Checking the new IEC 61853.1-4 with high quality 3rd party data to benchmark its practical relevance in energy yield prediction

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Checking **IEC 61853 equations and methods vs. GI’s OTF measured data and modelling**
for standards tests, designers, modellers and measurements

<table>
<thead>
<tr>
<th>IEC 61853- <em>Photovoltaic module performance testing and energy rating</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 Ed 1.0 2011 : Irradiance and temperature performance matrix</td>
</tr>
<tr>
<td>-2 Ed 1.0 2016 : Spectral responsivity, incidence angle</td>
</tr>
<tr>
<td>-3 Ed 1.0 2018 : Energy rating</td>
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<td>-4 Ed 1.0 2018 : Climatic profiles</td>
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</table>

**Gantner Instruments’ Outdoor Test Facility (OTF)**

- High quality Meteorological and Electrical PV measurements
- Works with all module technologies and climates
- Good fitting and modelling with GI/SRCL’s Loss factors model (2011) and Mechanistic performance model (2017) (LFM/MPM)
## Comparing IEC 61853 vs. GI’s OTF testing

<table>
<thead>
<tr>
<th>IEC 61853 energy rating</th>
<th>OTF e.g. GI energy yield</th>
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<tbody>
<tr>
<td>“Indoor and/or steady”</td>
<td>“Real weather data”</td>
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</table>

### Characterise modules → Estimate expected energy rating at given climate by module type and technology

- Measure Energy yield → Derive module characteristics to optimise and validate performance at test site

### # Samples

- 1-3 Specific modules for testing
- Actual modules measured (may only be flash tested before use?)

### Characterisation vs. input e.g. Gi, Tmod, AOI, SR ...

- Independent e.g. P vs Gi(Tmod=25) then P vs Tmod(Gi=1) etc.
- Correlated weather params e.g. High insolation ~ Hot, Low AOI, Blue rich ...

### Steady/transient conditions?

- Steady state (thermal equilibrium)
- Includes transient weather (but can wait for steady)

### Direct or Global irradiance?

- All or mostly Direct
- Direct+Diffuse+Reflected

### Module status

- New, clean, uniform
- Aged, Soiling? Shading? Snow?
Gantner Instruments’ OTF Tempe AZ measurements
For further information email: otf@gantner-instruments.com or authors.

**Irradiance**: Plane of array Gi from pyranometers, cSi and KG3 reference cells
Horizontal Gh, Dh; Beam normal Bn, spectral 350-1050nm ...

**Met data**: WindSpeed and direction, Relative Humidity, Tambient...

**PV**: Fixed and 2D track; IV curve every minute, Tmodule
Derive parameters using Loss Factors and Mechanistic Performance Models

Continuous measurements in Arizona since 2010; Other sites available around the world
Flow chart for DC Energy Yield and Energy Rating

IEC 61853
GI OTF calcs that can be checked

1) CLIMATE
- Date, Time
- Global Irradiance Gb, G=20 tilt
- Direct Irradiance Bh, B=20 tilt
- Spectrum G(\lambda) 300-4000nm
- Tambient Tamb
- Wind Speed v

2) REFLECTIVITY AOI +
- AOI correction Bcorr, Dcorr
- Spectral irradiance correction Cs
- Corrected irradiance Gi.corr

3) SPECTRAL RESPONSE

4) TMODULE RISE
- Tmodule Tmod

5) PERFORMANCE MATRIX (G,T)
- ENERGY YIELD Emody=ΣP(Gi,Tmod)
- CSER =Emody/Pstc/H

Gantner Instruments

20-Jun-19 www.steveransome.com SRCL
Steve Ransome Consulting Limited
**CLIMATE:** %Insolation (colour) vs. Irradiance, Tamb $\rightarrow$ Tmodule (calc)

- 0.0%-0.2%
- 0.2%-0.4%
- 0.4%-0.6%
- 0.6%-0.8%
- 0.8%-1.0%
- 1.0%-1.2%
- 1.2%-1.4%
- 1.4%-1.6%
- 1.6%-1.8%
- 1.8%-2.0%

For an equivalent site
GI OTF $\sim$ 61853 data

How do some climates differ from the norm?

1 High elevation
2 Subtropical arid desert
3 Subtropical coastal
4 Temperate coastal
5 Temperate Continental
6 Tropical humid
7 (Sub)Tropical Desert
8 (Sub)tropical Desert

Fractional Insolation at spectral distributions also compared, not enough time to discuss

0 IRRADIANCE kW/m$^2$ 1
SPECTRAL: ASTM G-173-03

61853 Satellite spectra 306-4660nm of varying bin widths. GI 350-1050nm but can extend on new OTFs

Spectral bins, AM0, AM1.5G and AM1.5D

The image displays a graph of IEC 61853 Spectral Bands with spectral data plotted against wavelength (nm) and irradiance (W/m²/nm). The graph includes labels for PV limits and cSi/CIGS, along with various spectral bands and irradiance levels.

Spectral Fraction

\[ SF = \frac{\sum G_{350...650nm}}{\sum G_{350...1050nm}} \]
SPECTRAL:

GI OTF 350-1050 every 3.3nm → 61853 bins

- Clear day and Variable days
- Most PV only sensitive ~350 to <=1050nm

GI OTF measurements are accurate and can be used 350-1050nm

Spots morning shading from transmission lines
REFLECTIVITY AOI and SPECTRAL :

- IEC 61853 irradiance correction methods rely on knowing the spectral response and the reflectivity/AOI of a test device before using this for energy rating calculations.

- Many test modules won’t have had spectral response or reflectivity/AOI measurements.

- Find AOI and spectral correction factors from standard GI OTF data 350-1050nm vs. pyranometer ~280-2800nm $nI_{sc,T}$ vs. AOI and Spectral fraction.

- (Not yet analysed 1D or 2D tracker data – for a future paper)
REFLECTIVITY vs. AOI (high beam fraction)

\[ n_{\text{SC-T}} = \frac{\text{meas.}I_{\text{SC}}}{\text{ref.}I_{\text{SC}}G_I} \times (1 - \alpha_{\text{ISC}} \times (T_{\text{MOD}} - 25)) \] (1)

Compare with Riedel et al 12\textsuperscript{th} PVPMC 2019 “Incident Angle Modifier (IAM) Round Robin Updates”

GI OTF agrees well with round robin
Spectral correction factor SCF vs. Spectral fraction SF

\[
SF = \frac{\sum G_{350\ldots650nm}}{\sum G_{350\ldots1050nm}}
\]

Simple fits SCF vs. SF

1 Junction = Linear fit
- a-Si, CdTe, c-Si
2 Junction = Concave down
- a-Si:uc-Si, a-Si:uc-Si

GI Measured nIscT vs. SF
Spectral correction factor vs. SF and AOI/Beam fraction

for a 1 junction device (2+ Junction equation to come later)

- **SF** = Spectral fraction
- **BF** = Beam fraction
- **AOI** = Angle of incidence
- **cXXX** = Fitted Mechanistic coefficients

\[
n_{\text{ISC}_{T,SPEC,\text{AOI}}} = n_{\text{ISC}_{T}} \times \left( 1 + c_{\text{SF}} \times (\text{SF} - c_{\text{SF}}) \times \left( 1 - \text{BF} \times c_{\text{AOI}} \times \left( 1 - 1/\cos(\text{AOI}) - 1 \right) \right) + \text{cBF} \times \text{BF} \right)
\]

Correcting \( G_{\text{I,REFCELL}} \rightarrow G_{\text{I,PYRANOMETER}} \)

Corr_{T,SPEC,\text{AOI}} and Gi.pyr/Gi.refcell vs. time

\( n_{\text{ISC}} \)

Spectral

AOI (ASHRAE)

or other ...
### MODULE TEMPERATURE RISE vs. Irradiance and Windspeed

#### IEC 61853 formula

\[ T_{\text{RISE}} = T_{\text{MOD}} - T_{\text{AMB}} = \frac{G_{\text{CORR.AOI}}}{U_0 + U_1 \cdot W_S} \quad (2) \]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Example value from Gi meas</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_0 )</td>
<td>0.0322</td>
<td>C/(kW/m(^2))</td>
</tr>
<tr>
<td>( U_1 )</td>
<td>0.0018</td>
<td>C/(kW/ms(^{-1}))</td>
</tr>
</tbody>
</table>
MODULE TEMPERATURE RISE vs. Irradiance and Windspeed

Best fit to Gl measurements in AZ (1 measurement/h for 4000 pts, 1 year)

\[ T_{\text{RISE}} = T_{\text{MOD}} - T_{\text{AMB}} = \frac{G_{\text{CORR.AOI}}}{U_0 + U_1 \cdot W_S} + U_2 \]

New temperature coefficient \( U_2 \sim -2.0 \degree C \) fixes low irradiance \( T_{\text{RISE}} \) discrepancy but won’t alter energy yield much.

Higher efficiency modules are cooler, and glass-glass hotter.
Matrix Performance Measurements “Raw data”

$PR_{DC}$ vs. Irradiance $kW/m^2$ and $T_{module}$ C (colours), not 23 points

61853-1 : c-Si indoor
Old, poor quality, temp sensor problems (zoomed in)

GI OTF:
4000 points 1 year, 1/h, Avg $PR_{DC}$ per Irradiance bin, corrected to $T$

Some values are higher than expected

Some points have “crossed over”

Real weather = “Non rectangular” (G,T) distribution.
Dull+Cold $\downarrow$ to Bright+hot $\uparrow$
# Matrix Performance Measurements fitting

<table>
<thead>
<tr>
<th>Effect</th>
<th>Linear Interpolation</th>
<th>Mechanistic model</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Points with wrong values?</td>
<td>✗ Nearby interpolated and extrapolated values badly affected</td>
<td>✓ “Sanity check” easily finds them. Erase, correct or remeasure!</td>
<td>1, 2</td>
</tr>
<tr>
<td>2) Noisy Data?</td>
<td>✗ No noise reduction</td>
<td>✓ Robust fit, noise averages out</td>
<td>3)</td>
</tr>
<tr>
<td>3) Missing Points?</td>
<td>✗ Affects extrapolations</td>
<td>✓ Can still can get good fits</td>
<td>4)</td>
</tr>
<tr>
<td>4) Reduced or outdoor data (points&lt;&gt;23)</td>
<td>✗ Can’t easily interpolate too few or too many points</td>
<td>✓ Can fit any number of points, weighted if needed</td>
<td>5)</td>
</tr>
<tr>
<td>5) Useful Coefficients to analyse?</td>
<td>✗ No coefficients from analysis</td>
<td>✓ Yes, useful normalised orthogonal coefficients for a database</td>
<td>6)</td>
</tr>
<tr>
<td>6) Data storage</td>
<td>✗ Every point needs to be stored</td>
<td>✓ Only 5-6 coefficients stored +rmse</td>
<td>7)</td>
</tr>
<tr>
<td>7) Module variability or degradation Binning</td>
<td>✗ Hard to compare datasets without coefficients</td>
<td>✓ Normalised coefficients can determine rates and causes Pmax binning → C1?</td>
<td></td>
</tr>
</tbody>
</table>
MPM “Mechanistic Performance Model”
meaningful, orthogonal, robust, normalised
(see 7th PVPMC, 44th PVSC, 33rd EUPVSEC, PVSEC-27 for more details www.steveransome.com)

Where \( G_i \) in kW/m\(^2\), \( dT_{MOD} = T_{MOD} - 25\)C

\[
PR_{DC} = C_1 + C_2 \times dT_{MOD} + C_3 \times \log_{10}(G_i) + C_4 \times G_i + C_5 \times WS + \frac{C_6}{G_i}
\]

<table>
<thead>
<tr>
<th>Dependency</th>
<th>Comment</th>
<th>Normalised Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>Tolerance</td>
<td>Actual/Nominal value ~100%</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>Tmodule-25C</td>
<td>Temperature coefficient ~ -0.25 to -0.50%/K</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>( \log_{10}(G_i) )</td>
<td>Low light fall due to ( V_{OC} ) (and ( R_{SHUNT} )?)</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>( G_i )</td>
<td>High light fall – ( R_{OC} ) due to ( R_{SERIES} )</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>Wind speed</td>
<td>Small correction</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>( 1/G_i )</td>
<td>Only some modules (depends on how their ( R_{SHUNT} ) behaves)</td>
</tr>
</tbody>
</table>

\( G_i \) Irradiance kW/m\(^2\) →
MPM validation on different PV technologies from SUPSI, NIST, ASU, ESTI, TÜV Rheinland, CFV, SANDIA, CREST, SAPM, PVSYST, Gantner instruments and many more ...
MATRIX Performance Measurements fitted with MPM

61853-1 : c-Si (Indoor)
Known bad measurements thermal sensors etc.

MCM RMSE good 0.55%
even with bad data points indoors

GI OTF Avg PR\textsubscript{DC} corrected T\textsubscript{mod}

MCM RMSE very good 0.28%
even with “missing data” outdoors

\textbf{PR\textsubscript{DC,STC} = 97.9\%}
\textbf{Gamma = -0.43\%/K}
\textbf{PR\textsubscript{DC,LIC} = 92.1\%}
\textbf{PR\textsubscript{DC,PTC} = 89.1\%}

\textbf{PR\textsubscript{DC,STC} = 92.0\%}
\textbf{Gamma = -0.43\%/K}
\textbf{PR\textsubscript{DC,LIC} = 96.6\%}
\textbf{PR\textsubscript{DC,PTC} = 92.0\%}

Temp corr :l| MPM_000 :112|Hansen
CSSP_220M :GAMMA= -0.420% :SR=0 :rms= 0.51% :NF=0.0% :S=0

Normalized Efficiency PR\textsubscript{DC}

Gantner instruments
Current status on energy yield/energy rating predictions

- Simulation programs have been predicting energy yields vs. technology, climate, temperature coefficients, spectral effects etc. well enough for manufacturers, investors etc. for many years.

- Binning of module $P_{\text{MAX}}$ ($\pm2.5\%$?), manufacturing variability and irradiance sensor tolerance may limit the accuracy of any energy rating validation.

- A “Cookie cutter approach” is often used to guarantee performance by making similar new sites to old ones that are known to work.

- How useful is this IEC 61853 method?

- Will it duplicate existing predictions/measurements or differ?
Summary

Hourly climate – GI OTF good results
Reflectivity vs. AOI – GI OTF good results
Spectral response
  - if 61853 SR not available, simpler GI OTF method presented (can extend nm range)

$T_{MOD}$ (vs. $T_{AMB}$, Gi and WS)
  - GI OTF suggests a small correction at low irradiance

Matrix performance fitting (vs. Gi, $T_{MOD}$)
  61853 - bilinear fit
    ✗ Poor choice, particularly for noisy or missing data

GI OTF - MPM
  ✓ meaningful, orthogonal, robust, normalised
  ✓ validated on data from many test institutes
  ✓ technology and site independent

• Check 61853 energy rating vs. existing working methods (e.g. simulation programs)

Thank you for your attention!

More data analysis will be presented in PVSEC Marseille
Other advantages available from using the MPM

\[
PR_{DC} = C_1 + C_2 \times dT_{MOD} + C_3 \times \log_{10}(G_I) + C_4 \times G_I + C_5 \times WS + \frac{C_6}{G_I}
\]

- **Tolerance** – Gives expected performance at STC, LIC etc.
- **Degradation studies** – quantify changes with coefficients over time
- **Temperature coefficients** – \( C_2 = \text{gamma} \)
- **Loss characterisation** and identification e.g. \( V_{OC} \) loss is due to \( C_3 \), \( R_{SERIES} \) loss is low \( C_4 \)
- **Fault finding** – coefficients that glitch or aren’t expected values
- **Database comparison** – normalised values should be similar by technologies but differ c-Si vs. thin film (e.g. TempCoeff=\( C_2 \), low light=\( C_3 \), high light=\( C_4 \))
- **It’s a proven, optimised and validated model**