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Incident Angle Modifier (IAM) Round Robin Updates

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Outline

• Incident angle modifier (IAM)
  – Theory and measurement procedure
• IAM round robin history
• Results
  – High level
  – Delta to Fresnel
  – Model fitting
  – Impact on energy rating (IEC 61853)
• Conclusions
The Incidence Angle Modifier (IAM)

- When a PV device is not positioned normal to the sun, a loss of effective irradiance occurs due to \textit{geometry} and \textit{reflection}.
- Geometrical effect (Lambert Cosine Law)
  - Reduction of irradiance is proportional to \text{cosine}(\text{AOI}).

\begin{align*}
\text{Normal Incidence} \\
\text{AOI (}\theta\text{)} &= 0^\circ \\
\text{Non-normal Incidence} \\
\text{AOI (}\theta\text{)} &> 0^\circ \\
A2 &= A1 \times \text{cos}(\theta)
\end{align*}
The Incidence Angle Modifier (IAM)

- The IAM normalizes the cosine effect to isolate reflection losses.
- IAM is obtained by measuring short circuit current ($I_{SC}$) over a range of AOIs ($\theta$).
  - Normalized to the $I_{SC}$ measured at normal incidence (AOI = 0).
  - Indoor and outdoor test procedures are stipulated in IEC 61853-2:2016

\[
IAM(\theta) = \frac{I_{SC}(\theta)}{\cos(\theta) \cdot I_{SC}(0^\circ)} = \frac{\text{Beam irradi. received by PV Device}}{\text{Total beam irradi. available to PV Device}}
\]

![Graph showing IAM values and typical PV response](image-url)
International IAM Round-Robin Recap

The results from 8 European labs showed:

- Five of eight labs were comparable w/in their stated $U_C$ out to $\pm 80^\circ$ AOI [1].

- IAM measurements at $\pm 85^\circ$ AOI are challenging!
  - 75% range + low comparability w/in $U_C$.

- Two labs w/ suspect measurements due to:
  - Misalignment of DUT w/ axis of rotation.
  - Excessive reflections w/in the test bed.

- Samples w/ identical BoM were sent to these two labs for retest.
  - The two suspect IAM profiles from these labs are not included in this presentation.
  - 1 available retest dataset is presented instead.

International IAM Round-Robin Recap

• In Jan. ’19 the DUTs were shipped to the US.

• Only 1 of 8 European labs performed the IAM measurements outdoors.
  • Comparability of methods?

• 3 of 4 US labs performing the IAM test outdoors.
  • 2 labs have yet to measure the DUTs.

• Labs are asked to measure from ±85° in 5° steps.

• Labs asked to report:
  – IAM for each angle of incidence (AOI) θ
  – $U_C (k=2)$ of IAM(θ)
  • Only 7 of 10 labs provided $U_C$
Devices Under Test (DUTs)

• Common characteristics among all DUTs:
  – Cell size: 156 mm x 156 mm
  – Glass: 3.2 mm thick, finely textured PV glass
    ▪ **No anti-reflective coating (ARC)**
  – Encapsulant: ethylene-vinyl acetate (EVA)
  – The glass edges were covered with tape

• Three different cell surface textures
  1. Standard mono-silicon (**Mono-si**)
  2. mc-Si black silicon textured under reactive ion etch (RIE) treatment (**Black-Si A**)
  3. mc-Si black silicon textured under atmospheric pressure dry etching (ADE) treatment (**Black-Si B**)

All DUTs have the same glass, so the IAM measurements [not surprisingly] show little difference.

**Only the measurements of the Mono-Si sample will be presented here.**
Participating Laboratory Measurement Systems

- Five unique light sources.
- Light sources represent different illumination levels and spectral distributions.
- Various approaches for rotating the DUTs.
  - From single cells -> mini modules -> full-sized modules.
- Two labs w/ outdoor test systems remain to measure the DUTs (end of summer ‘19?).
- Labs have been assigned anonymous ID#s

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Automated Rotation Stage</th>
<th>Manual Rotation Stage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe Flash (Pasan)</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Sunlight</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Halogen</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Laser driven Xe plasma</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tuneable laser</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>
Comparing Measurements to Theory

- The following slides will refer to the Fresnel model.
  - This is a simplified approach to calculating the IAM using Snell’s law and the Fresnel equations [2].
- For the single slab model (no ARC) $n_2 = 1.523$.
- For the two slab model (ARC) $n_2 = 1.3$ and $n_3 = 1.523$.
- Unpolarized light (50% p-polarized, 50% s-polarized).

\[ \text{Spectral dependence of refractive index } n \text{ of soda lime glass [3]} \]

\[ \begin{align*}
\Theta_{1,(i)} & \quad \text{normal} \\
N_1 &= 1 \\
N_2 &= 1.523 \\
\Theta_{2,(t)} & \\
\text{Single slab model (glass w/ no ARC)}
\end{align*} \]

\[ \begin{align*}
\Theta_{1,(i)} & \quad \text{normal} \\
N_1 &= 1 \\
N_2 &= 1.3 \\
N_3 &= 1.523 \\
\Theta_{3,(t)} & \\
\text{Two slab model (glass w/ ARC)}
\end{align*} \]

Results – All Labs

- 8 of 9 labs show IAM differences of < 2% at ±80°
  - (Symmetry requirement of IEC 61853-2)

- Lab No. 1 shows IAM symmetry of 2.3% at ±80°

- If Lab 1’s measurement at 85° AOI is excluded:
  - The measurement range at 85° decreases from 40% to 10%.

Results from the Mono-Si sample.
Results – Delta to Fresnel Model w/o ARC

\[ \Delta = (IAM(\theta)_{lab} - IAM(\theta)_{Fresnel}) \cdot 100 \]

- Median IAM(\theta) shows agreement within \( \pm 1\% \) of Fresnel no ARC model out to 75° AOI.
Results – Delta to Median by Test Location

\[ \Delta = (IAM(\theta)_{lab} - IAM(\theta)_{RR\,Median}) \cdot 100 \]

- IAM results not dependent on test location (i.e. indoor vs. outdoor).
- ‘Outdoor 2’ IAM measurements tend to follow Fresnel ARC model.
Results – Delta to Median by Light Source

\[ \Delta = (IAM(\theta)_{lab} - IAM(\theta)_{RR Median}) \cdot 100 \]

- IAM results not dependent on light source used.
- 5 Xe Flash systems show no clear tendency toward agreement with a particular Fresnel model.
Angular Loss Models

1. **ASHRAE**
   - Single parameter \(b_0\)

2. **Martin and Ruiz**
   - Single parameter \(a_r\)

3. **Sandia**
   - 5th order polynomial fit (5 coefficients)

4. **Physical model (DeSoto)**
   - Based on Snell’s and Bougher’s laws.
   - Two coefficients \((K\) and \(L\))

\[
IAM(\theta) = 1 - b_0 \left( \frac{1}{\cos \theta} - 1 \right)
\]

\[
IAM(\theta) = \frac{1 - \exp(\cos \theta/a_r)}{1 - \exp(-1/a_r)}
\]

\[
IAM(\theta) = e^{-\frac{KL}{\cos \theta_r}} \left[ 1 - \frac{1}{2} \left( \frac{\sin^2 \theta_r - \theta}{\sin^2 \theta_r + \theta} + \frac{\tan^2 \theta_r - \theta}{\tan^2 \theta_r + \theta} \right) \right]
\]

\[
e^{-K} \left[ 1 - \left( \frac{1 - n}{1 + n} \right)^2 \right]
\]

\[
\theta_r = \sin^{-1}\left( \frac{1}{n} \sin \theta \right), n = 1.523
\]

Model coefficients are extracted from the measured IAM data using a Gauss-Newton fitting method.
Model Fitting Results

Coefficients and goodness of fit summary for ASHRAE and Martin & Ruiz models

<table>
<thead>
<tr>
<th>Lab</th>
<th>a_r</th>
<th>b_0</th>
<th>a_r RMSE</th>
<th>b_0 RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.221</td>
<td>0.089</td>
<td>0.073</td>
<td>0.016</td>
</tr>
<tr>
<td>2</td>
<td>0.157</td>
<td>0.056</td>
<td>0.013</td>
<td>0.027</td>
</tr>
<tr>
<td>3</td>
<td>0.155</td>
<td>0.053</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>4</td>
<td>0.163</td>
<td>0.058</td>
<td>0.007</td>
<td>0.026</td>
</tr>
<tr>
<td>5</td>
<td>0.169</td>
<td>0.059</td>
<td>0.007</td>
<td>0.028</td>
</tr>
<tr>
<td>6</td>
<td>0.155</td>
<td>0.055</td>
<td>0.013</td>
<td>0.025</td>
</tr>
<tr>
<td>7</td>
<td>0.149</td>
<td>0.052</td>
<td>0.019</td>
<td>0.028</td>
</tr>
<tr>
<td>8</td>
<td>0.165</td>
<td>0.058</td>
<td>0.011</td>
<td>0.027</td>
</tr>
<tr>
<td>9</td>
<td>0.178</td>
<td>0.062</td>
<td>0.008</td>
<td>0.033</td>
</tr>
</tbody>
</table>

- Table shows average $a_r$ and $b_0$ coefficients from the forward (+AOI) and reverse (-AOI) measurement directions.

- Variability chart shows goodness of fit results from fitting 4 models to 9 labs’ measurements of the mono-si sample.
- RMSE from fitting forward and reverse directions shown.
- Orange dots represent Lab Outdoor 1.
IAM U_C Impact on Energy Rating (IEC 61853-3)

- The climate specific energy rating (CSER) was calculated using the IAM data measured by the RR labs and IEC CDV 61853-3 procedures.
- DTU measured spectral response (SR), multi-G (@25°C) and multi-T (@1000 W/m²).
- Assumptions made for U_0 and U_1 based on [4].
  - U_0 = 26 W/m²·K, U_1 = 6 W·s/m³·K
- All calculations done for South facing 20° tilt.

\[
\begin{align*}
\text{Beam}_{AOI,\text{corr}} &= IAM(\theta) \cdot DNI \cdot \cos(\theta) \\
\text{Diff}_{AOI,\text{corr}} &= \int_A IAM(\theta) \cdot \cos(\theta) \, d\omega \\
&= \int_A \cos(\theta) \, d\omega
\end{align*}
\]

\text{Where:}
- \(\omega\) = solid angle of incident diffuse irrad.
- \(A\) = range of \(\omega\) visible to PV

\(\text{Spectral and AOI corrected global irradiance}\)

\(\text{Module temperature}\)

\(\text{Module power output}\)

\(j = 8760?\)

\(\text{Energy energy yield (kWh) and climate specific energy rating}\)

IAM $U_C$ Impact on Energy Rating (IEC 61853-3)

Climate Specific Energy Rating (CSER) = module performance ratio (MPR)

$$CSER = \frac{EY \cdot 1000 \left[ \frac{W}{m^2} \right]}{P_{STC} \cdot H}$$

$EY$ = Annual energy yield [Wh]
$H$ = Annual insolation in array plane [Wh/m²]
$P_{STC}$ = Power at STC [W]

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Lat./Long.</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38° N, 3° W</td>
<td>Mediterranean</td>
</tr>
<tr>
<td>2</td>
<td>48° N, 12° E</td>
<td>Temperate continental</td>
</tr>
<tr>
<td>3</td>
<td>54° N, 24° E</td>
<td>Continental (Central Europe)</td>
</tr>
<tr>
<td>4</td>
<td>56° N, 4° W</td>
<td>Temperate coastal</td>
</tr>
</tbody>
</table>

The four reference climates suggested by [5].

IAM U_{C} Impact on Energy Rating (IEC 61853-3)

When the reported IAM measurements are used to calculate CSER:

- CSER varies by **0.9-1.2%**
  - If lab 1 is excluded
- CSER varies by **2.3-3.5%**
  - If lab 1 is included.

Red dot below lower whisker represents lab 1.
Conclusions

• Improved agreement in IAM measurements compared to 2018 RR results.
  • Retests and filtering of suspect measurement profiles.

• Differences in robust IAM measurements from 8 international laboratories cause ~1% difference in climate specific energy rating.

• Median IAM agrees w/in ±1% of Fresnel model when AOI ≤ 75°
  • The simple Fresnel model can be reasonably used in this range as a sanity check when measuring DUTs with smooth glass.
  • To Do: Calculate angular losses via ray trace simulations w/ ISFH.

• IAM results not dependent on type of measurement system used.
  • Suggests that experience can count for something.
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12PV Evolution Labs (PVEL), Berkeley, CA, USA

Thank you!