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Precision PV Performance Assessment at ESTI

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- Uncertainty in power measurement
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- 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

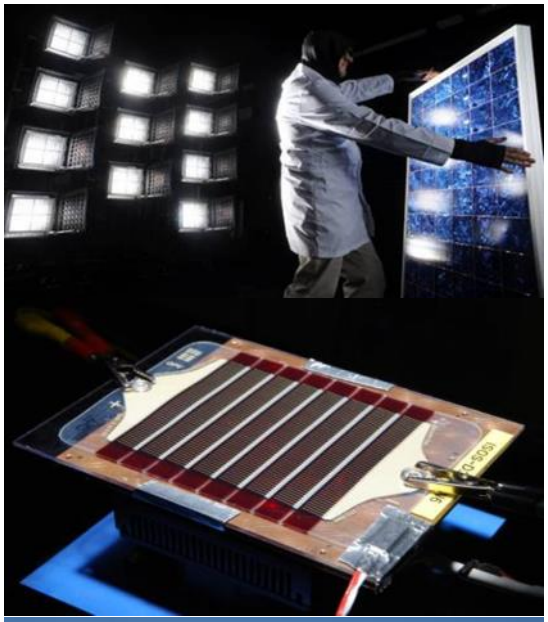
- Pasan flash system (2 m x 2m)
- Oriel system (cells, modules)

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)



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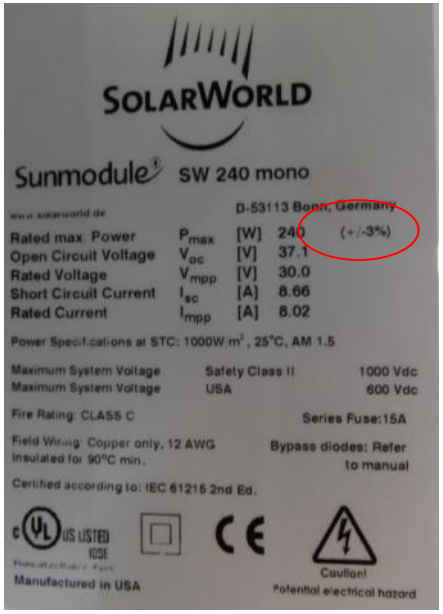
Power (and Efficiency) Measurement Uncertainty

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[j]	68.8	ESTI (6/14)
Organic	8.7 ± 0.3[m]	802 (da)	17.47	0.569[j]	70.4	AIST (5/14)



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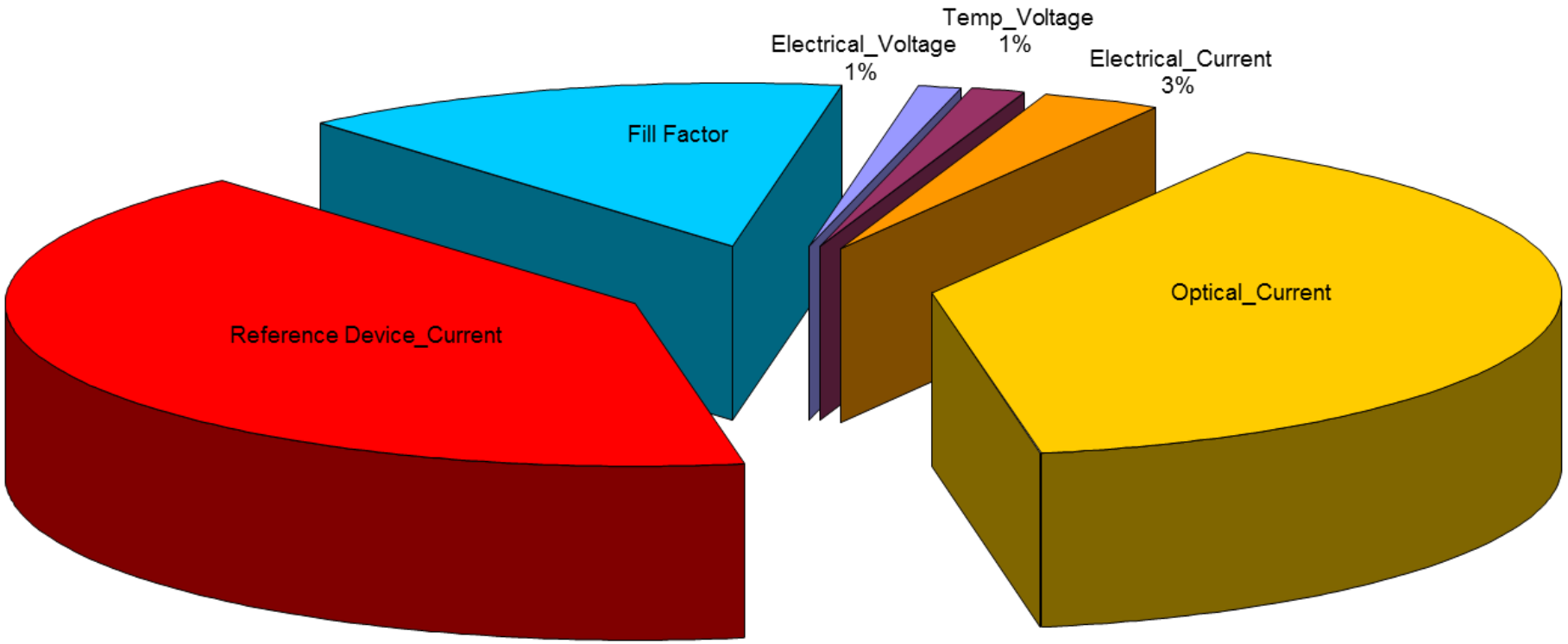
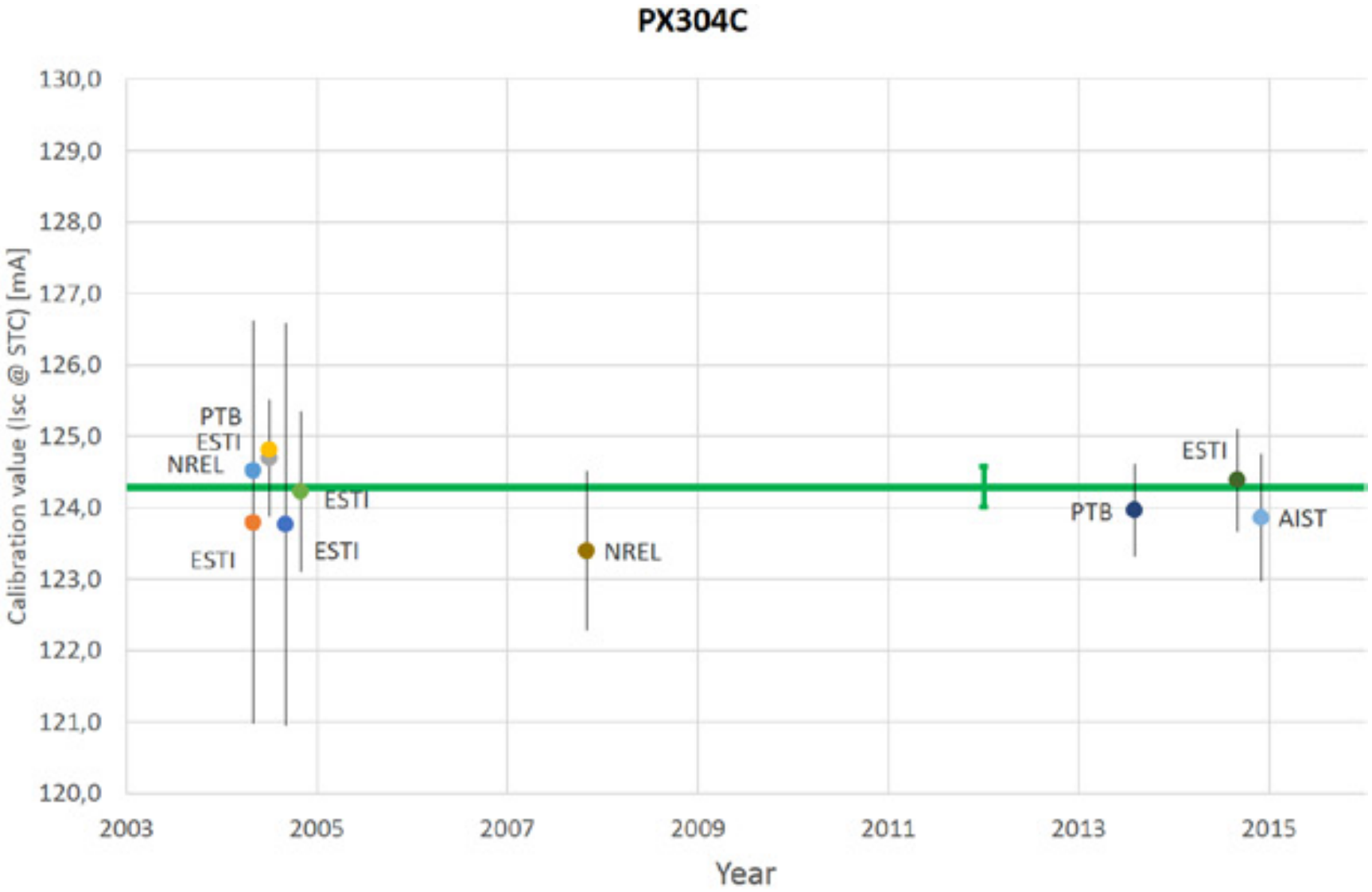
Example of contributions to P_{max} uncertainty



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



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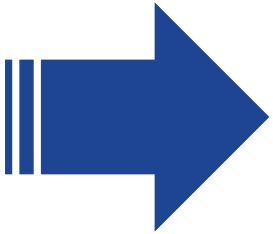
New ESTI primary reference cell analysis

- 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.

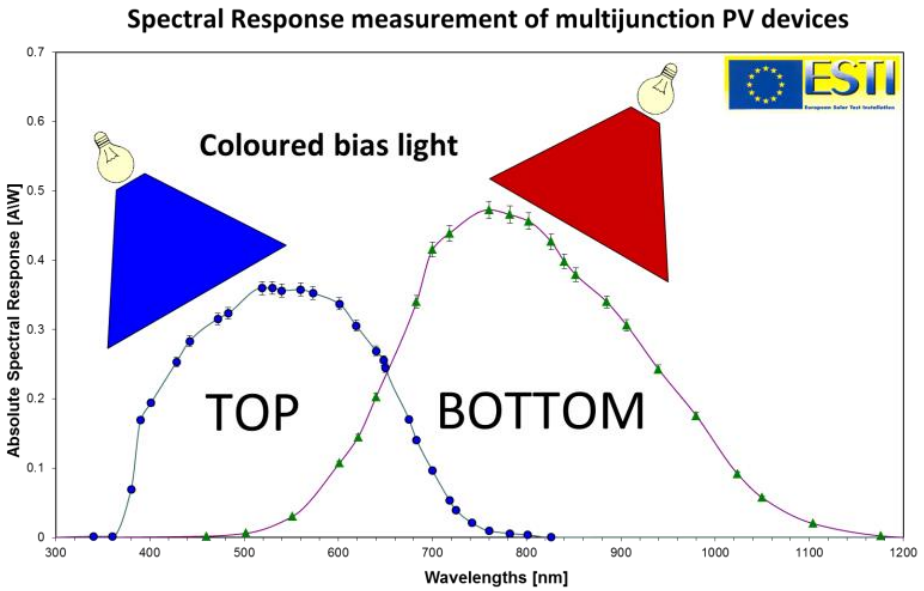


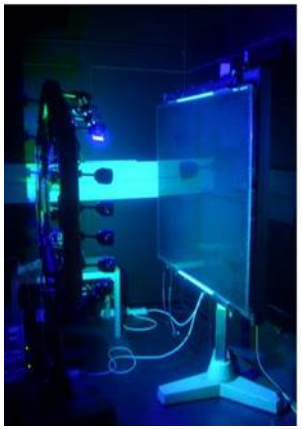
Should be possible to calibrate ref cells by cheaper and faster secondary methods, with UCs ≤ primary methods.

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

DUT = Bottom junction

***MMF*$_{TOP}$**

***MMF*$_{BOTTOM}$**

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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.

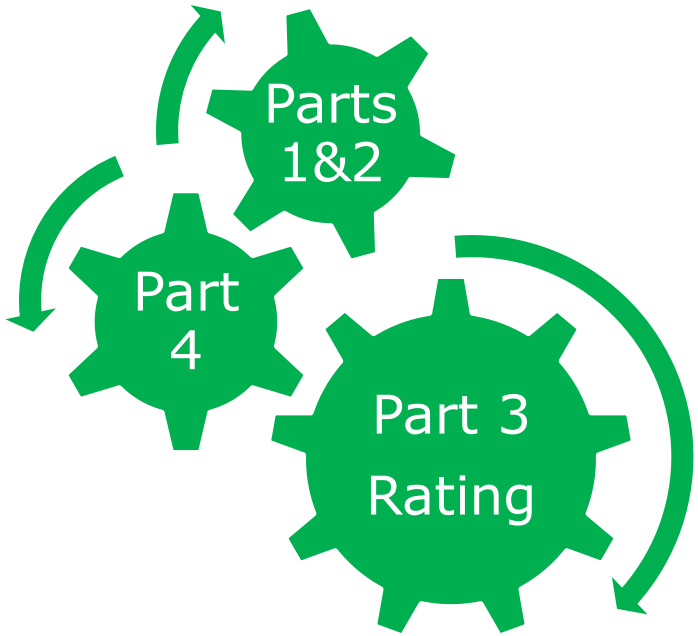
IEC 61853 series: photovoltaic modules performance testing and energy rating

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)



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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:

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

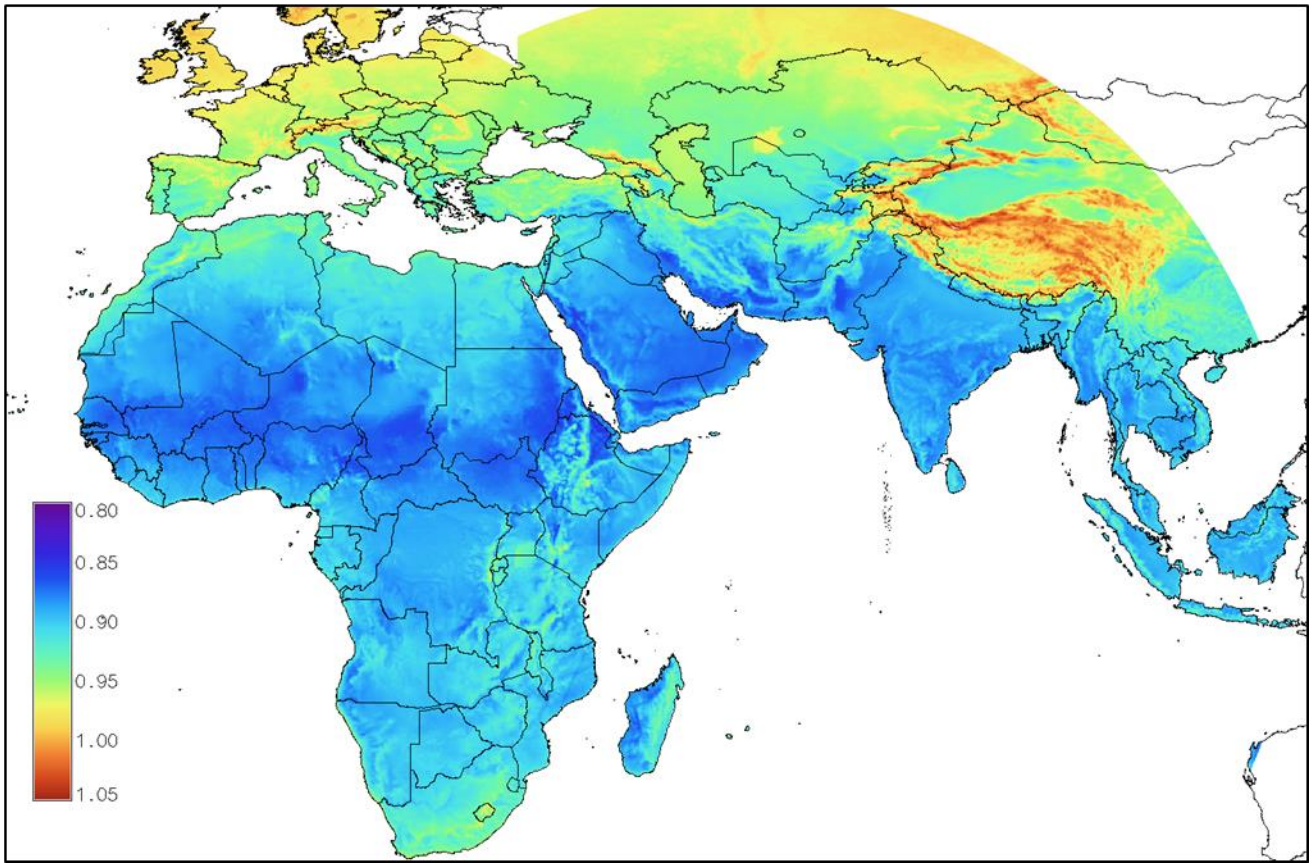
H_{tot} is the total in-plane irradiation (kWh/m^2)

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



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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.

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