Module Characterization

Angle of Incidence Response of First Solar Modules

This document provides supplemental information about the response of the First Solar FS Series Modules to incident light at different angles. The data is intended to support the proper design of systems using modules with and without anti-reflective coatings (ARC) as well as the development of more accurate models for energy prediction. All data reported in this document is the result of consolidation of multiple characterization studies made on individual modules within the First Solar product family. These studies were performed by First Solar and PV Evolution Labs ("PVEL").

First Solar modules with ARC are indicated in the product name by an "A" descriptor. For example, a module labeled FS-497A would include ARC while an FS-497 would not. The benefits of ARC are twofold. First, the efficiency at normal incidence increases. Part of the increase in efficiency seen in STC flash tests can be attributed to this, which translates directly to an increase in the nameplate rating of the module. Because the bin class of the module reflects the normal incidence benefit of ARC, this benefit does not need to be accounted for in an energy prediction, except through the choice of module bin class.

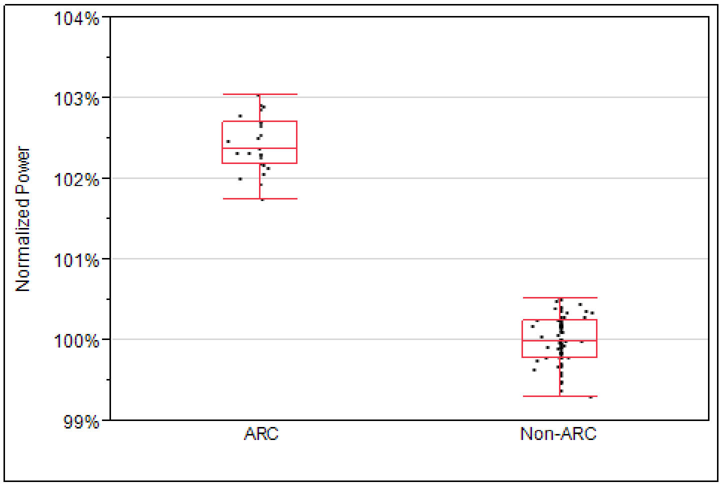

Figure 1. Distribution of P_{mp} at normal incidence for modules with and without ARC. An average P_{mp} increase of 2.4% is measured.

The second benefit of ARC is the increase in light transmissivity at non-normal incidence angles. This benefit needs to be explicitly accounted for in energy predictions in order to accurately reflect the module energy output. The short circuit current (I_{sc}) of multiple First Solar modules with and without ARC is characterized at varying angles of incidence. When these results are normalized to the Isc at Standard Test Conditions (1000 W/m^2 total irradiance with AM1.5 global spectrum and 25°C module temperature) and for cosine irradiance losses, the relative short circuit current as a function of angle-of-incidence can be determined as shown in Figure 1. For brevity, the relative short circuit current will be termed the "IAM" (Incident Angle Modifier).

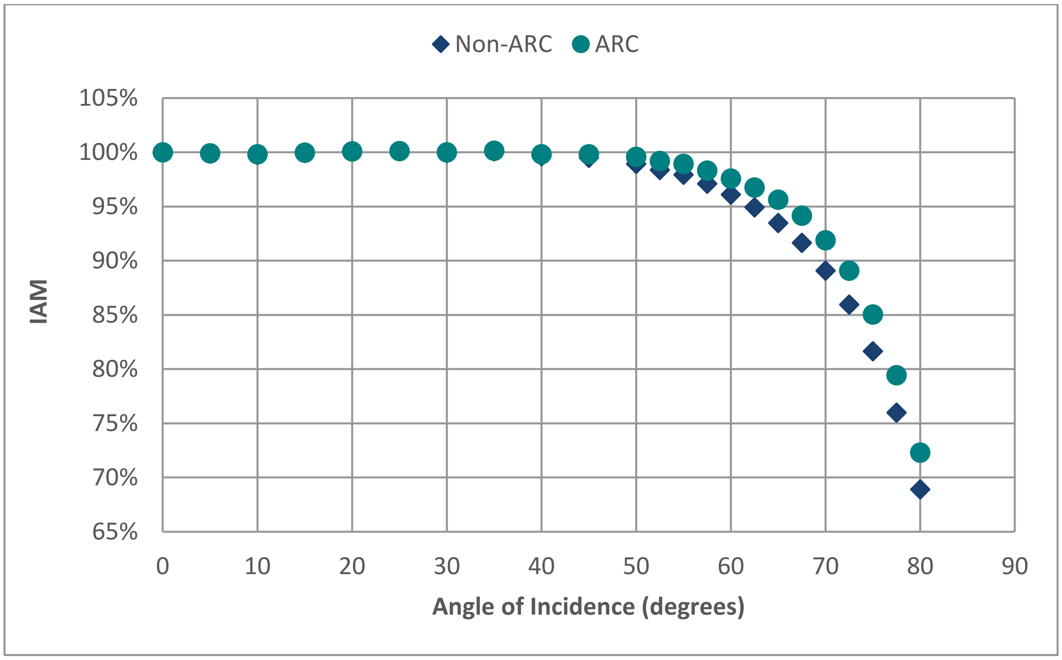

Figure 1. Measured I_{sc} relative to Isc at normal incidence for First Solar modules with and without ARC.

Historically, the ASHRAE model has been used in prediction models to estimate the IAM response of PV modules. This model is the default in PVsyst and First Solar has previously recommended a b_o value of 0.05 to match standard (non-ARC) glass response.

$$IAM = 1 - \frac{b_o}{\cos(AOI) - 1}$$

With the release of ARC, it was recognized that the ASHRAE model does not provide the necessary precision to fully capture the difference in the IAM responses of standard glass modules and modules with ARC. We found that the Sandia IAM response model is a more accurate functional representation of IAM losses:

$$\text{IAM} = C_0 + C_1 AOI + C_2 AOI^2 + C_3 AOI^3 + C_4 AOI^4 + C_5 AOI^5$$

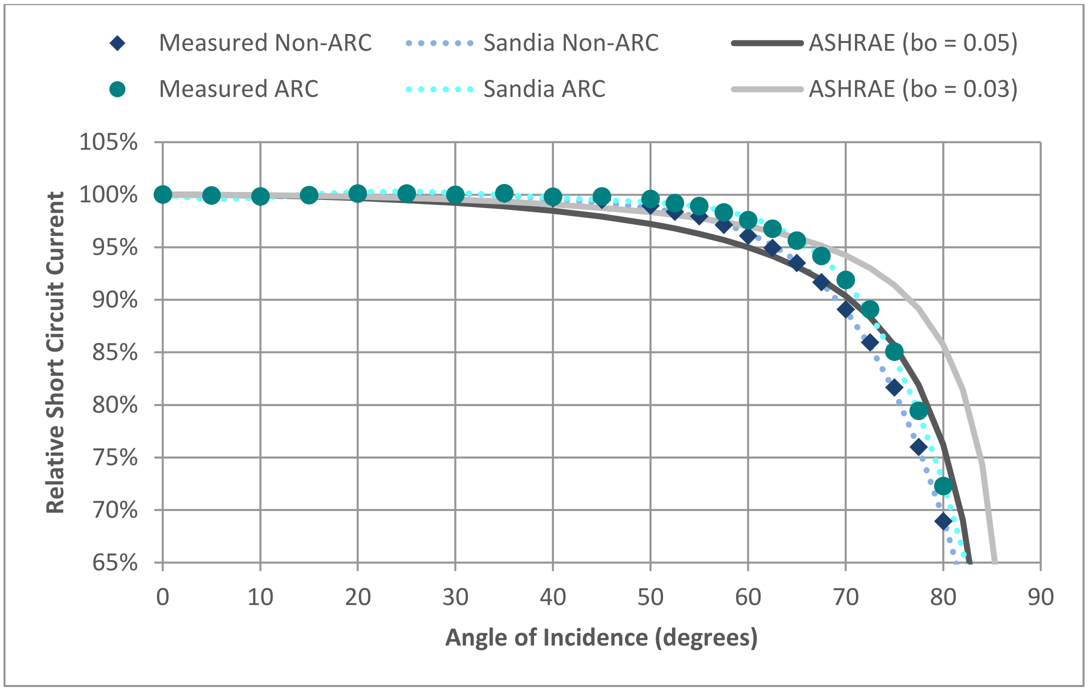

Figure 2. Measured Isc relative to Isc at normal incidence for First Solar modules without ARC shown with the ASHRAE and Sandia IAM response models.

With the release of ARC, First Solar's prediction guidance changed to ensure that users fully capture the response of modules both with ARC and standard glass. For software tools which allow a custom IAM function or include the Sandia IAM model, we recommend use of the Sandia model for both ARC and standard glass modules. For PVsyst, we recommend use of tabulated values for both ARC and standard glass modules. PAN files provided by First Solar after May 2014 which are used in PVsyst V6.0 and later include these tabulated values and the user therefore does not need to enter them into PVsyst. In PVsyst V5 and earlier, we recommend inputting tabulated values into the Detailed Losses dialogue box. These recommendations are summarized in Table 1.

Table 1. Recommended prediction inputs for PVsyst and other user defined toolsets for modules with and without ARC.

<table>
<tr><th>Module Type</th><th>User Defined Toolset (i.e., Isis)</th><th>PVsyst V6</th><th>PVsyst V5 and earlier</th></tr>
<tr>
<td>with ARC
(i.e. FS-4XXXA, FS-4XXXA-2, FS-4XXXA-3)</td>
<td>Sandia Model
(5th-order polynomial)

C_0 = 1.0000E+00
C_1 = -1.9386E-03
C_2 =2.5854E-04
C_3 = -1.1229E-05
C_4 = 1.9962E-07
C_5 =-1.2818E-09</td>
<td>Included in May 2014 and later manufacturer PAN file
<table>
<tr><th>AOI</th><th>IAM</th></tr>
<tr><td>0</td><td>1.00</td></tr>
<tr><td>30</td><td>1.00</td></tr>
<tr><td>55</td><td>0.99</td></tr>
<tr><td>60</td><td>0.98</td></tr>
<tr><td>65</td><td>0.96</td></tr>
<tr><td>70</td><td>0.92</td></tr>
<tr><td>75</td><td>0.85</td></tr>
<tr><td>80</td><td>0.72</td></tr>
<tr><td>90</td><td>0.00</td></tr>
</table></td>
<td>User input into Detailed Losses dialogue box
<table>
<tr><th>AOI</th><th>IAM</th></tr>
<tr><td>0</td><td>1.00</td></tr>
<tr><td>30</td><td>1.00</td></tr>
<tr><td>55</td><td>0.99</td></tr>
<tr><td>60</td><td>0.98</td></tr>
<tr><td>65</td><td>0.96</td></tr>
<tr><td>70</td><td>0.92</td></tr>
<tr><td>75</td><td>0.85</td></tr>
<tr><td>80</td><td>0.72</td></tr>
<tr><td>90</td><td>0.00</td></tr>
</table></td>
</tr>
<tr>
<td>without ARC
(i.e. FS-4XXX, FS-4XXX-2, FS-4XXX-3)</td>
<td>Sandia Model
(5th-order polynomial)

C_0 = 1.0000E+00
C_1 = -1.6754E-03
C_2 = 2.1896E-04
C_3 = -9.3467E-06
C_4 = 1.6452E-07
C_5 = -1.0767E-09</td>
<td>Included in May 2014 and later manufacturer PAN file
<table>
<tr><th>AOI</th><th>IAM</th></tr>
<tr><td>0</td><td>1.00</td></tr>
<tr><td>30</td><td>1.00</td></tr>
<tr><td>50</td><td>0.99</td></tr>
<tr><td>60</td><td>0.96</td></tr>
<tr><td>65</td><td>0.94</td></tr>
<tr><td>70</td><td>0.89</td></tr>
<tr><td>75</td><td>0.82</td></tr>
<tr><td>80</td><td>0.69</td></tr>
<tr><td>90</td><td>0.00</td></tr>
</table></td>
<td>User input into Detailed Losses dialogue box
<table>
<tr><th>AOI</th><th>IAM</th></tr>
<tr><td>0</td><td>1.00</td></tr>
<tr><td>30</td><td>1.00</td></tr>
<tr><td>50</td><td>0.99</td></tr>
<tr><td>60</td><td>0.96</td></tr>
<tr><td>65</td><td>0.94</td></tr>
<tr><td>70</td><td>0.89</td></tr>
<tr><td>75</td><td>0.82</td></tr>
<tr><td>80</td><td>0.69</td></tr>
<tr><td>90</td><td>0.00</td></tr>
</table></td>
</tr>
</table>

Evaluation of FS Series PV modules across all rated power bins has shown strong performance consistency for the entire series with minor variation from module to module. Limited variation from module to module is normal and is to be expected when comparing measured results to actual field performance.