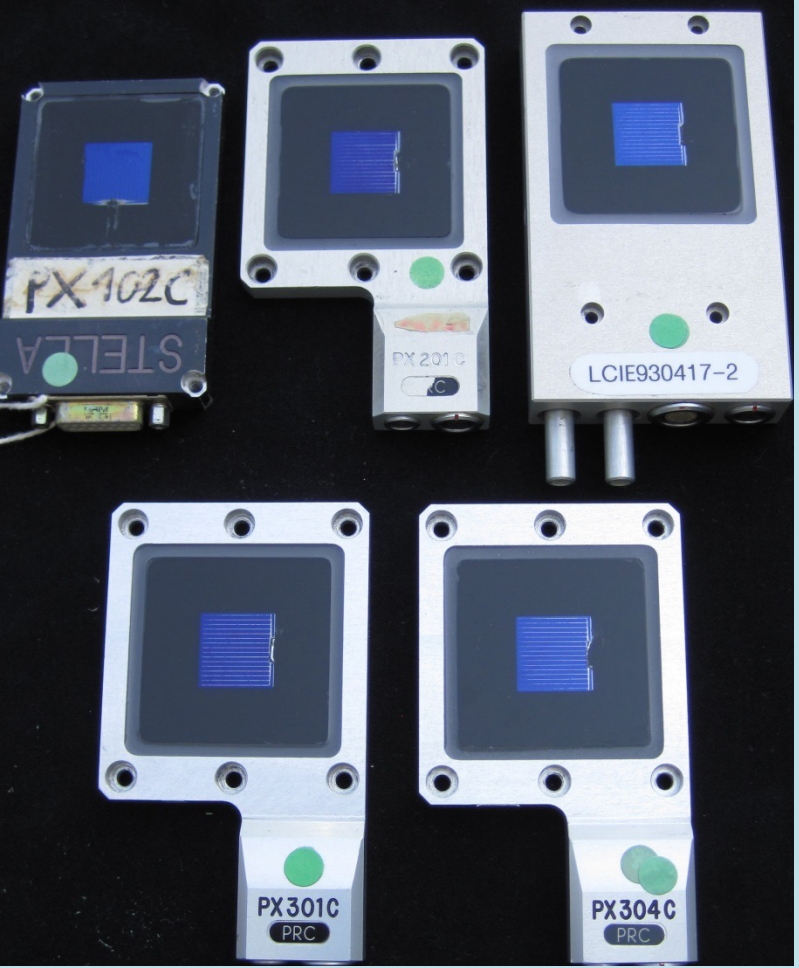


The European Commission's science and knowledge service

Joint Research Centre

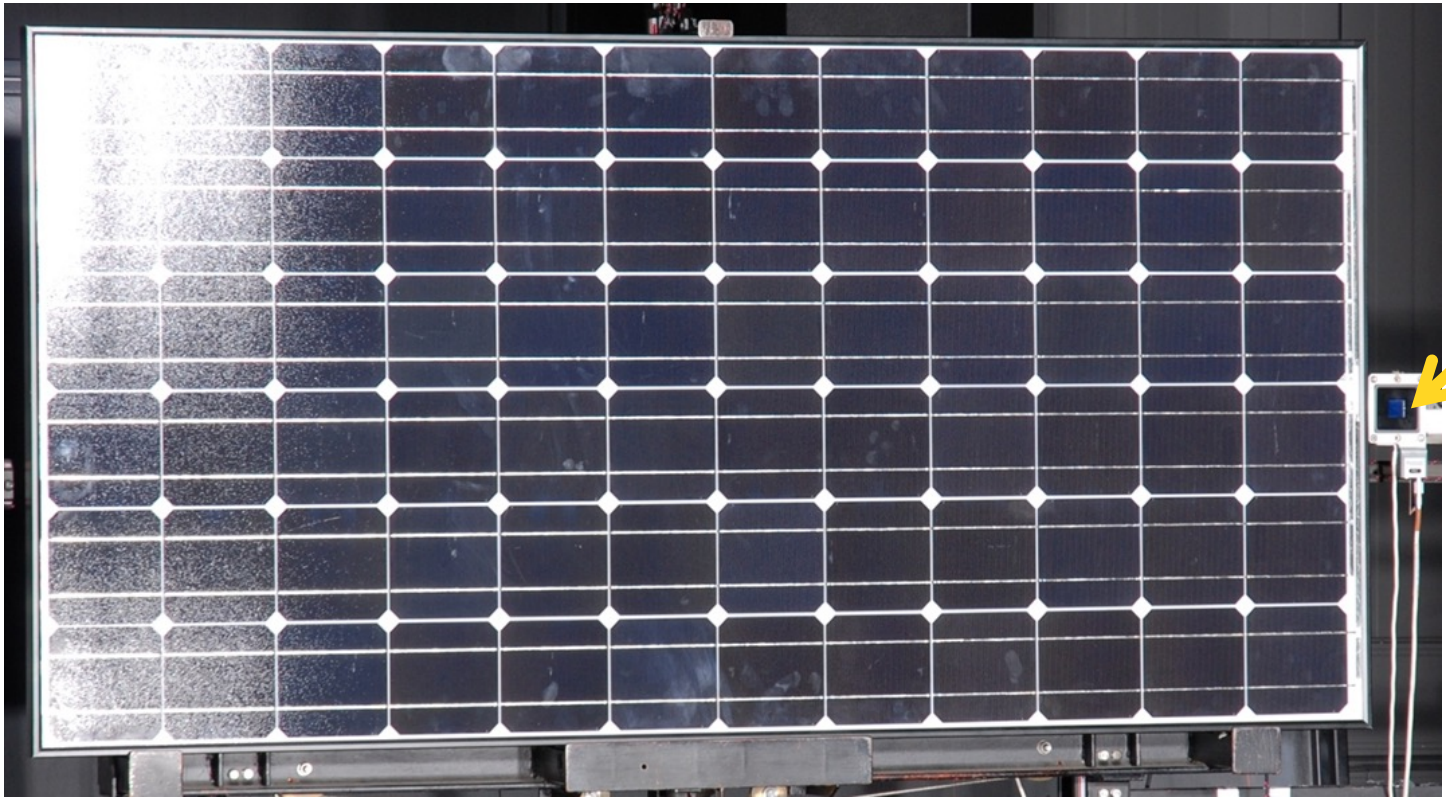
From Sunlight to Power
The History of Achieving a Globally Harmonised Approach to Photovoltaic Measurement

Harald Müllejans
Willem Zaaiman, Ewan D. Dunlop

European Solar Test Installation (ESTI)

European Commission

What is the maximum power of this PV module?

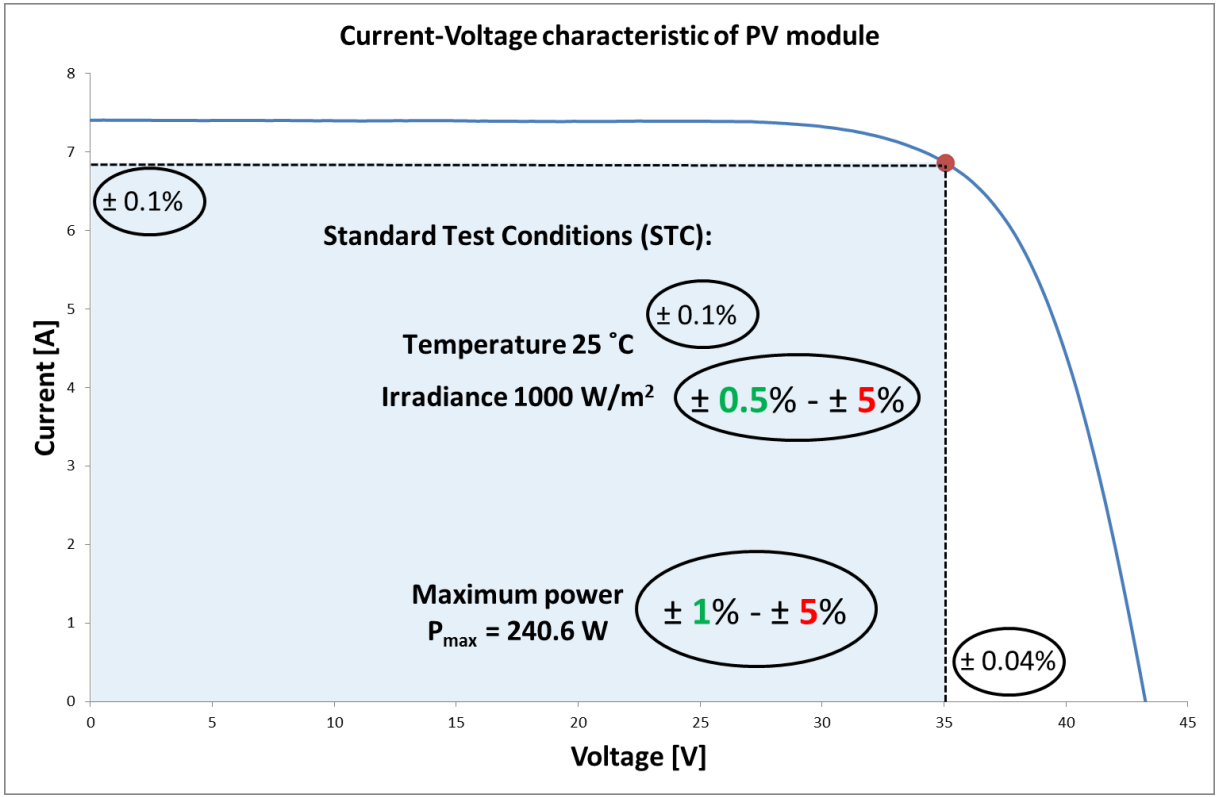


PV reference cell as irradiance sensor

Determination of maximum power

- Module label
- Power matrix
- Energy rating
- STC (1000 W/m²)

Maximum power is power/irradiance



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Why not use cavities for PV modules?

- Impractical
  - Slow response
  - PV module temperature
  - Weather dependent
  - Only direct sunlight
- Complex spectral mismatch correction
  - PV devices have limited range of spectral responsivity

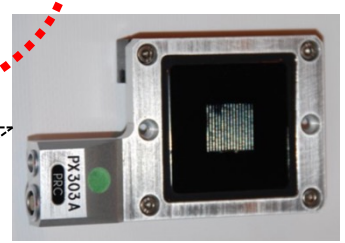
Solar irradiance measurement

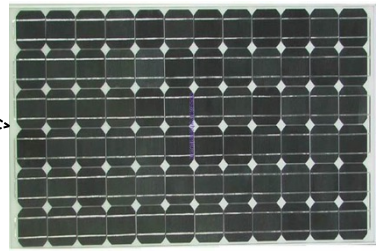
World Radiation Centre (WRC)
WMO mandate for PMOD, Davos (CH)

World Radiometric Reference (WRR)
primary reference for calibration of solar radiometers world-wide

World Standard Group (WSG)
6 absolute cavity radiometers

Traceability of PV device calibration (IEC 60904-4)





WRR

SI

Primary standard

Secondary standard

Primary reference

Secondary reference

Working reference

WSG

Cryogenic radiometer

Black body

IPC

Absolute radiometer

Trap detector

Standard lamp

ISO 9059

IEC 60904-4

Normal Incidence Pyrheliometer

PV reference device

ISO 9846

IEC 60904-2

Pyranometer

PV reference device

ISO 9847

IEC 60904-2

Pyranometer

PV reference device

From (sun-)light to electrical power

European Commission

World Photovoltaic Scale (WPVS)

Photovoltaic Solar Energy Project (PEP) of Summit (G7)

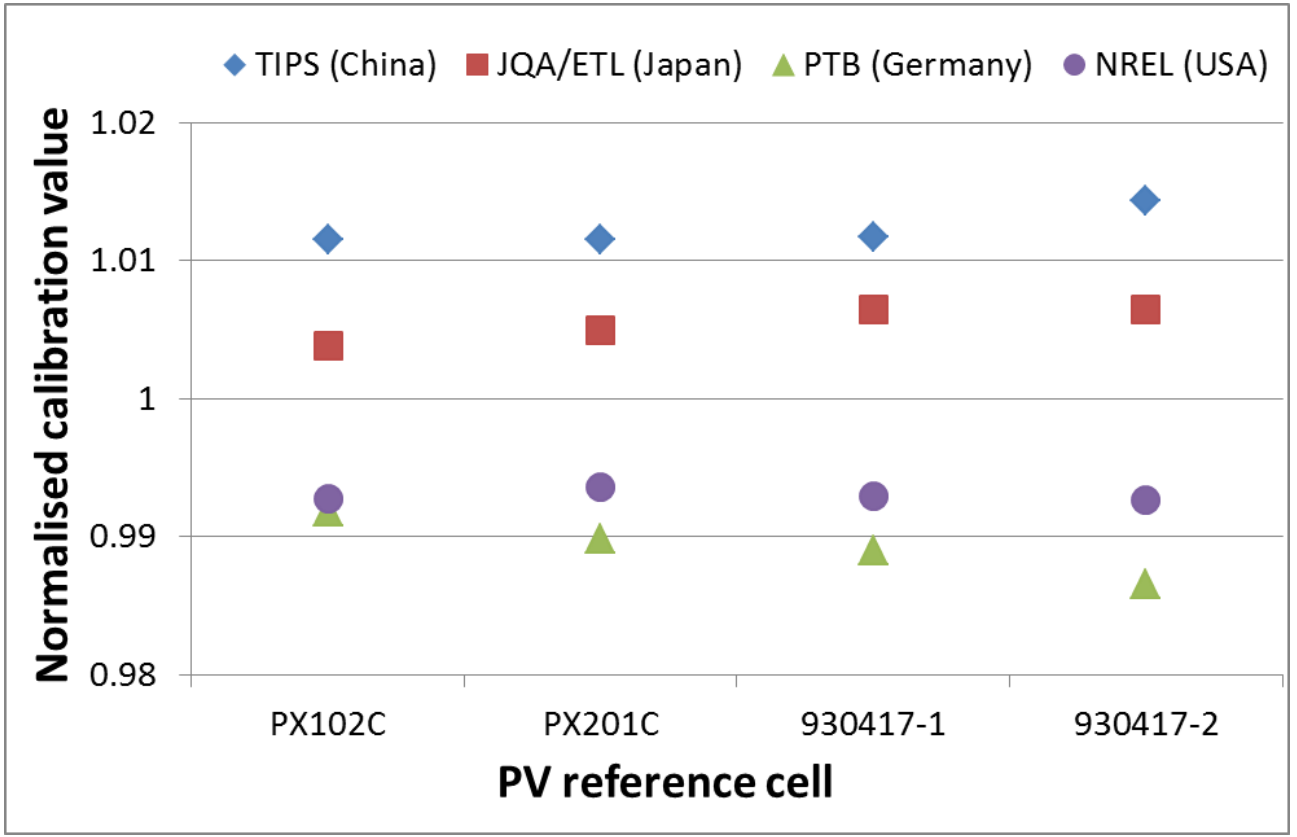
- PEP'84
  Dispersion of results larger than expected
- PEP'87
  Evaluation of primary calibration methods for accuracy and suitability for standardisation within IEC
- PEP'93
  International scale for PV irradiance measurement
  World Photovoltaic Scale (WPVS) established
  - average of four methods by four laboratories in the world
  - uncertainty taken as standard deviation of data

WPVS: Birth

PEP'93

- Four laboratories
- Four methods
- Arithmetic average
- UC (=2*σ) = 1.9%

WPVS



Osterwald et al. "The results of the PEP'93 intercomparison of reference cell calibrations and newer technology performance measurements: Final report" NREL/TP-520-23477 (1998)
Osterwald et al. "The World Photovoltaic Scale: An International Reference Cell Calibration Program" Prog. Photovolt: Res. Appl. **7** (1999) 287-297

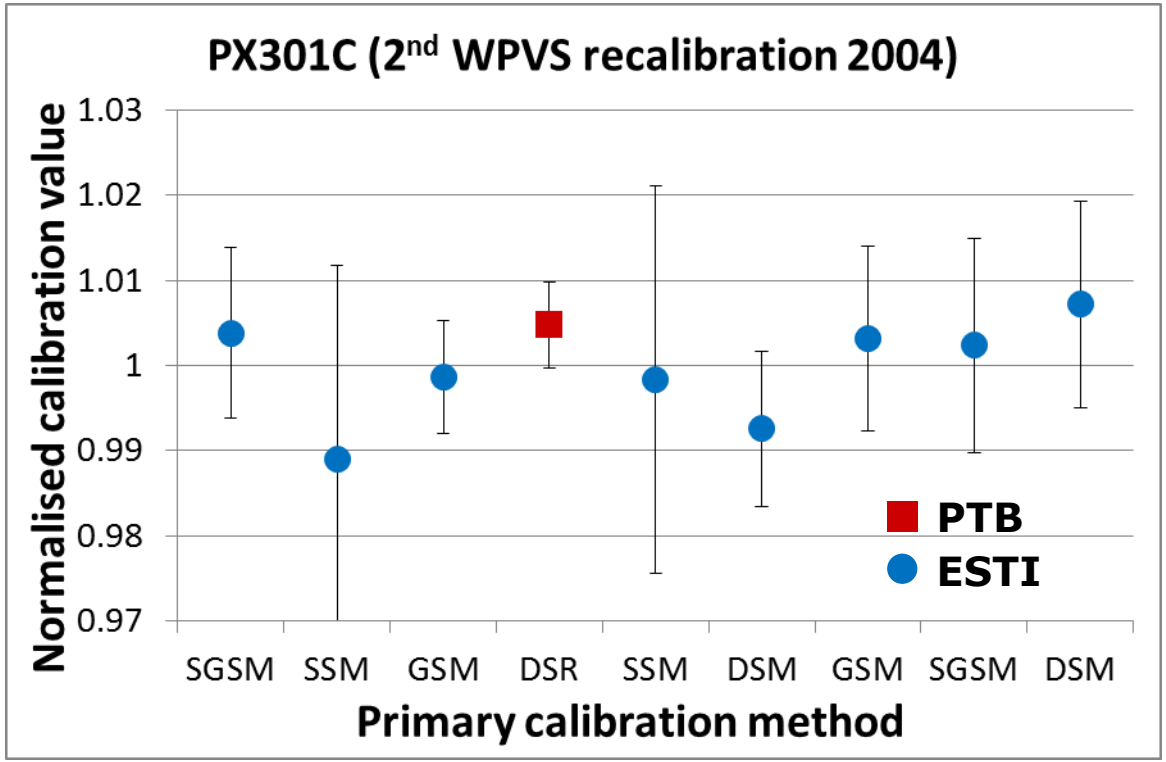
European Commission

WPVS: Recalibrations since PEP'93

1st : 1999 at NREL
- new WPVS values assigned to the cells
- UC unchanged

2nd : 2004 with PTB as coordinator (star-like)
- check for consistency between laboratories
- no new WPVS values
- ESTI implemented several primary calibration methods with multiple traceability

3rd : planned



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WPVS: Implementation

- European Solar Test Installation (ESTI): traceability to WPVS (since 1997)
  i.e. average of world's best labs

- Other labs: only for consistency

2005: ESTI reference cell set established (based on 2nd recalibration 2004)

2008: Update due to new reference spectrum IEC 60904-3 ed.2 (2008)

2015: Update to key comparison reference value (**KCRV**) concept and shift of WRR to SI

ESTI reference cell set

Five c-Si reference cells

- 3 original WPVS: PX102C, PX201C, 930417-2
- 2 new (2nd recal): PX301C and PX304C

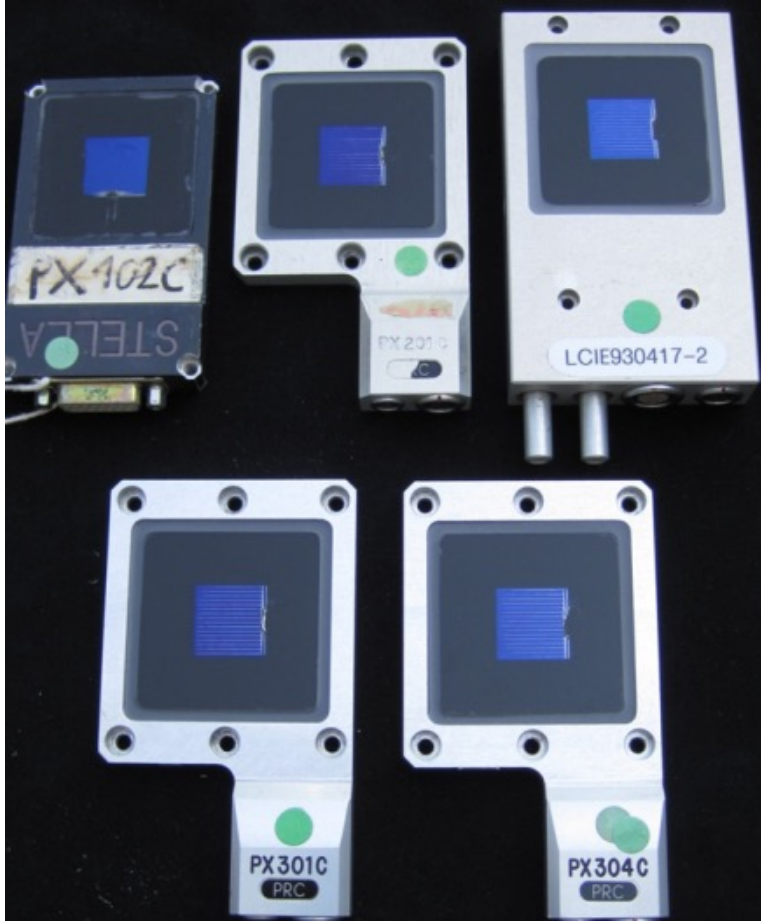
Calibration value 2005: WPVS approach

- average of all primary calibrations
- UC (=2*σ_m) = 0.64%

Updated in 2008

- new IEC 60904-3 ed.2 (+0.65%)

Long-term stability monitored



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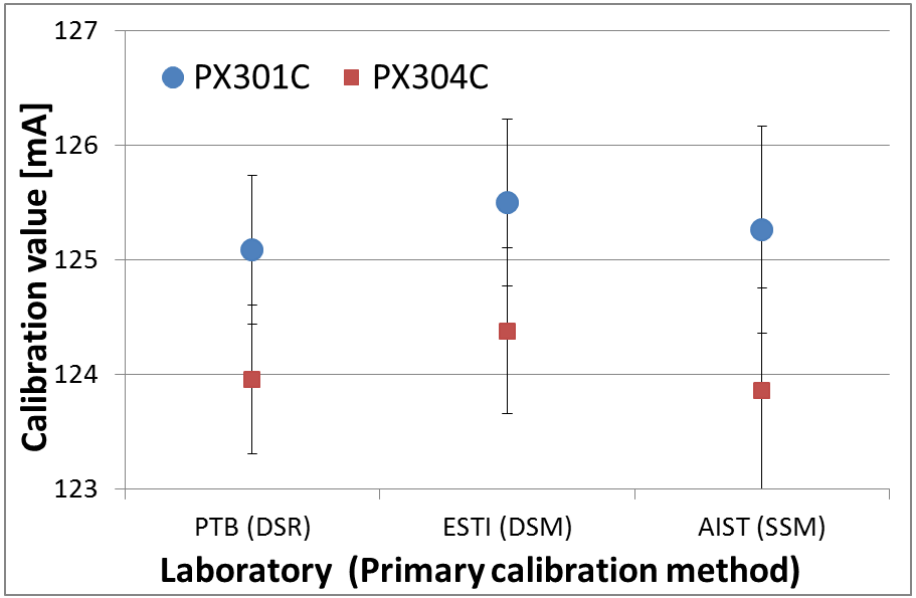
ESTI reference cell set – 2015 update

More primary calibration values

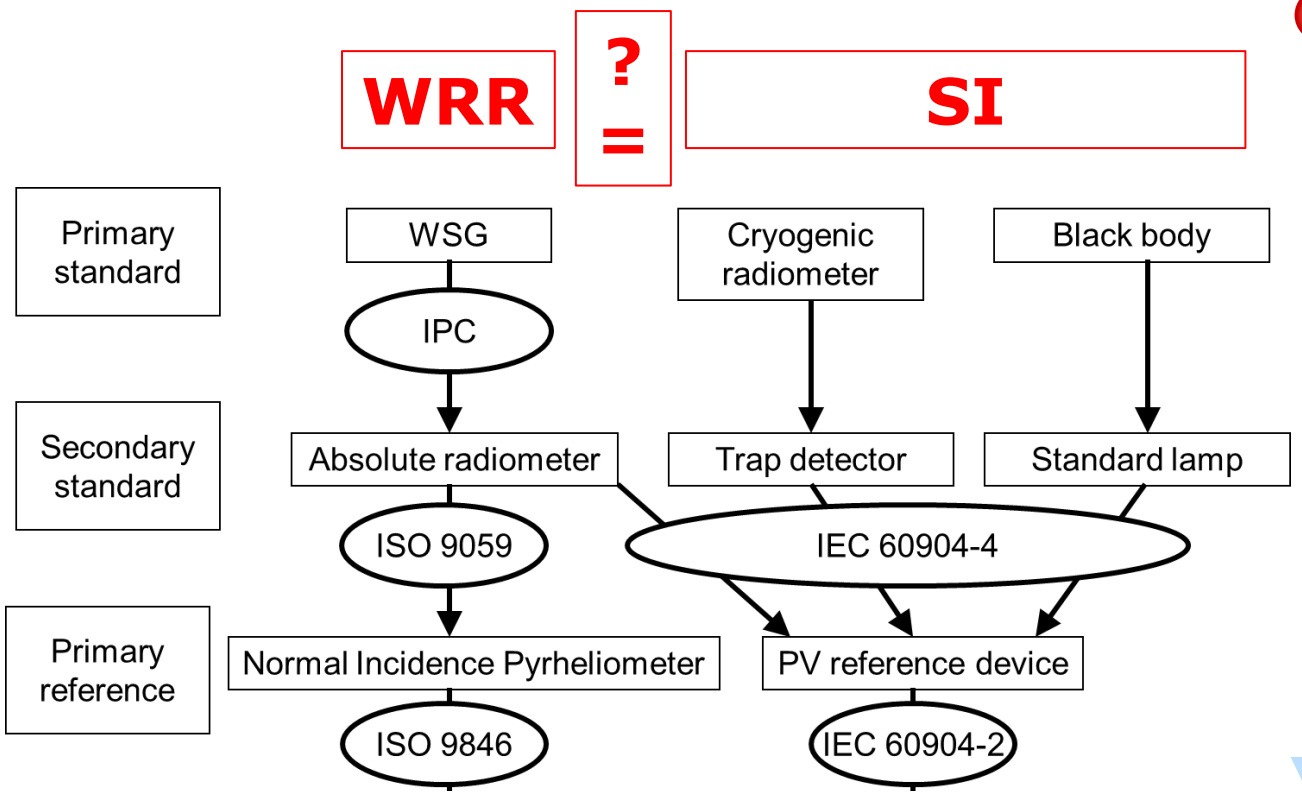
Advanced data analysis
- KCRV approach
- **weighted** average (based on declared UCs)
- UC of weighted average (≈0.25%)

Deviation between WRR and SI irradiance scale
- implemented in the analysis
- also retroactively



E_n	PTB-ESTI	ESTI-AIST	AIST-PTB
PX301C	0.45	0.21	0.15
PX304C	0.47	0.48	0.09

Irradiance scale equivalence



indistinguishable

2012

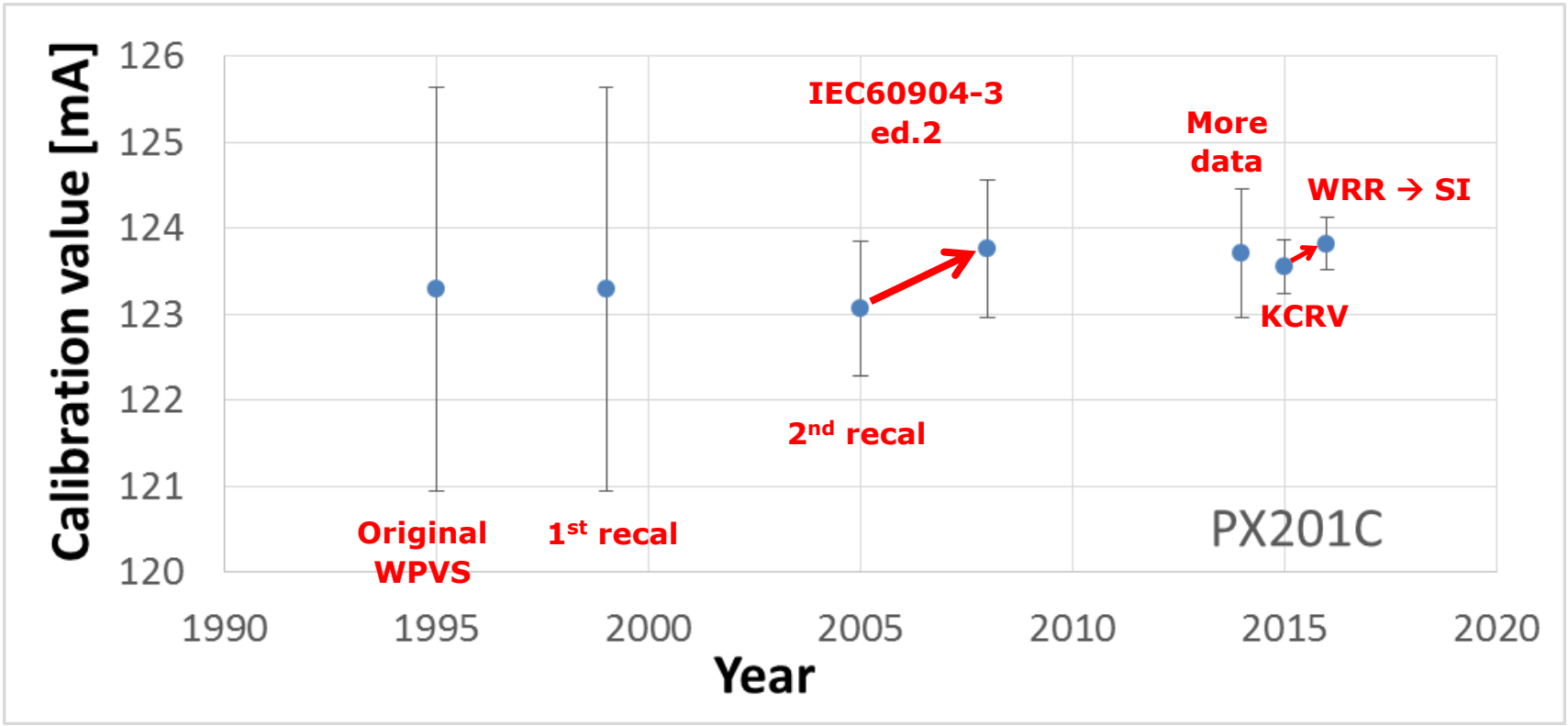
- differ
- WRR +0.34%
- present but not detected previously due to instrumental limitations
- WRR stable

Shift to SI scale

ISO/IEC 17025

European Commission

WPVS: Evolution of calibration value for one cell



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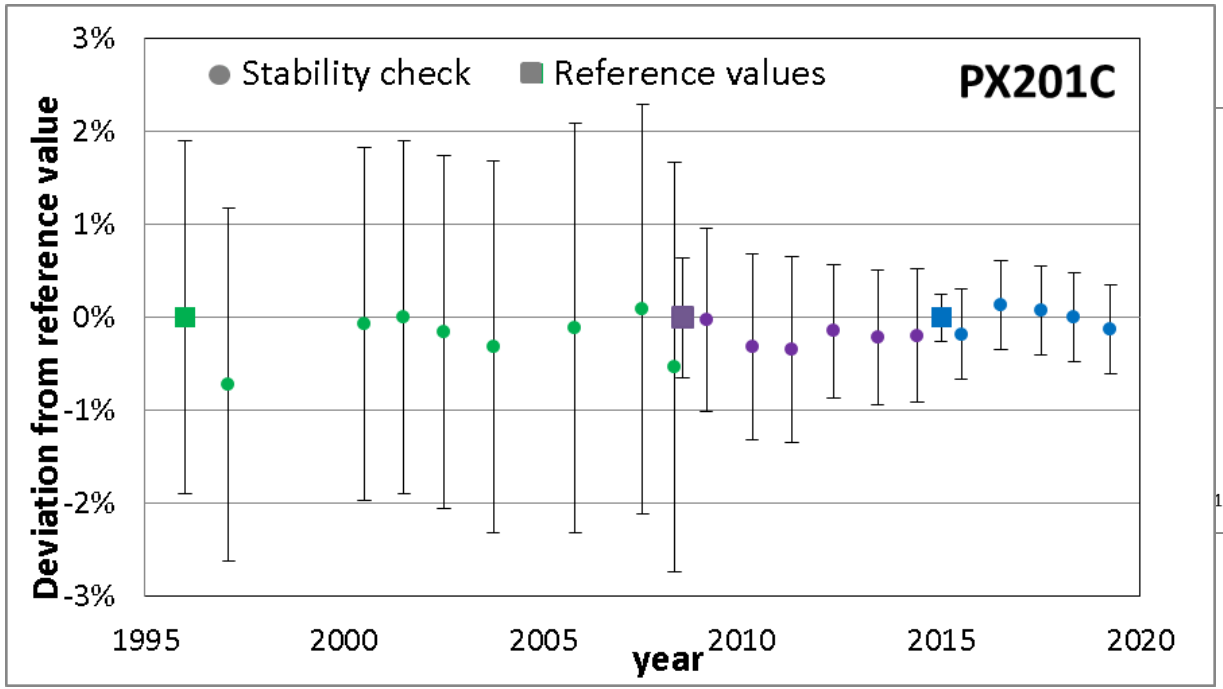
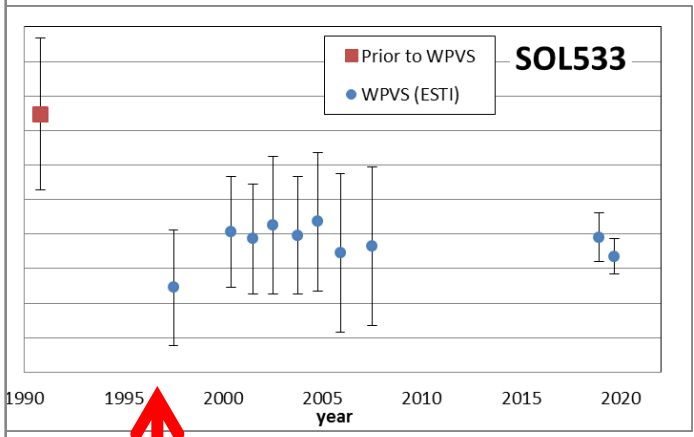
Long-term stability of PV cells





WPVS established

No drift detectable during annual verification

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ESTI reference cell set: Primary calibration data

Year		1993	1994	1994	1995	1999	2004	2004	2004	2004	2004	2004	2005	2005	2005	2007	2013	2014	2014	2016	2016	2019	2019
Laboratory		NREL	JQA/ETL	PTB	TIPS	NREL	ESTI	ESTI	ESTI	PTB	ESTI	NREL	ESTI	ESTI	ESTI	NREL	PTB	ESTI	AIST	PTB	ESTI	ESTI	ESTI
Method		DSM	SSM	DSR	SL	DSM	SGSM	SSM	GSM	DSR	SSM	DSM	GSM	SGSM	DSM	DSM	DSR	DSM	SSM	DSR	DSM	SSM	SSM
PX102C	[mA]	117.42	118.33	116.91	119.24	116.85	116.89	117.52	117.06	116.66	117.34	116.30	117.22	116.29									
PX201C	[mA]	123.74	124.73	122.86	125.55		123.56	123.29	123.76	124.27	123.79	123.33	124.45	123.72	124.75			123.48			123.67		
930417-2	[mA]	123.49	124.78	122.31	125.76	123.70	123.99	123.79	124.27	124.62	123.17	123.48	124.19	123.42				123.80		123.66			
PX301C	[mA]						125.20	123.73	125.36	125.70	124.89	124.59	125.92	125.02	126.43		125.09	125.50	125.26		125.55	125.5	124.3
PX304C	[mA]						124.52	123.80	124.69	124.80	123.77	124.23				123.40	123.96	124.38	123.86			124.1	122.9
UC	k=2	1.0%	1.4%	1.0%	2.7%	1.0%	1.0%	2.3%	0.66%	0.50%	2.3%	0.91%	1.1%	1.3%	1.2%	0.91%	0.52%	0.58%	0.72%	0.50%	0.48%	3.0%	3.0%

	KCRV [mA]	UC (k=2) [mA]	UC (k=2) [%]
PX102C	116.92	0.31	0.27
PX201C	123.79	0.27	0.22
930417-2	123.92	0.28	0.22
PX301C	125.39	0.25	0.20
PX304C	124.28	0.29	0.23

Weighted mean

$$\overline{x} = \frac{\sum_{i=1}^{n} \frac{x_i}{UC_i^2}}{\sum_{i=1}^{n} \frac{1}{UC_i^2}}$$

Expanded UC (k=2)

$$\overline{UC} = \frac{1}{\sqrt{\sum_{i=1}^{n} \frac{1}{UC_i^2}}}$$

Data consistency check (95% confidence level)

$$E_{n_i} = \frac{x_i - \overline{x}}{\sqrt{(UC_i)^2 + \left(\overline{UC}\right)^2}} \in [-1;1]$$

(ISO/IEC 17043)

E_n for single primary calibration against KCRV																						
PX102C	0.41	0.84	-0.01	0.72	-0.06	-0.03	0.22	0.17	-0.39	0.16	-0.56	0.23	-0.40									
PX201C	-0.04	0.53	-0.74	0.52		-0.18	-0.18	-0.03	0.71	0.00	-0.40	0.48	-0.04	0.37			-0.40			-0.18		
930417-2	-0.34	0.49	-1.28	0.54	-0.17	0.06	-0.04	0.41	1.03	-0.26	-0.38	0.16	-0.20				-0.15		-0.38			
PX301C						-0.15	-0.59	-0.04	0.46	-0.18	-0.69	0.38	-0.23	0.67		-0.43	0.14	-0.14		0.24	0.03	-0.29
PX304C						0.19	-0.17	0.47	0.75	-0.18	-0.04				-0.76	-0.45	0.13	-0.45			-0.05	-0.37

χ^2- test $F_N(\overline{x}) = \sum_{i=1}^{N} \left(\frac{x_i - \overline{x}}{UC_i/2} \right)^2 \leq \chi^2_{N-1,\alpha}$

Analysis acording to COX in Metrologia 44 (2007) p. 189																							N	chi^2	FN
PX102C	0.724	2.896	0.000	2.077	0.014	0.003	0.200	0.131	0.797	0.098	1.374	0.220	0.654										13	21.03	**9.19**
PX201C	0.006	1.167	2.277	1.082		0.135	0.125	0.004	2.418	0.000	0.663	0.956	0.007	0.541			0.735			0.155			15	23.68	**10.27**
930417-2	0.478	0.976	6.905	1.178	0.123	0.014	0.008	0.741	5.091	0.283	0.605	0.111	0.156				0.106		0.687				15	23.68	**17.46**
PX301C						0.093	1.386	0.006	0.968	0.124	1.995	0.595	0.222	1.846		0.856	0.090	0.084		0.279	0.003	0.342	15	23.68	**8.89**
PX304C						0.146	0.117	0.982	2.755	0.132	0.009				2.469	0.983	0.074	0.896			0.010	0.562	12	19.68	**9.13**
all																							**70**	89.39	**54.95**

Note: data more consistent after shift from WRR to SI

H. Müllejans, W. Zaaiman and E.D. Dunlop "Reduction of uncertainties for photovoltaic reference cells" *Metrologia* **52** (2015) 646-653

Long-term weighted average

- Reference cells are stable (verified separately)
- Stated UCs are reliable
- Calibrations are uncorrelated
  - different traceability chain
  - long period

	KCRV [mA]	UC (k=2) [mA]	UC (k=2) [%]
PX102C	116.92	0.31	0.27
PX201C	123.79	0.27	0.22
930417-2	123.92	0.28	0.22
PX301C	125.39	0.25	0.20
PX304C	124.28	0.29	0.23

1 result per lab / method

	KCRV [mA]	UC (k=2) [mA]	UC (k=2) [%]
PX102C	116.81	0.43	0.37
PX201C	123.96	0.36	0.29
930417-2	123.78	0.40	0.32
PX301C	125.27	0.35	0.28
PX304C	124.15	0.34	0.27

Significance

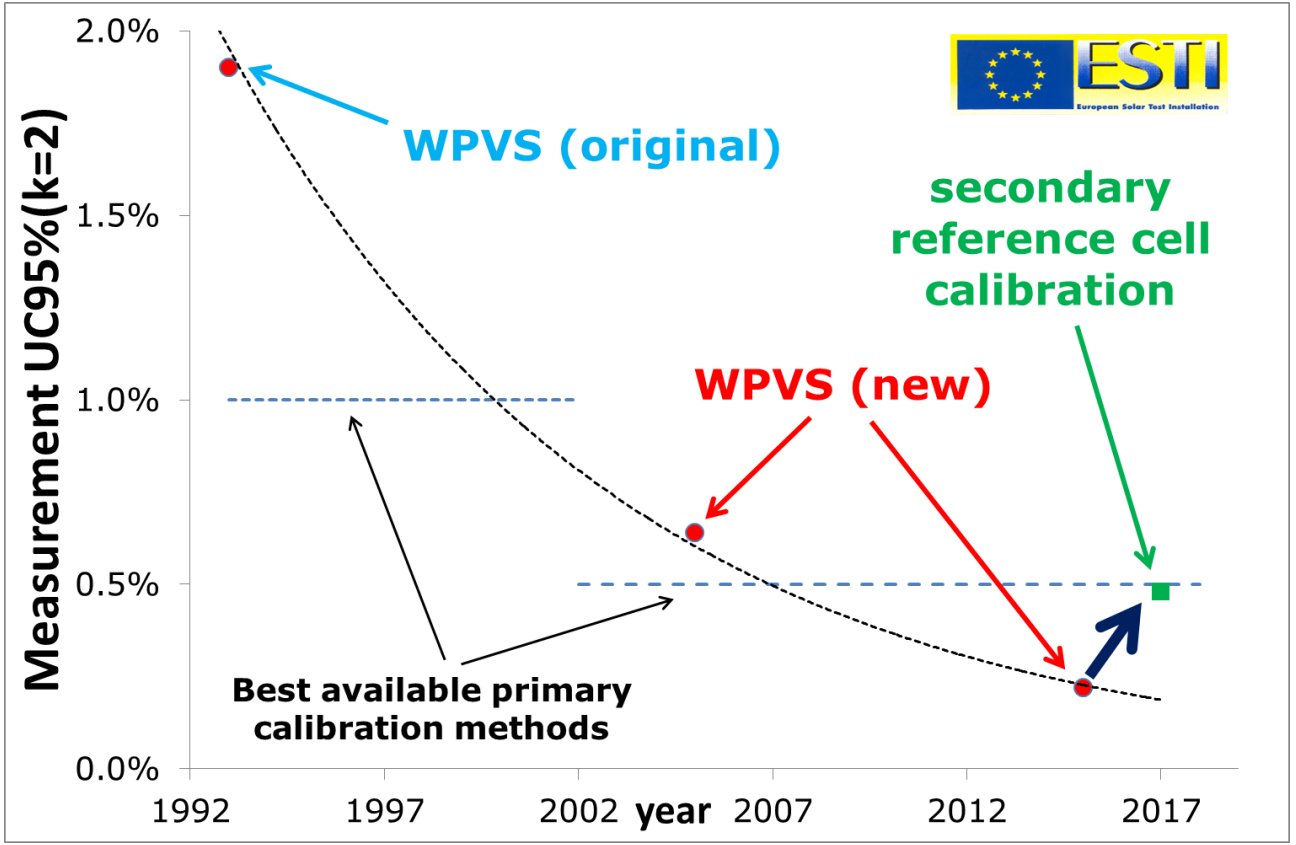
ESTI reference cell set

"WSG" for PV devices

"True" WPV**S**

Stable

Highest possible reliability and accuracy for PV devices



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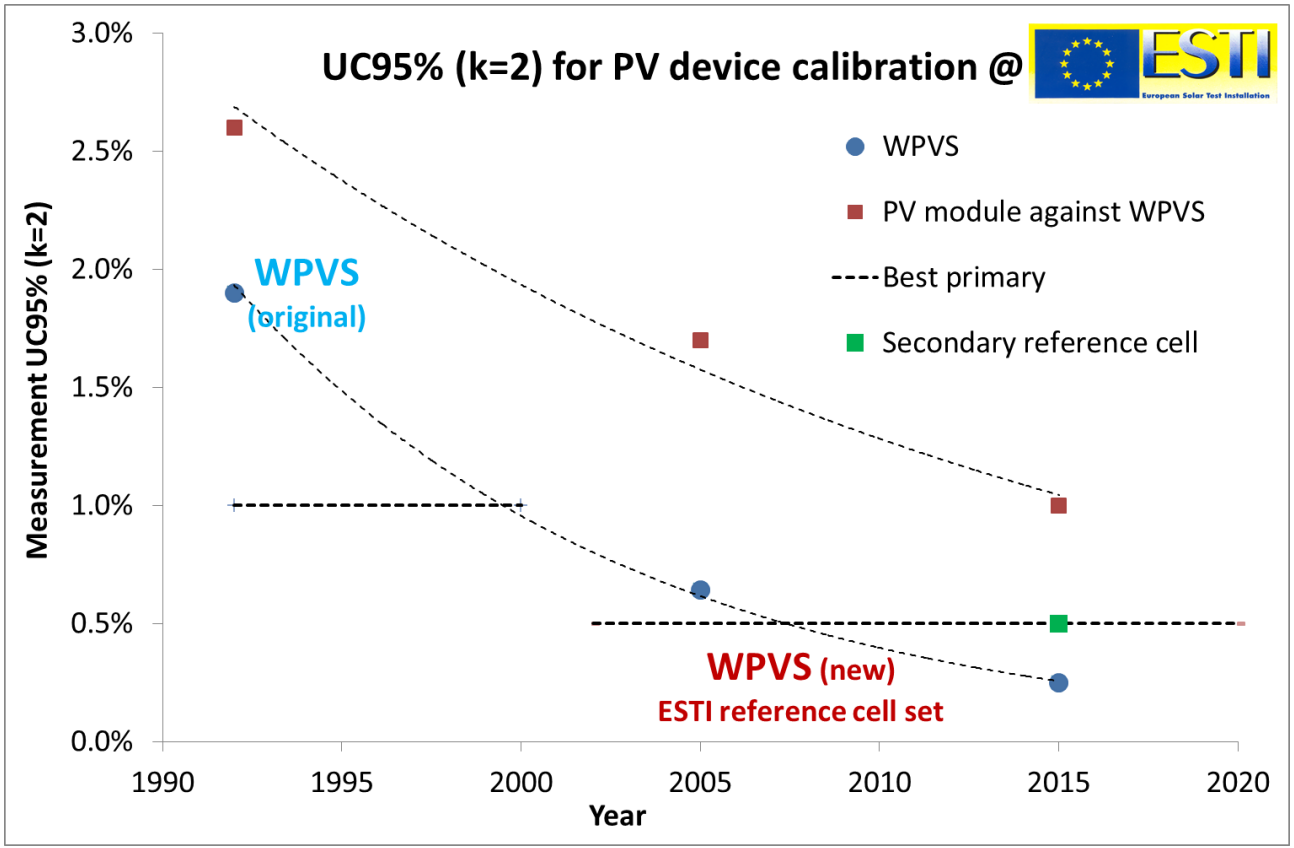
Use in PV module calibration

Calibration for clients

Traceability chain

ISO/IEC 17025 accreditation

ACCREDIA
L'ENTE ITALIANO DI ACCREDITAMENTO



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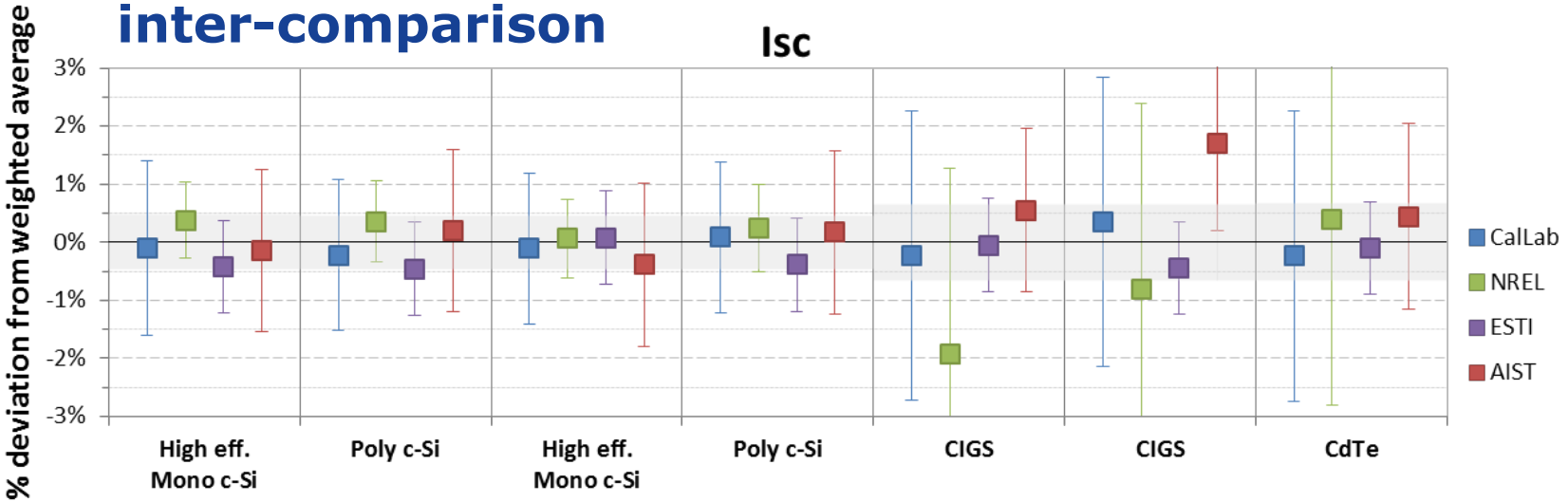
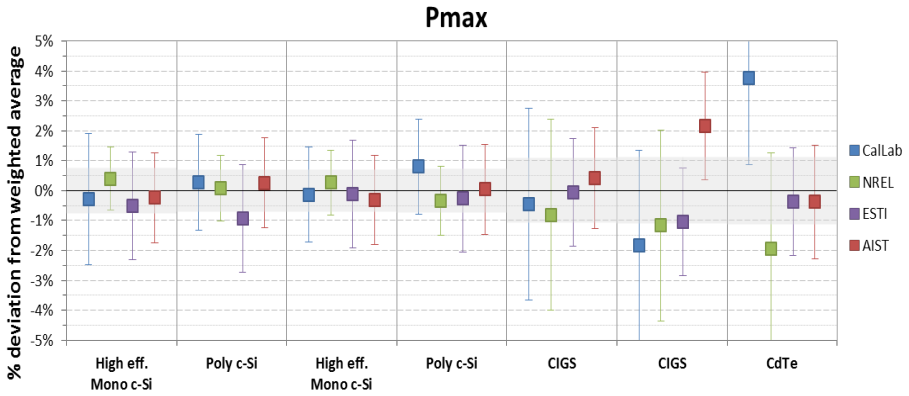
From WPVS to PV module calibration: a world-wide inter-comparison





World-wide equivalence of electrical performance measurements of PV modules of different technologies

E. Salis et al. "Improvements in world-wide intercomparison of PV module calibration" *Solar Energy* **155** (2017) 1451-1461

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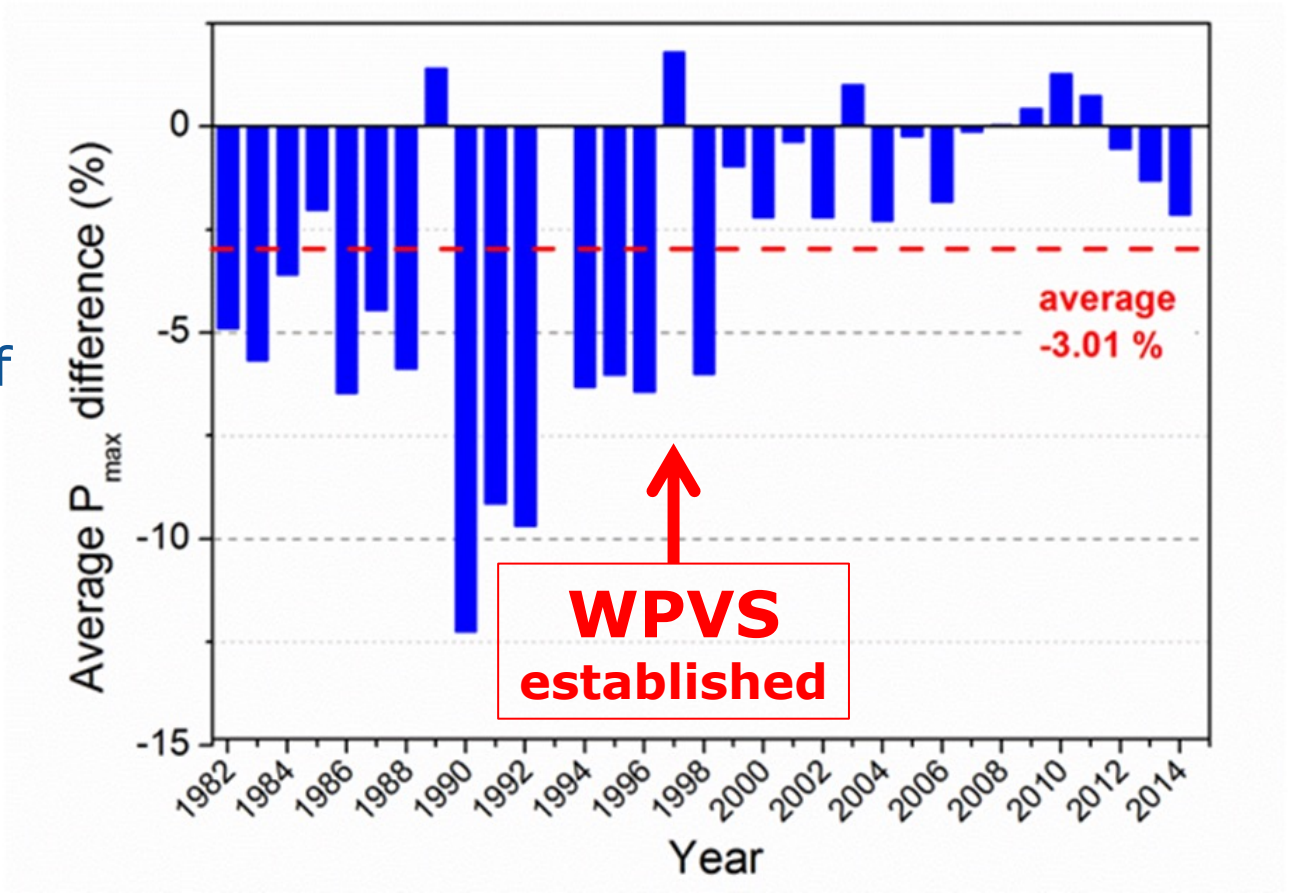
Verification of labelled PV module power

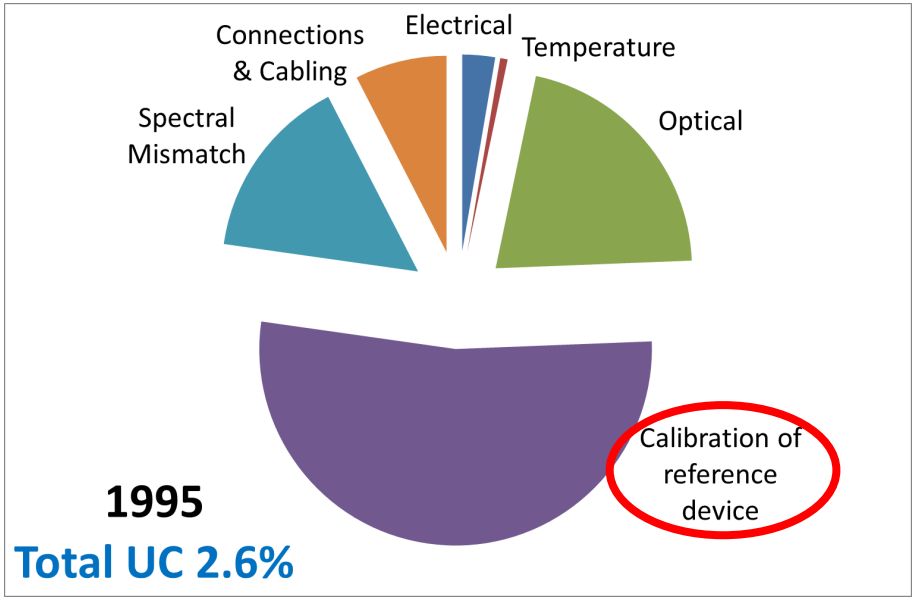
Better consistency of labelled and verified PV module power due to improved measurement capabilities



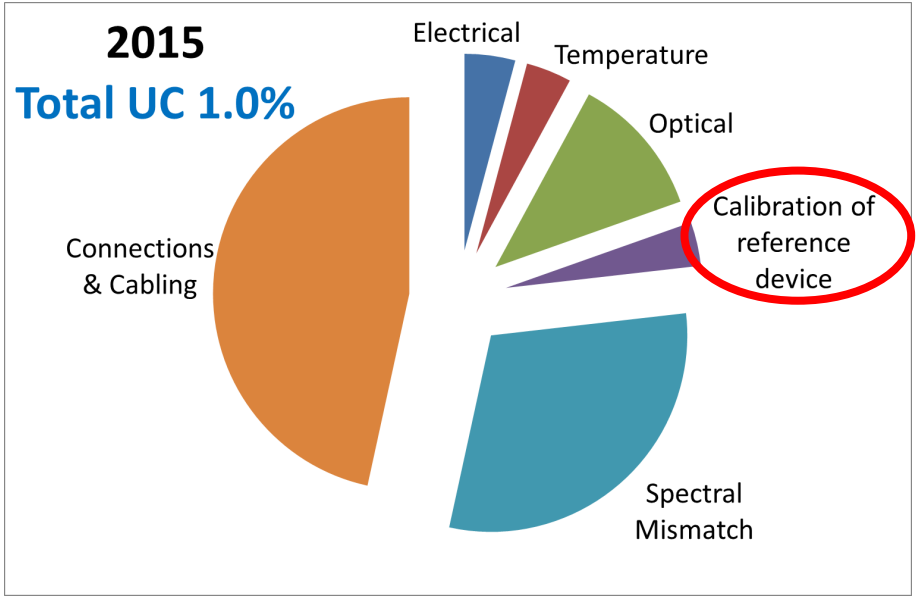
J. Lopez-Garcia and T. Sample "Evolution of measured module characteristics versus labelled module characteristics of crystalline silicon based PV modules" *Solar Energy* **160** (2018) 252-259

European Commission

Contributions to measurement UC of PV module maximum power at ESTI



Irradiance:
was major, now minor



Others: Spatial NU, SMM, Cabling & Capacitance, Device Stability

H. Müllejans, W. Zaaiman, R. Galleano "Analysis and mitigation of measurement uncertainties in the traceability chain for the calibration of photovoltaic devices" *Measurement Science and Technology* **20** (2009) 075101 1-12

WPVS vs WRR – ESTI reference cell set vs WSG

- PV devices are not inherently absolute
- Require calibration
- Various methods available

- ESTI reference cell set
- Average of methods
- Average of instruments (i.e. reference cells) would be possible

- Stability
- Stability better than reproducibility
- Long term average

- No official mandate

Summary

- 35 years of { calibration work; advanced data analysis }

WPVS UCs

1.9% (1995) → **0.25%** (today)

- Further reduction of UCs of irradiance measurement will require significant improvements in single primary calibration methods
- Secondary calibration of PV reference cells is possible with UC comparable to primary calibration
- PV module calibration has improved due to improvements in WPVS

Conclusions

World Photovoltaic Scale (WPVS)

- lowest UC world-wide for PV irradiance measurement based on average of primary calibrations with multiple traceability

ESTI reference cell set

- most advanced implementation of WPV**S** concept

Positive impact

- world-wide consistency in PV device power measurement
- improved accuracy for PV energy rating

European Commission

Acknowledgements

ESTI team,
especially
D. Pavanello

Long-term collaboration with PV reference laboratories
- PTB (Germany)
- NREL (USA)
- AIST (Japan)
- FhG-ISE (Germany)

Stay in touch

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