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Precision PV Performance Assessment at ESTI

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- Uncertainty in power measurement
- Multi-junction flat plate modules
- Energy rating
- What ESTI can do for you



- Improve PV performance measurement methods and standards (power, energy yield, reliability and lifetime)
- Enabler for European PV research and innovation (calibrations, benchmarking, workshops/training, lab access, EUPVSEC technical programme coordination)
- SET-Plan PV technology and market assessment

ESTI Facilities

Power Measurement

- Large area (2 m x 2 m) steady state simulator
- Flash simulator (3 m x 3 m, 10 ms)
- Long flash simulator (2m x 2 m, 80 ms)
- Steady state simulator for up to 12 cm x 12 cm
- High intensity flash simulator
- Outdoor/natural sunlight set-up (2m x 2m)

Spectral Response

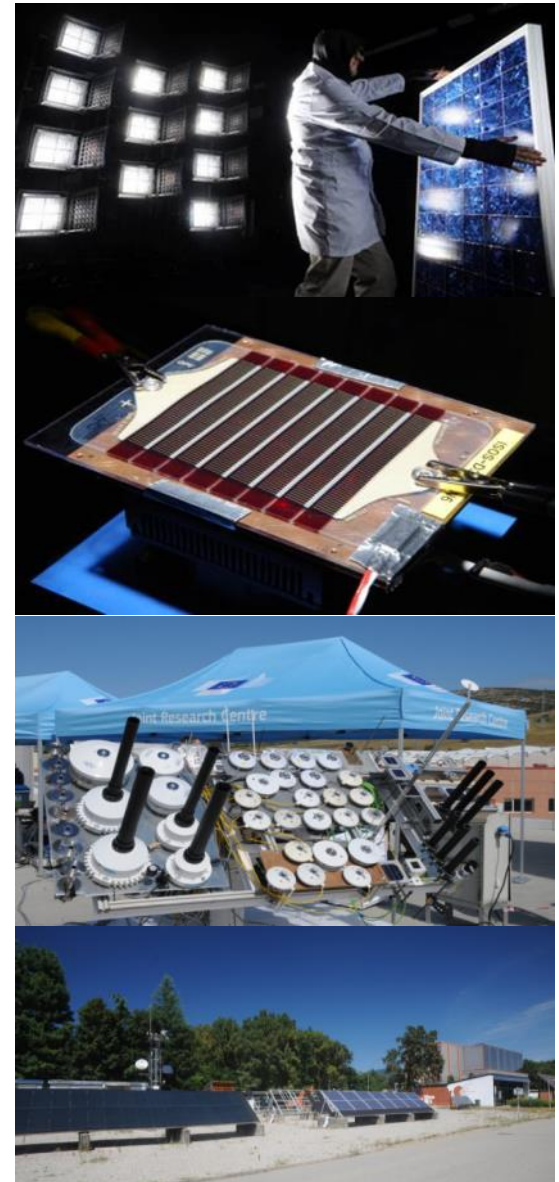
- Pasan flash system (2 m x 2m)
- Oriel system (cells, modules)

Environment Conditioning

- Light soaking/stabilisation (with T control)
- Thermal Cycling
- Damp Heat
- Laser Lab

Energy yield

- Continuous performance measurement (I-V sweeps)
- Long term power monitoring (DC/AC)



Power (and Efficiency) Measurement Uncertainty

Classification ^a	Effic. ^b (%)	Area ^c (cm ²)	V _{oc} (V)	I _{sc} (A)	FF ^d (%)	Test centre (date)
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96) ^e
Si (large crystalline)	22.4 ± 0.6	15775 (ap)	69.57	6.341 ^f	80.1	NREL (8/12)
Si (multicrystalline)	18.5 ± 0.4	14661 (ap)	38.97	9.149 ^g	76.2	FhG-ISE (1/12)
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255 ^h	84.2	NREL (11/12)
CdTe (thin-film)	17.5 ± 0.7	7021 (ap)	103.1	1.553 ⁱ	76.6	NREL (2/14)
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408 ^j	72.8	AIST (6/14)
CIGS (thin-film)	15.7 ± 0.5	9703 (ap)	28.24	7.254 ^k	72.5	NREL (11/10)
a-Si/nc-Si (tandem)	12.2 ± 0.3 ^l	14322 (t)	202.1	1.261 ⁱ	68.8	ESTI (6/14)
Organic	8.7 ± 0.3 ^m	802 (da)	17.47	0.569 ⁱ	70.4	AIST (5/14)

SOLARWORLD

Sunmodule[®] SW 240 mono

www.solarworld.de D-53113 Bonn, Germany

Rated max. Power	P _{max} [W]	240	(+/-3%)
Open Circuit Voltage	V _{oc} [V]	37.1	
Rated Voltage	V _{mpp} [V]	30.0	
Short Circuit Current	I _{sc} [A]	8.66	
Rated Current	I _{mpp} [A]	8.02	

Power Specifications at STC: 1000W/m², 25°C, AM 1.5

Maximum System Voltage	Safety Class II	1000 Vdc
Maximum System Voltage	USA	600 Vdc

Fire Rating: CLASS C Series Fuse:15A

Field Wiring: Copper only, 12 AWG Bypass diodes: Refer to manual

Insulated for 90°C min.

Certified according to: IEC 61215 2nd Ed.

UL US LISTED IEC CE Caution Potential electrical hazard

Manufactured in USA

First Solar, LLC
28101 Cedar Park Blvd.
Perrysburg, OH 43551
www.FirstSolar.com

First Solar.

CE **TUV SÜD**

Made in USA

Nominal Power (+/-5 %)	60 W
Current at mpp	0.97 A
Voltage at mpp	62 V
Short Circuit Current	1.15 A
Open Circuit Voltage	90 V
Maximum System Voltage (600V UL)	1000 V
Max Source Circuit Fuse (2A UL)	10 A
Protection Class	Class II
Cell Type	CdTe

specifications (+/- 10 %) at STC: Irrad. 1,000 W/m², AM 1.5, Cell T 25 °C

Warning - Electrical shock hazard

This solar module produces high voltages in sunlight. Read and observe all instructions before attempting installation or service. Do not disconnect under load.

Serial Number **F01260301** Model Number **FS-260**

Covered by United States Patents: 5,248,349; 5,470,397; 5,536,333; 5,945,163; 6,037,241; 6,559,411; 6,719,848; and by Corresponding Foreign Patents; Others Pending.

LG Electronics

LG250S1C - G2

Serial No. **120113**

Manufactured Date **1632X906X42** mm

Standards Size **250 W**

Maximum Power (Pmax) **-0/+3 %**

Power Tolerance **29.90 V**

Maximum Power Voltage (Vmpp) **8.37 A**

Maximum Power Current (Impp) **37.10 V**

Open Circuit Voltage (Voc) **8.76 A**

Short Circuit Current (Isc) **1,000 V**

Maximum System Voltage **15 A**

Maximum Series Fuse **5400 Pa**

Maximum Load

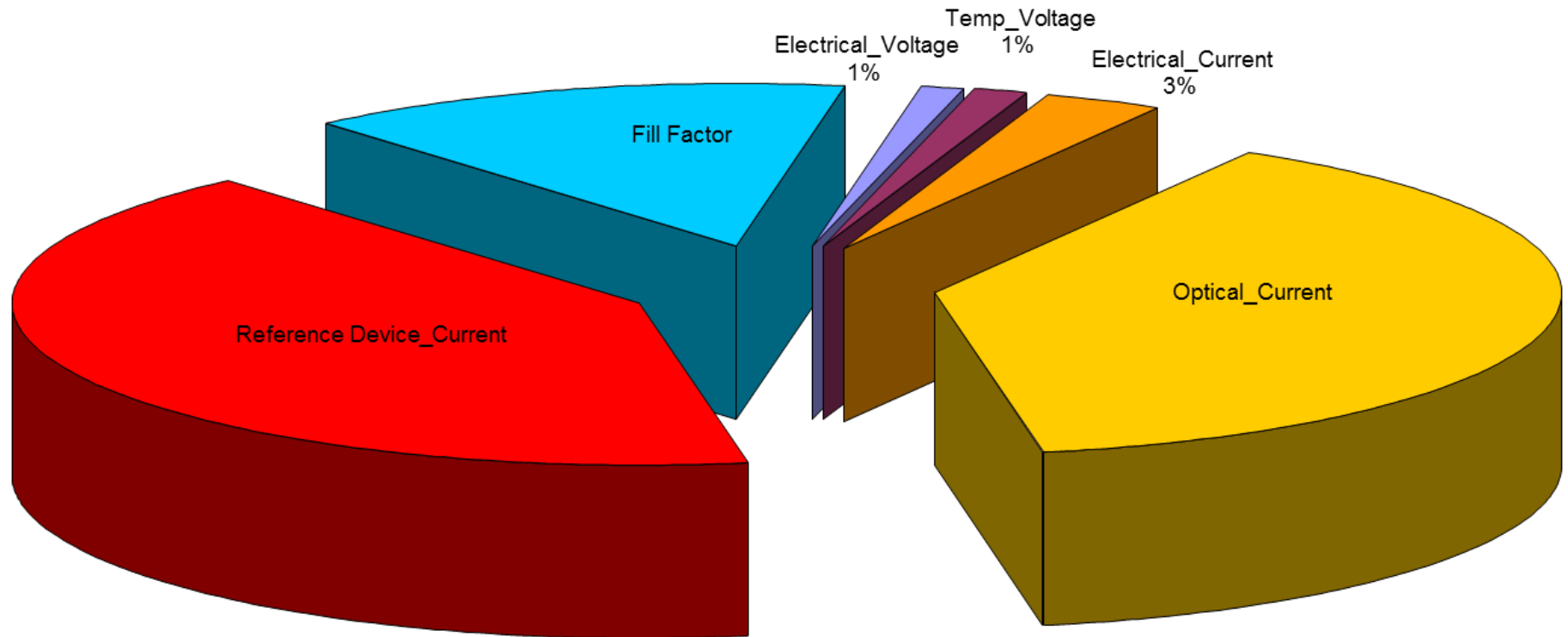
Electrical nominal value at STC
(1,000W/m², AM 1.5 Spectrum, Cell Temperature 25 °C)

WARNING

Refer to Installation and Operation Manual before installing, operating or servicing this unit. **DO NOT** connect or disconnect plug contacts while system is under load current. Failure to



Example of contributions to $P_{\max}$ uncertainty



Electrical: Data acquisition; Shunts; Reference cell shunt or TIA

Temperature: Indicators; Measurement condition; Temperature non-uniformity

Optical: Spatial non-uniformity of irradiance; Orientation; Alignment

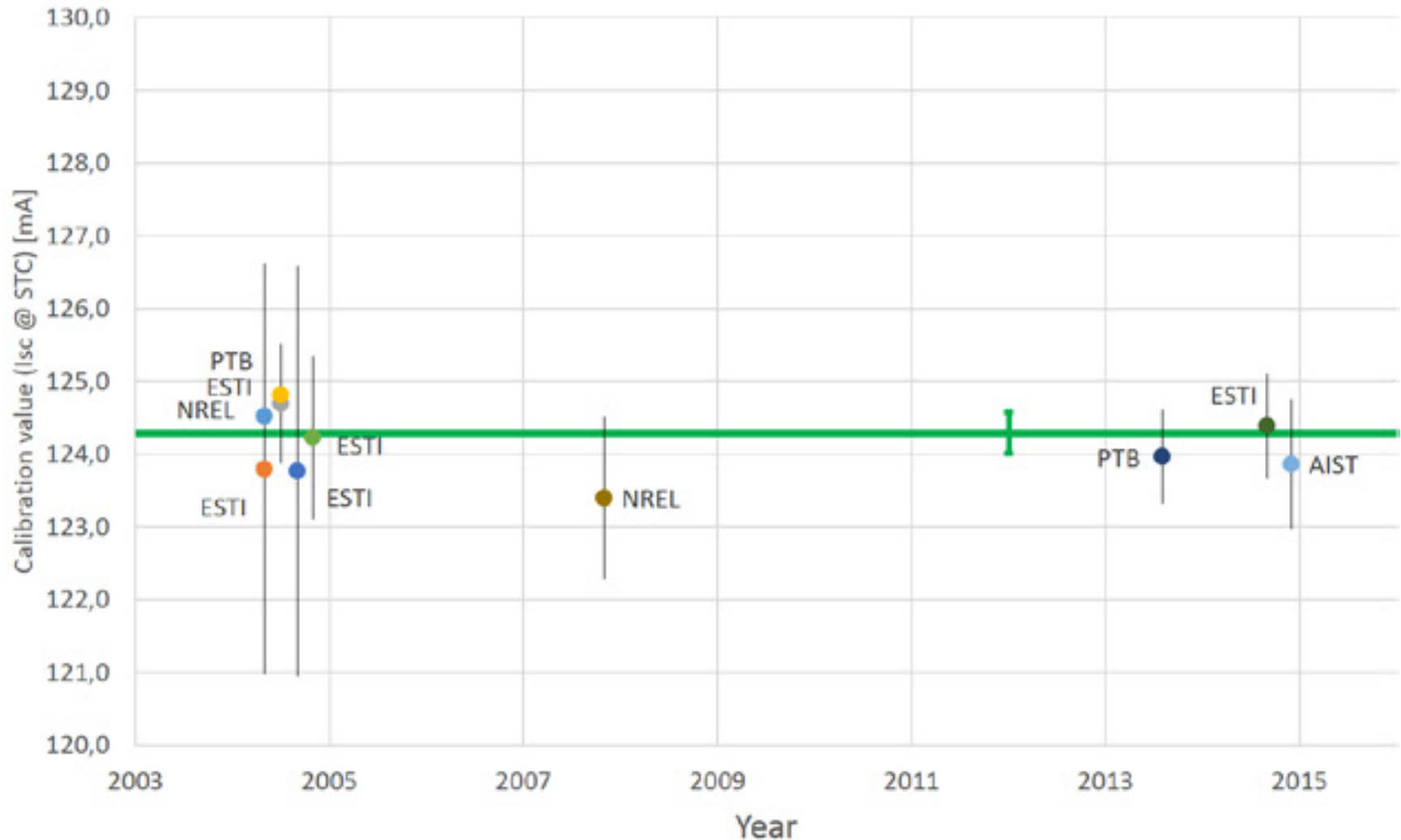
Reference Cell: Calibration; spectral mismatch; drift

Fill Factor: cabling

Repeatability: Measurements of device; system drift

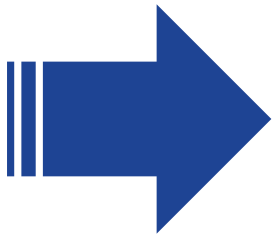
New ESTI primary reference cell analysis

PX304C



New ESTI primary reference cell analysis

- Rigorous statistical analysis of a set of five c-Si PV reference cells used as irradiance primary references
- Lowest expanded uncertainty of 0.23% ($k = 2$), a factor of two below that of any single method.

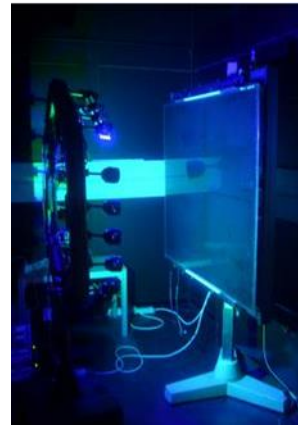
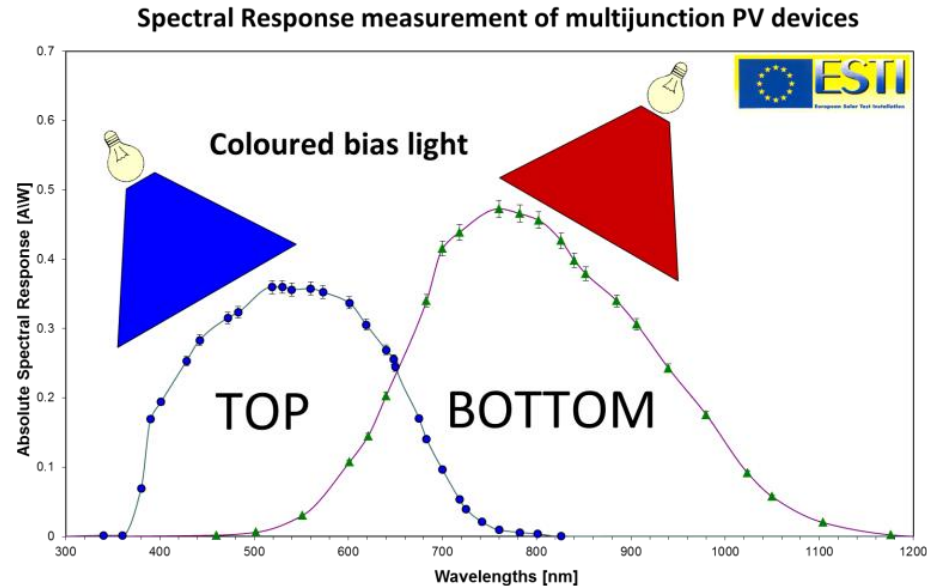


**Should be possible to calibrate ref cells
by cheaper and faster secondary
methods, with UCs $\leq$ primary methods.**

***See H. Müllejans, W. Zaaiman & E. Dunlop, Reduction of uncertainties
for photovoltaic reference cells, Metrologia 52 (2015) 646–653***

Multi-Junction Flat-Plate Devices

MJ flat-plate modules are likely to become common in the future as a route to obtaining higher efficiencies



Proposed IEC standards (at committee draft with vote stage)

- IEC 60904-1-1 Measurement of current-voltage characteristics of multi-junction photovoltaic devices
- IEC 60904-8-1 Measurement of spectral responsivity of multi-junction photovoltaic (PV) devices

Spectral deviation from AM1.5G (G^{REF})

Correction: Mismatch (MM) as defined by IEC 60904-7

$$MMF = \frac{1}{MM} = \frac{\int SR^{DUT}(\lambda) G^{REF}(\lambda) d(\lambda) \times \int SR^{RC}(\lambda) G^{meas}(\lambda) d(\lambda)}{\int SR^{DUT}(\lambda) G^{meas}(\lambda) d(\lambda) \times \int SR^{RC}(\lambda) G^{REF}(\lambda) d(\lambda)}$$

**DUT = Top
junction**

MMF_{TOP}



**DUT = Bottom
junction**

MMF_{BOTTOM}

Energy rating

- **Energy rating** (dimensionless) is a measure of how a module type performs in a certain climate, relative to other module types.
- **Yield prediction** (unit: kWh/year) is an estimate of the energy output of a specific PV installation.

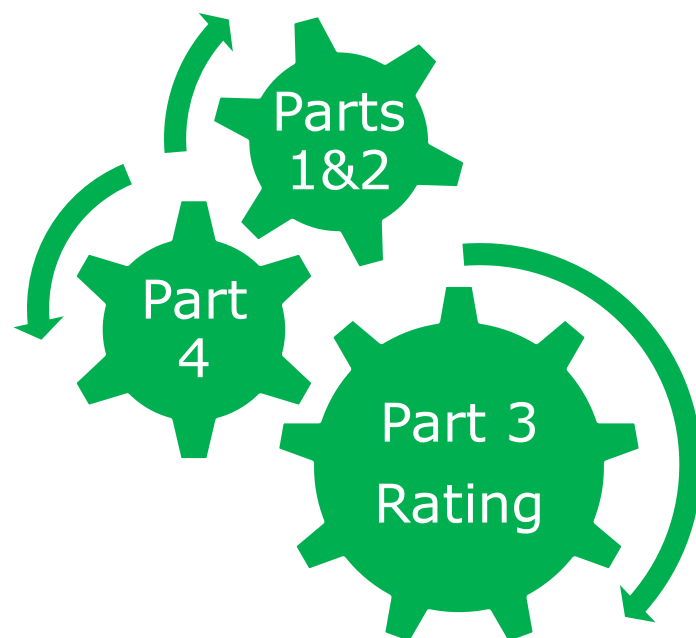
IEC 61853 series: photovoltaic modules performance testing and energy rating

Part 1: Irradiance and temperature performance measurements and power rating (published)

Part 2: Spectral response, incidence angle and module operating temperature measurements (Approved for FDIS)

Part 3: Energy Rating of PV Modules (Committee Draft)

Part 4: Standard reference climatic profiles (Committee Draft)



Module performance ratio (MPR)

Ratio of actual module energy output under a given reference climate year to the output if the module always had the efficiency measured at STC.

It can be expressed as:

$$MPR = 1000E_{tot} / (P_{stc}H_{tot})$$

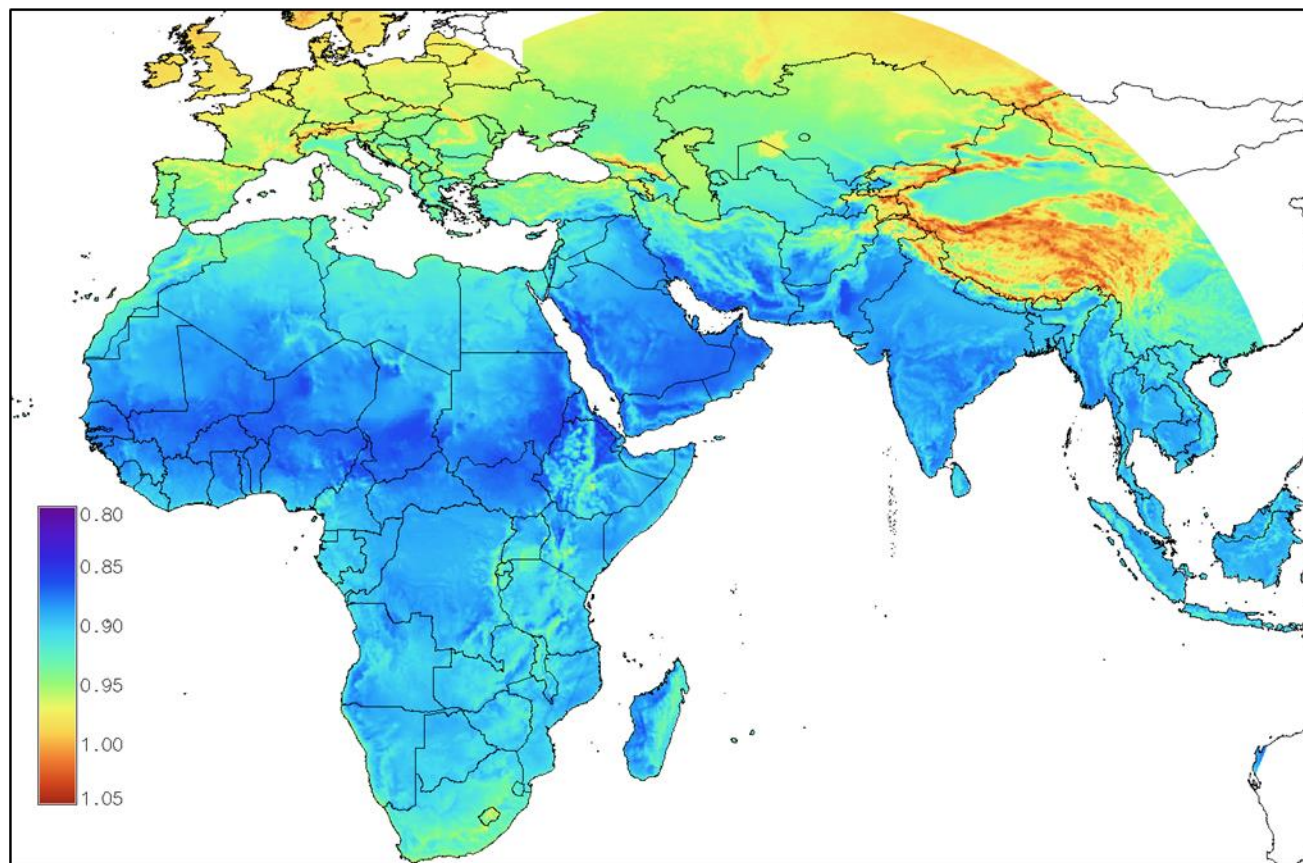
H_{tot} is the total in-plane irradiation (kWh/m²)

E_{tot} is the total module energy output during the same period (kWh)

The reference climate year is represented by a sets of hourly values of G, spectral content, wind speed and T.

MPR, all effects, c-Si

Annual average
MPR, AOI and
spectrally
corrected,
temperature &
wind.
c-Si modules



The research work presented was partly carried out within the EMRP ENG55 project Photoclass "Towards an energy-based parameter for photovoltaic classification". The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

What ESTI can do for you:

- a) Calibration (fee-free) of reference devices for national laboratories and verification on request of PV technologies developed in EU programmes
- b) Collaborative research with industrial partners on new materials and/or concepts to promote European competitiveness and improved standards.
- c) Commercial calibration service for external customers, focusing on new technologies and respecting subsidiarity principles.

Stay in touch

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