach

In the initial tests full sized modules, with 72 (12.5 by 12.5 cm) cells, were fabricated using the 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.

3.2 STC Results on test modules

The electrical results for the 3 series screen print multi and 7 series LGBC mono are given in Table 1. Power gains of 2.5 to 3% on the flash tester with direct radiation at 0° angle of incidence 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 3160	**Control**	43.4	4.96	**156.3**
	AR	43.5	5.10	**160.5**
	Δ	0.2%	2.8%	**2.7%**
LGBC Mono-Si 7180	**Control**	43.9	5.52	**180.4**
	AR	44.0	5.62	**184.9**
	Δ	0.2%	1.8%	**2.5%**

Table 1: Laboratory results for AR coated glass vs Control

3.3 Environmental testing

Modules made using the coated AR glass have been subjected to BP Solar's extended version of the IEC 61215 [3] test sequence. The test sequence included

- 500 thermal cycles from -40 °C to +85 °C
- 1250h damp heat at 85 °C at 85% relative humidity
- combined UV/50 thermal cycles/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.

3.4 Outdoor measurements of test modules.

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 7 shows a plot of normalised dc current Idn (see table 4) and AR gain versus time for 1 year of BP-7180 Saturn monocrystalline modules installed at ISET in Germany. (Similar results were obtained in Sydney although there the horizontal Global and Diffuse irradiances weren't measured so most of the detailed studies have been performed on ISET modules). The variability in current is due to dirt and other weather related effects. The current was used to study the ARC effect as although it would have been better to have calculated the power, this also depends on temperature compensation. The voltages of the ARC modules are always similar to the controls.

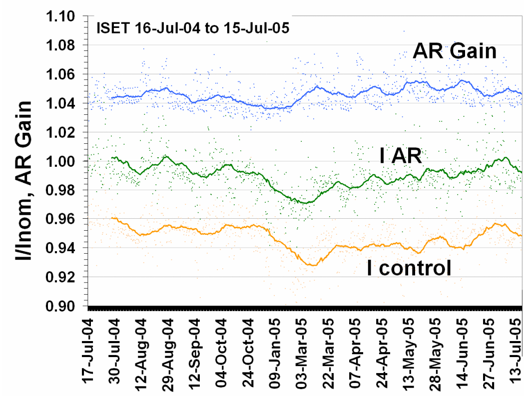

Figure 7: Normalised DC Current Idn for 7180AR and Control and current gain versus time (July-04 to July-05) for AR coated glass in Germany for irradiances > 200 W/m^2

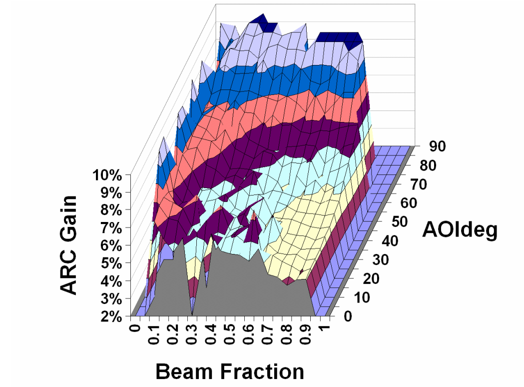

Figure 8: Measured AR gain vs Beam Fraction and Angle of Incidence for BP7180 at ISET 2004-2005. (Note the slightly higher measured gain than predicted due to a 1 module sample).

Figure 8 shows the ARC gain between these 7180 modules versus beam fraction and angle of incidence (and should be compared with the modelled data in Figure 6).

Because we are only measuring one module of each type there will be some small random fluctuations on the module Isc due to the natural variability from the production line (whereas in the pilot run described later several hundred modules of each type were made).

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.

Figure 9 shows the good performance of the BP 7180 under all six measured conditions at ISET for 1 year, comments on each graphic are in table 2.

The blue dots show 23000 x 10 minute averaged measurement points, the red lines give a cubic best fit and the yellow histograms show the amount of insolation energy in each bin for six parameters listed A to F on the x axis .

Figure 9: BP 7180 efficiency (top) and proportion of insolation (bottom) measured at ISET for 1 year.

	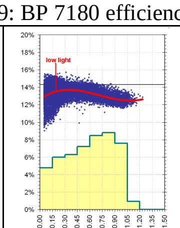	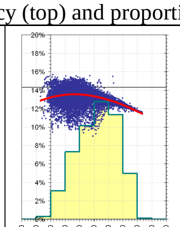	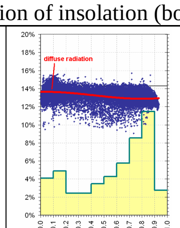	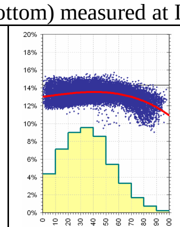	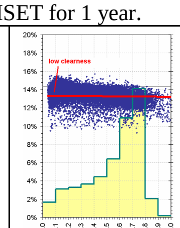	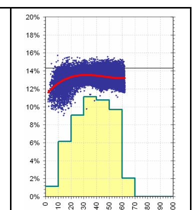
x-axis	A Irradiance (kW/m²)	B Tmodule (C)	C Beam Fraction (beam/global)	D Angle of Incidence (°)	E Clearness Index (global/extraterrestrial horizontal)	F Solar height (°)
comment	Very high efficiency even under low irradiance (left)	Only a small drop at high module temperature (right) when the proportion of energy is small	Very high efficiency even under high diffuse (left)	Small drop at high angle of incidence (right) only when the proportion of energy is small	Very high efficiency even under low clearness (left)	Small drop at low solar height (left) only when the proportion of energy is small

Table 2: Comments on each graphic in figure 9

Important points to note are

- The Module temperature (B) is very rarely more than 60C in ISET
- Module efficiency is high (>13%) even under low light (A), high diffuse light (C) and low clearness (E).
- Histograms show there is more energy available at high light levels (A), high diffuse light (C) and high clearness (E) than at low values (even in Kassel, Germany).

Based on all these results a larger size pilot run was conducted.

4 PILOT RUN

4.1 Pilot run module production

In order to further evaluate the performance of AR coated glass, a pilot run was conducted building more than 460 modules each 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
- 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 results of the pilot run are given in Table 3. 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	**183.7**
Δ	0.2%	2.2%	**2.4%**

Table 3: Cell results from the AR glass pilot run

Figure 10 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 i.e. around 4Wp.

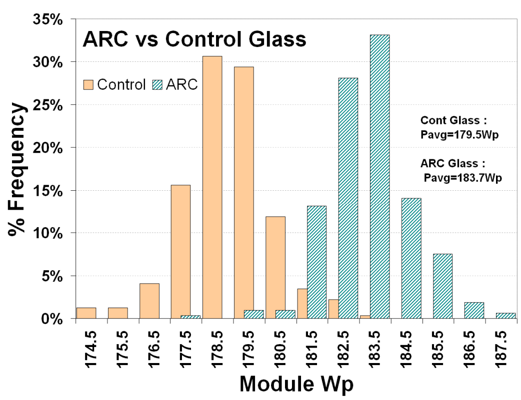

Figure 10: Distribution of module power from the AR pilot run

4.2 Outdoor Array

The pilot run modules were installed on the roof of a building in Assamstadt, Germany. The two arrays are tilted at 20° (this is less than optimal as the arrays were required to be close together for maximum power yet not to shade each other). They were oriented almost due south and suffer very little shading from trees or buildings.

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 11. The difference in reflection can clearly be seen in the picture.

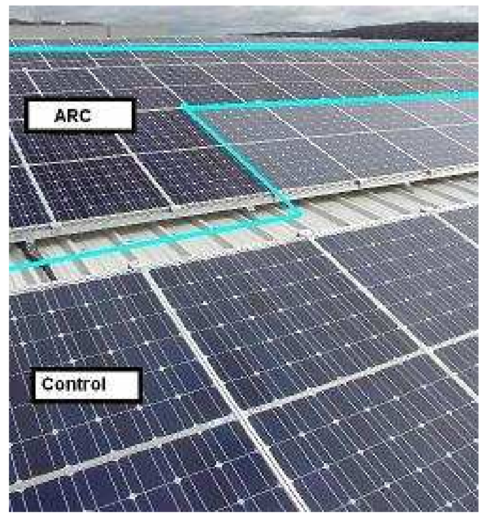

Figure 11: Picture of test arrays in Germany. Back and left centre rows of darker modules have AR glass. The remainder have standard glass.

The Sunny Boy Control system takes measurements every 5 minutes of the following variables of each of the 42 strings; the AC Energy and Power of each of the 14 inverters.:

1. Date and time
2. Tilted Plane Irradiance from reference cell Gi
3. Ambient Temperature Tam
4. Module Temperature (one) Tm
5. Wind Speed from anemometer WS
6. DC string voltage (42 substrings) Vdc
7. DC Power (42 substrings) Pdc
8. AC Power (14 strings) Pac

From the data set we calculate normalised parameters as given in Table 4 as functions of date/time, irradiance and temperature. (See also IEC 61724)

Symbol	Name	Units	Extreme 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	Plane of array Insolation	kWh/m²	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 4: Some normalised measurement parameters and their definitions

Figure 12 shows the Performance Ratio of the AR vs Control arrays on a typical sunny day. It can be seen that for the AR coated glass modules the Performance Ratio is higher all day, particularly early morning and late afternoon when the irradiance is low and the AOI high.

The AR gain varies from ~3% at noon (high beam fraction and low angle of incidence) to around 8% at the beginning and end of the day (high beam fraction and high angle of incidence).

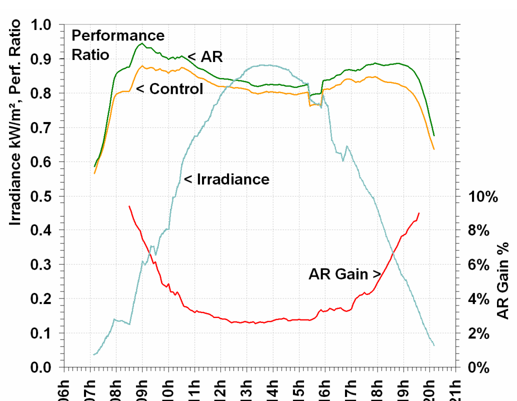

Figure 12: Typical sunny day AC performance of the AR vs Control arrays.

Figure 13 shows the average daily AC energy gain of the AR array over the control array and also the daily insolation in kWh/m²/d. There was an unusually bad winter in Germany with low temperatures meaning there was intermittent snow on the modules from November 05 to March 06 which explains the erratic AR gain, some days all the snow melted in the afternoon, at other times there was snow on parts of the array only.

After all the snow had melted instantaneous measurements showed AR gains of usually > 4%.

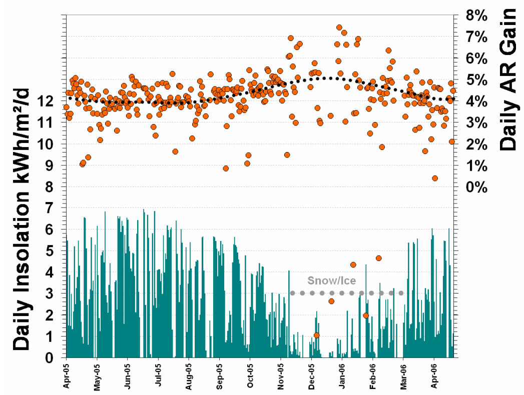

Figure 13: Daily AR gain (right y-axis) of about 4-5% for the AR modules vs the controls, also showing the Insolation in kWh/m²/d (left y-axis).

Figure 14 shows how all of the 7 inverters from the ARC strings (#10-16) had better performance than the 7 from the control modules (#17-23) indicating that this gain is due to the modules and not just due to different inverters. Inverter #13 failed and was not replaced for 3 months Dec-05 to Feb-06, its kWh during that period has been interpolated as the average of the other 6 working AR inverters.

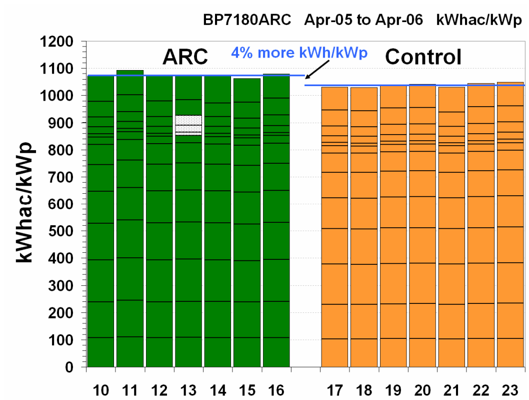

Figure 14: Monthly cumulative kWhac/kWp gain of about 4% from Apr-05 (bottom) to Apr-06 (top) for the 7 x AR inverters (left) vs the 7 x controls (right).

5 PRODUCTION

Due to these good results on the test modules and pilot run the whole of the production of the BP 7 series modules in Tres Cantos, Madrid was changed to AR glass during 2005.

Figure 15 shows the average daily performance of cells and modules from BP Solar's Tres Cantos factory. Small oscillations in the cell efficiency can be seen, partly due to different quality incoming wafers and small drifts in the processing conditions but a step jump of around 3% is seen when the AR glass was introduced as standard.

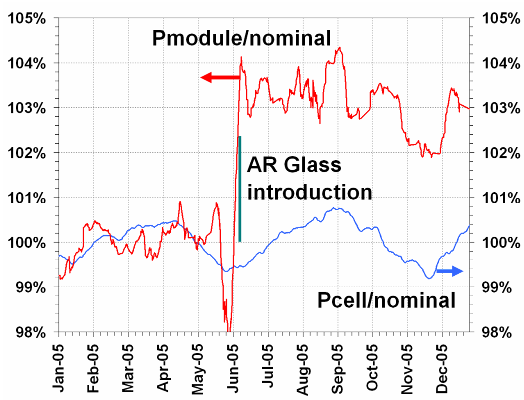

Figure 15: Average daily cell efficiency (lower line) and Module power (upper line) for Tres Cantos plant during 2005.

6 CONCLUSIONS

- BP Solar have extensively studied Anti-reflective (AR) coated glass from several different manufacturers.
- The best manufacturers gave 2.4 to 3.0% increase in output power at STC.
- Because the AR coating changes the reflection in both Angle of Incidence (AOI) and wavelength dependent the outdoor gain on a test array was higher at 4% in Germany.
- AR was introduced as standard on BP Solar 7 series Saturn modules in 2005

7 ACKNOWLEDGEMENTS

Peter Funtan ISET Kassel [4], André Pohl activ solar [5] Germany, Stephen Poropat BP Solar Australia, Ruperto Gomez & Richard Russel at BP Solar Madrid and other staff at BP Solar worldwide.

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