Reliability of Power Rating and Labeling

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Reliability of Power Rating and Labelling
Introduction to TÜV Rheinland

TÜV RHEINLAND worldwide operates 6 accredited PV laboratories

<table>
<thead>
<tr>
<th>Testing and certification of PV modules and PV components:</th>
<th>&gt; 30 years experience and research in PV</th>
<th>Active in national and international standardization committees (IEC, CENELEC, IECEE, DKE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- IEC 61215 (crystalline PV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- IEC 61646 (thin-film PV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- IEC 62108 (concentrating PV)</td>
<td></td>
<td></td>
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<tr>
<td>- IEC 61730 (safety)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ANSI / UL 1703 (safety US)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reliability of Power Rating and Labelling

Content

- Introduction to Production Tolerance
- Tolerance seen in the Market
- Laboratory Experience
- Review of relevant Standards
- Measurement Uncertainty
- Manufacturing Sorting
Introduction to Production Tolerance

Tolerance seen in the Market

Laboratory Experience

Review of relevant Standards

Measurement Uncertainty

Manufacturing Sorting

Reliability of Power Rating and Labelling
Reliability of Power Rating and Labelling
Uncertainty Factors of Inline PV Module Power Rating

- Module sorting into power classes
- Light-Induced Degradation (LID)

- Calibration accuracy of the reference device
- Traceability of calibration to World PV Scale (WPVS)

Internal Factor: Production

- Accuracy of measuring equipment:
  - Data acquisition, sensors
  - Solar simulator performance

- Measuring technique:
  - Design and use of reference device
  - Equipment connectors
  - Module temperature
  - Capacitive effects of modules
  - I-V correction

External Factors

Internal Factor: Measurement
Reliability of Power Rating and Labelling
Loss of Money due to Measurement Uncertainty

- Approx. 265 Mio $ lost per 1% of uncertainty per year
- High uncertainty leads to money loss

2 PVXchange Module Price Index, PV Magazine (Jul. 2016)
Reliability of Power Rating and Labelling

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Reliability of Power Rating and Labelling
Example Datasheets and Labels

**Production Tolerance**
Power: +10/-5% *

* (...) output with positive tolerance.

**Rated Power Tolerance ≥96%**

**Sorting limits of performance: 0/+5W**

---

Electrical data (at STC)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>220 W</th>
<th>225 W</th>
<th>230 W</th>
<th>235 W</th>
<th>240 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. power (W)</td>
<td>245</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Max. power (A)</td>
<td>4.3</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Max. current (Isc) [A]</td>
<td>5.54</td>
<td>5.51</td>
<td>5.51</td>
<td>5.51</td>
<td>5.51</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>53.0</td>
<td>52.4</td>
<td>52.4</td>
<td>52.4</td>
<td>52.4</td>
</tr>
<tr>
<td>Short circuit current (Isc) [A]</td>
<td>5.86</td>
<td>5.85</td>
<td>5.85</td>
<td>5.85</td>
<td>5.85</td>
</tr>
<tr>
<td>Max. power (W) (at max)</td>
<td>245</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Max. power (A) (at max)</td>
<td>4.3</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Max. current (Isc) [A] (at max)</td>
<td>5.54</td>
<td>5.51</td>
<td>5.51</td>
<td>5.51</td>
<td>5.51</td>
</tr>
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<td>Open circuit voltage (Voc) (at max)</td>
<td>53.0</td>
<td>52.4</td>
<td>52.4</td>
<td>52.4</td>
<td>52.4</td>
</tr>
<tr>
<td>Short circuit current (Isc) [A] (at max)</td>
<td>5.86</td>
<td>5.85</td>
<td>5.85</td>
<td>5.85</td>
<td>5.85</td>
</tr>
</tbody>
</table>

Note: All modules measured by 1000 W/m², cell temp. 25°C
* All modules measured by output with positive tolerance.

Electrical data under STC (Standard Test Conditions: 1000 W/m², 25 °C, AM 1.5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>235 W</th>
<th>240 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (W)</td>
<td>245 W</td>
<td>240 W</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>29.87 V</td>
<td>29.87 V</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>37.62 V</td>
<td>37.62 V</td>
</tr>
<tr>
<td>Short circuit current (Isc) [A]</td>
<td>8.44 A</td>
<td>8.44 A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>15.2%</td>
<td>15.5%</td>
</tr>
</tbody>
</table>

© Measured at Standard Test Condition (STC): Irradiance of 1000 W/m², AM 1.5, and Cell Temperature 25°C.
© Normal Operating Cell Temperature (NOCT): Irradiance of 1000 W/m², Temperature 20°C, Wind Speed 1 m/s.
Reliability of Power Rating and Labelling
Label Tolerance seen in the Market

Sample size: 87 c-Si PV module manufacturers

Claimed Tolerance in PV Module Labels [%]

Origin of data

- China, 57
- Taiwan, 10
- India, 8
- Japan, 3
- Korea, 2
- Europe, 3
- US, 3
- Canada, 1
- Other, 3

11.10.2016
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Reliability of Power Rating and Labelling Laboratory Experience from Measurements at STC

- Significant number of modules underperforms at STC tests.
- Modules are typically not solarized (LID not included).

Unique SNs: 7179
Unique Module Classes: 935
Unique Manufacturers: 190
Test Period: 2015-2016
Test Lab: TR-SHG

Measurement Uncertainty: ±2.50%, k=2
Mean Deviation to Label: 0.74% ± 4.10%, k=2
Reliability of Power Rating and Labelling Experience from Pre-shipment Counter-Flash Measurements

- The majority of PV-modules for buyer’s projects are within tolerance.
- Modules are typically not solarized (LID not included).

Test Period: 2015-2016
Test Lab: TR-SHG
Measurement Uncertainty: ±2.50%, k=2

Modules: 2295; Batches: 30; Manufacturers: 9
2.50%±1.99%, k=2
Reliability of Power Rating and Labelling Experience from Pre-shipment Counter-Flash Measurements

- When LID is determined in the project phase the rating is often higher (approx. 1.5%) comparing to projects that LID is undermined.
Reliability of Power Rating and Labelling
Laboratory Experience from Buyer’s Projects

Deviation to label tolerance for different batches sampled in pre-shipment stage

<table>
<thead>
<tr>
<th>Coef. of Variation per Batch [%], k=2</th>
<th>Mean ( P_{MAX} ) Deviation to Low Tolerance Limit [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LID determined in project</td>
<td>![Blue circles representing data points]</td>
</tr>
<tr>
<td>LID not determined in project</td>
<td>![Green circles representing data points]</td>
</tr>
</tbody>
</table>

- **Test Period:** 2015-2016
- **Test Lab:** TR-SHG
- **Meas. Unc.:** ±2.50%, k=2
- **No. of Batches:** 30
- **Manufacturers:** 9
- **Sample:** 2295
- **Dev.:** 2.50% ±1.99%, k=2

Sample size

0.0%  1.0%  2.0%  3.0%  4.0%  5.0%  0.0%  1.0%  2.0%  3.0%  4.0%  5.0%

0.0%  0.5%  1.0%  1.5%  2.0%  2.5%  3.0%  3.5%  0.0%  0.5%  1.0%  1.5%  2.0%  2.5%  3.0%  3.5%
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Reliability of Power Rating and Labelling
PV Module Qualification Testing and Certification

Actual status

Crystalline silicon PV modules

IEC 61215 Ed. 2
- Test Methods
- Test Requirements

Thin-film PV modules

IEC 61646 Ed. 2
- Test Methods
- Test Requirements

Combined structure under new IEC 61215 series

Part 1 – General Requirements
- Part 1-1 c-Si
- Part 1-2 CdTe
- Part 1-3 a-Si & µc-Si
- Part 1-4 CIS & CIGS
- Part 1-x New technologies

Part 2 – Test Methods
Uncertainty of Power Rating in Production
New Test Requirements of IEC 61215-1

- Information on tolerances for $P_{\text{MAX}}$, $I_{\text{SC}}$, $V_{\text{OC}}$ must be stated on the type label of the PV module.

- Module type label information on tolerances will be confirmed within the new test sequence of IEC 61215 for product qualification testing.

- All test samples of a IEC 61215 certification project undergo electrical stabilization (MQT 19).

- Electrical performance at STC (MQT 6.1) after stabilization is referenced for confirmation of type label information.

- As nominal output power within a type family is typically classified in steps of 5 $W_p$, additionally two samples of lowest, highest and middle power class of the module type family will included in the test program.

- **PASS criterion**: With consideration of the lab measurement uncertainty, stabilized STC values of $P_{\text{MAX}}$, $I_{\text{SC}}$, $V_{\text{OC}}$ of all test samples must lie within the specified tolerances.
### Gate #1 Requirements

<table>
<thead>
<tr>
<th>Equation</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P_{\text{MAX}}(\text{Lab}) \times \left( 1 + \frac{</td>
<td>m_1[%]</td>
</tr>
<tr>
<td>[ \bar{P}_{\text{MAX}}(\text{Lab}) \times \left( 1 + \frac{</td>
<td>m_1[%]</td>
</tr>
<tr>
<td>[ V_{\text{OC}}(\text{Lab}) \times \left( 1 + \frac{</td>
<td>m_2[%]</td>
</tr>
<tr>
<td>[ I_{\text{SC}}(\text{Lab}) \times \left( 1 + \frac{</td>
<td>m_3[%]</td>
</tr>
</tbody>
</table>

- \( |m_x| \) = lab measurement uncertainty
- \( |t_x| \) = manufacturers tolerance stated on type label

\( P_{\text{MAX}}: x=1 \); \( V_{\text{OC}}: x=2 \); \( I_{\text{SC}}: x=3 \)
Reliability of Power Rating and Labelling
New Test Requirements of IEC 61215-1

Deficits of the Gate #1 practice:

- The standard does not define what is meant by tolerance: Is it based on manufacturers flash lists only? Is it corrected for potential LID effects (if c-Si technology)? Does it include the measurement uncertainty in the production line/s?
  - High risk for module manufacturer and buyer
- 2 samples per power class means a lack of statistical relevance
  Statistical relevance for the benefit of the manufacturer and buyer is not considered in PASS/FAIL criteria
- Sample picking is done by manufacturer ⇒ No objective results
- Unclear how FAIL of a single power class shall be treated
- How to handle transport damage? ⇒ Risk for module manufacturer
The **Operating Characteristic (OC)** curves describes how well a sampling plan discriminates between good and bad lots.

**ISO 2859** specifies an acceptance sampling system for inspection. It is indexed in terms of the **Acceptable Quality Level (AQL)**. Closely related term is the **Rejectable Quality Level (RQL)**.
Reliability of Power Rating and Labelling
Statistical Significance of Pass/Fail Criteria

- AQL assumes a 5% risk for the Producer that a lot with defects <AQL is rejected
- RQL assumes a 10% risk for the Consumer that a lot with defects >RQL is accepted

The sampling plan of IEC 61215-1, Gate#1 implies an unrealistically high quality control for production lines (AQL approx. 0.82%) and does not provide confidence for buyers.

A production line with a realistic acceptable quality level of 2.5% would have approx. 15% risk to fail gate#1 criteria.
The sampling plan of IEC 61215-1, Gate#1 implies an unrealistically high quality control for production lines (AQL approx. 0.82%) and does not provide confidence for buyers.

A production line with a realistic acceptable quality level of 2.5% would have approx. 15% risk to fail gate#1 criteria.

Increasing the sampling size would reduce risks for both producers and consumers.
### IEC 60904-9 Classification

<table>
<thead>
<tr>
<th>Component</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Irradiance</td>
<td>![Spectral Irradiance Graph]</td>
</tr>
<tr>
<td>Non-uniformity of Irradiance</td>
<td>![Non-uniformity Graph]</td>
</tr>
<tr>
<td>Short and Long Temporal Instability (LTI and STI)</td>
<td>![Temporal Instability Graph]</td>
</tr>
</tbody>
</table>
Reliability of Power Rating and Labelling
Factors affecting the Uncertainty of Power Measurement

<table>
<thead>
<tr>
<th>Reference Solar Device</th>
<th>Solar Simulator Performance</th>
<th>Operator Technique / Measurement Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Calibration uncertainty of reference device</td>
<td>Non-Uniformity of Irradiance:</td>
<td>• Calibration and measurement procedure</td>
</tr>
<tr>
<td></td>
<td>• Non-uniformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Measurement accuracy</td>
<td>• I-V corrections</td>
</tr>
<tr>
<td>• Implementation of reference device</td>
<td>Temporal instability of irradiance (LTI &amp; STI)</td>
<td>• Spectral mismatch</td>
</tr>
<tr>
<td>• Accuracy and calibration of temperature sensor</td>
<td>Electronic accuracy of I-V measurement channels</td>
<td>• Optical mismatch between reference module and test module</td>
</tr>
<tr>
<td>• Long-term drift and stability of reference device</td>
<td>Accuracy and calibration of temperature sensors</td>
<td>Temperature:</td>
</tr>
<tr>
<td>• Repeatability of reference irradiance acquisition</td>
<td>Repeatability of solar simulator</td>
<td>• Control</td>
</tr>
<tr>
<td>• Reproducibility of reference irradiance acquisition</td>
<td>Reproducibility of solar simulator</td>
<td>• Temperature non-uniformity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Connection technique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operation:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• System maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Human error</td>
</tr>
</tbody>
</table>

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Reliability of Power Rating and Labelling
Uncertainty impacts on I-V curve

Overall impact:
Temperature, irradiance correction, I-V data acquisition accuracy
Reliability of Power Rating and Labelling Traceability practice

SI units → Metrology authority

Primary calibration → WPVS cell

Test Laboratory

Solar simulator 1: Reference module Calibration (GOLDEN MODULE)

PV module manufacturer

Production line/s

Solar simulator 3: Production line power measurement, power classification

End user

Test laboratory

Solar simulator 2: Working standards for daily use (SILVER MODULES)
Reliability of Power Rating and Labelling
Uncertainty Assessment Service (UAS) Objective

- **UAS** shall give confidence in stated manufacturer’s tolerances for $P_{\text{MAX}}$, $V_{\text{OC}}$ and $I_{\text{SC}}$, which are subject to IEC 61215 certification.

<table>
<thead>
<tr>
<th>AIST, NREL, PTB</th>
<th>Primary calibration Reference cell (WPVS Design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Test Institute</td>
<td>Secondary calibration of reference module (GOLDEN MODULE)</td>
</tr>
<tr>
<td>PV module manufacturer</td>
<td>Working reference (SILVER MODULE)</td>
</tr>
<tr>
<td></td>
<td>Production line output power measurement</td>
</tr>
</tbody>
</table>

$\pm 0.6\%$ to $1\%$

$\pm 1.6\%$ to $3.0\%$

???

???
Variation in solar simulator performance: Spatial non-uniformity and temporal instability of irradiance, AM1.5 match of spectral irradiance

Measurement uncertainty

Tunnel system without diffuse light component

Tunnel system with diffuse light component

Table system With high diffuse light component
Reliability of Power Rating and Labelling Work Programme

- Documentation of measurement equipment
- Performance check of all solar simulators in manufacturers test lab and production lines
- Evaluation of PV module designs: Reference modules (REF) vs. production line modules (DUT)
- Review of calibration protocols for reference modules and measurement equipment (I-V load, temperature sensors, etc.)
- Evaluation of specific effects: I-V hysteresis, LID
- Random sample picking from production and comparison of manufacturer rating with TÜV Rheinland measurements
Reliability of Power Rating and Labelling Calculation Method

- **ISO/IEC Guide to the Uncertainty of Measurement (GUM)**
  Definition of general principles for Uncertainty of Measurement

\[
u_{P_{\text{MAX}}} = k \cdot \sqrt{u_1^2 + \ldots + u_N^2}
\]

- \( u_{P_{\text{MAX}}} \) = Expanded overall measurement uncertainty
- \( u_i \) = Standard uncertainty for uncertainty source
- \( k \) = Coverage factor (k=2 for 95% confidence interval)

- **\( P_{\text{MAX}} \) uncertainty sources \( u_i \)**
  - Calibration uncertainty of REF
  - Measurement equipment: Current, voltage, temperature measurement
  - Repeatability of measurement, drift of irradiance sensor
  - Spatial non-uniformity of irradiance
  - I-V curve temperature and irradiance correction
  - Electrical mismatch between REF and DUT (variation in spectral response)
  - Optical mismatch between REF and DUT (variation in angular response)
  - Measurement technique: Misalignment between REF and DUT, transient effects, temperature measurement, contacting technique, traceability practice
Reliability of Power Rating and Labelling
Example of Uncertainty in Silver Module Calibration

Case of Study:
Class AAA system
$P_{\text{MAX}}=2.8\%, k=2$

<table>
<thead>
<tr>
<th>Factor</th>
<th>Uncertainty Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Calib. $P_{\text{MAX}}$</td>
<td>±2.00%, $k=2$</td>
</tr>
<tr>
<td>Non-uniformity of irradiance</td>
<td>±1.1% (Rectangular)</td>
</tr>
<tr>
<td>Temp. Accuracy</td>
<td>±1.0°C (Rectangular)</td>
</tr>
<tr>
<td>Temp. non-uniformity</td>
<td>±1.0°C (Rectangular)</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>±0.8%, $k=2$</td>
</tr>
<tr>
<td>Electronic Accuracy</td>
<td>±0.2% (Rectangular)</td>
</tr>
<tr>
<td>Spectral mismatch</td>
<td>±0.35%, $k=2$</td>
</tr>
<tr>
<td>Non-uniformity of irradiance unc.</td>
<td>±0.25%, $k=2$</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>±10mΩ (Rectangular)</td>
</tr>
</tbody>
</table>
Reliability of Power Rating and Labelling
Module Sorting into Power Classes

- Sorting tolerance into power classes contributes to the production tolerance
- Sorting tolerance of 95% confidence level can be achieved ⇔ 95% of measurements lie within $P_{\text{AVG}} \pm 2\sigma$. 

![Bar Chart Illustrating Power Class Sorting](chart.png)
Reliability of Power Rating and Labelling
Factors affecting Sorting Tolerance

- The sorting tolerance of a power class is influenced by both sorting bins size and production frequency.
- Each power measurement has a degree of uncertainty, which will also affect the label tolerance.
Reliability of Power Rating and Labelling
Production Tolerance: Combining Sorting and Measurement

- Total tolerance is mainly limited by measurement uncertainty when module sorting is done per 5 Watt classes.

Limiting Factor

$\Delta_{ST95} = 1.74\%$

$\Delta_{MT95} = 3\%$

$\Delta_{TT95} = 3.46\%$
Reliability of Power Rating and Labelling

Conclusions

- The declared production tolerance of PV-modules in the market is sometimes unclear and can be inaccurate.
- The gate #1 requirements of IEC 61215-1 aim to provide confidence in PV-module labeling. However, the sampling size is currently low and does not provide statistical significance in the evaluation.
- To reach maturity PV community needs a common language, which is clear, transparent, and if possible consistent, on how production tolerances are declared on PV-module nameplates and what they cover.
- Measurement uncertainty analysis is complex and requires assumptions and experience for accurate estimates. Sorting tolerance and LID must be considered.
- Production tolerance in PV industry lies in the range 3% to 5% for c-Si modules, if appropriate quality assurance is in place.
- UAS aims in increasing confidence for consumers and reducing risks for producers.
- To reduce risks it is recommended to perform counter-flash measurements at accredited, laboratories for a small but representative PV-module sample.
Acknowledgements

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