This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

go PV

June. 22nd

How conditions impact the characterization of PV modules

co-organized with Università di Catania

(09:00-10:00)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

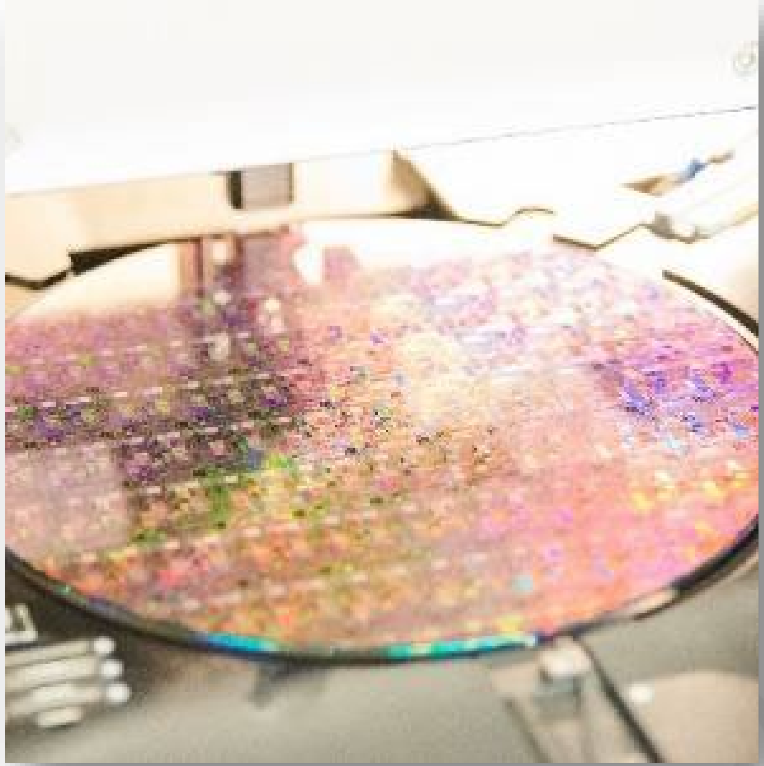
How conditions impact the characterization of PV modules
Romain COUDERC CEA-INES

Agenda

1. Quick overview of CEA-INES
2. PV modules characterization
3. Outdoor conditions
4. Conclusions

Technological Research

Economic Competitiveness



Defence & Security

French strategic independance

Nuclear Energy

French energetic independance

Fundamental Science

Material and Life Science

16,000 employees / 4 B€

► 750 patents/year

Technological Research

French economic
Competitiveness

4 500 employees
600 M€
600 patents/year

list

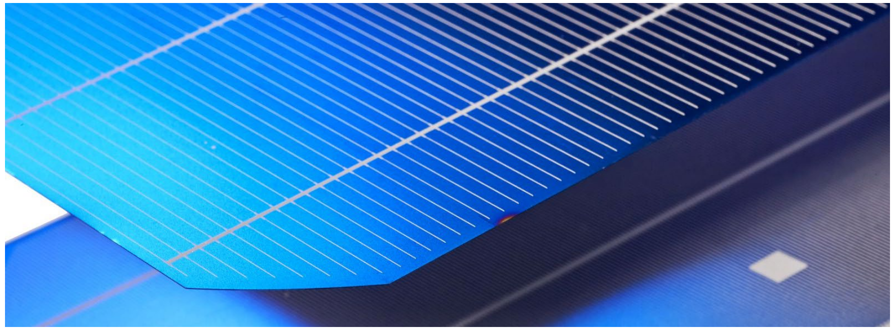
leti

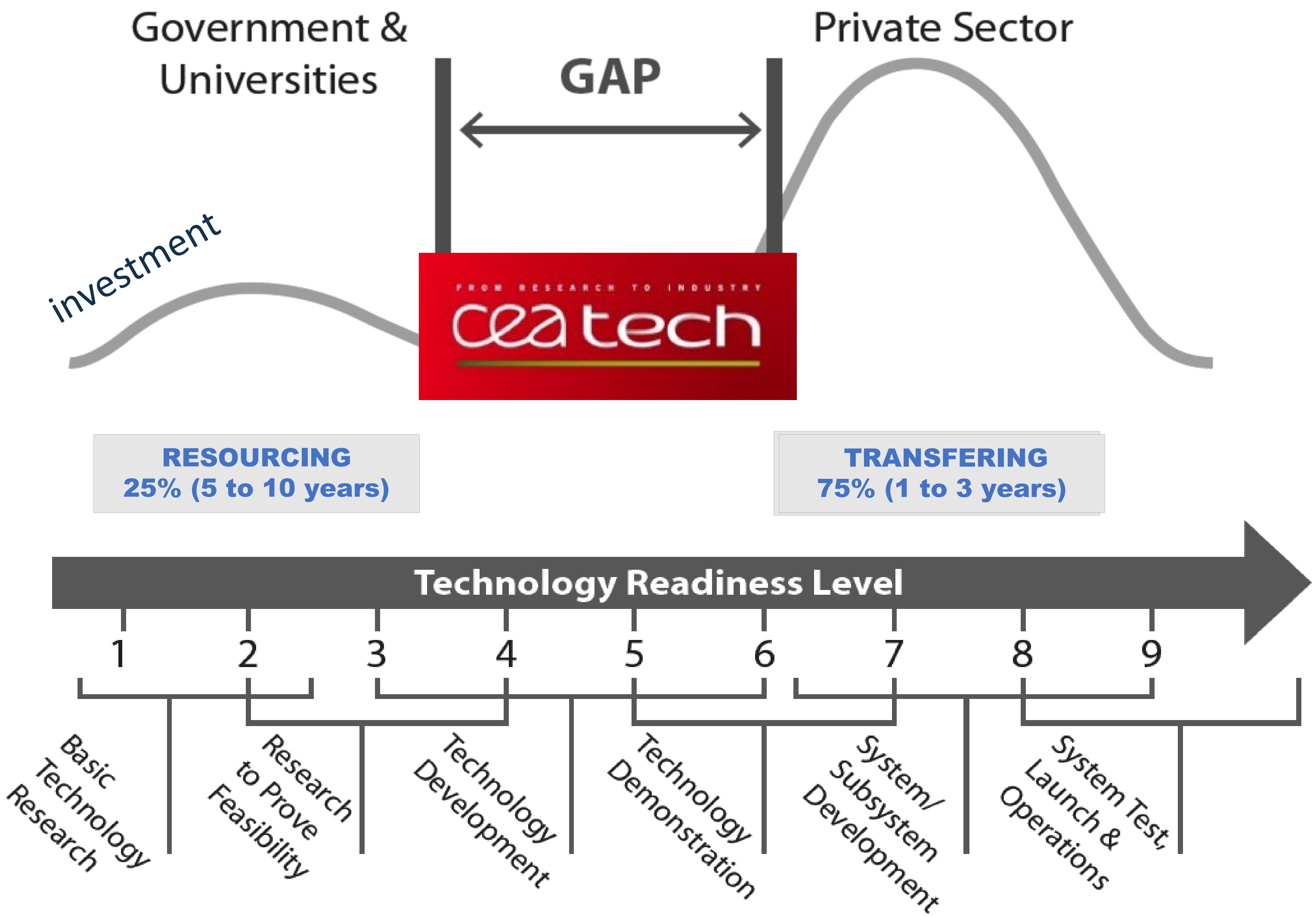
liten
cea tech

SMART DIGITAL SYSTEMS

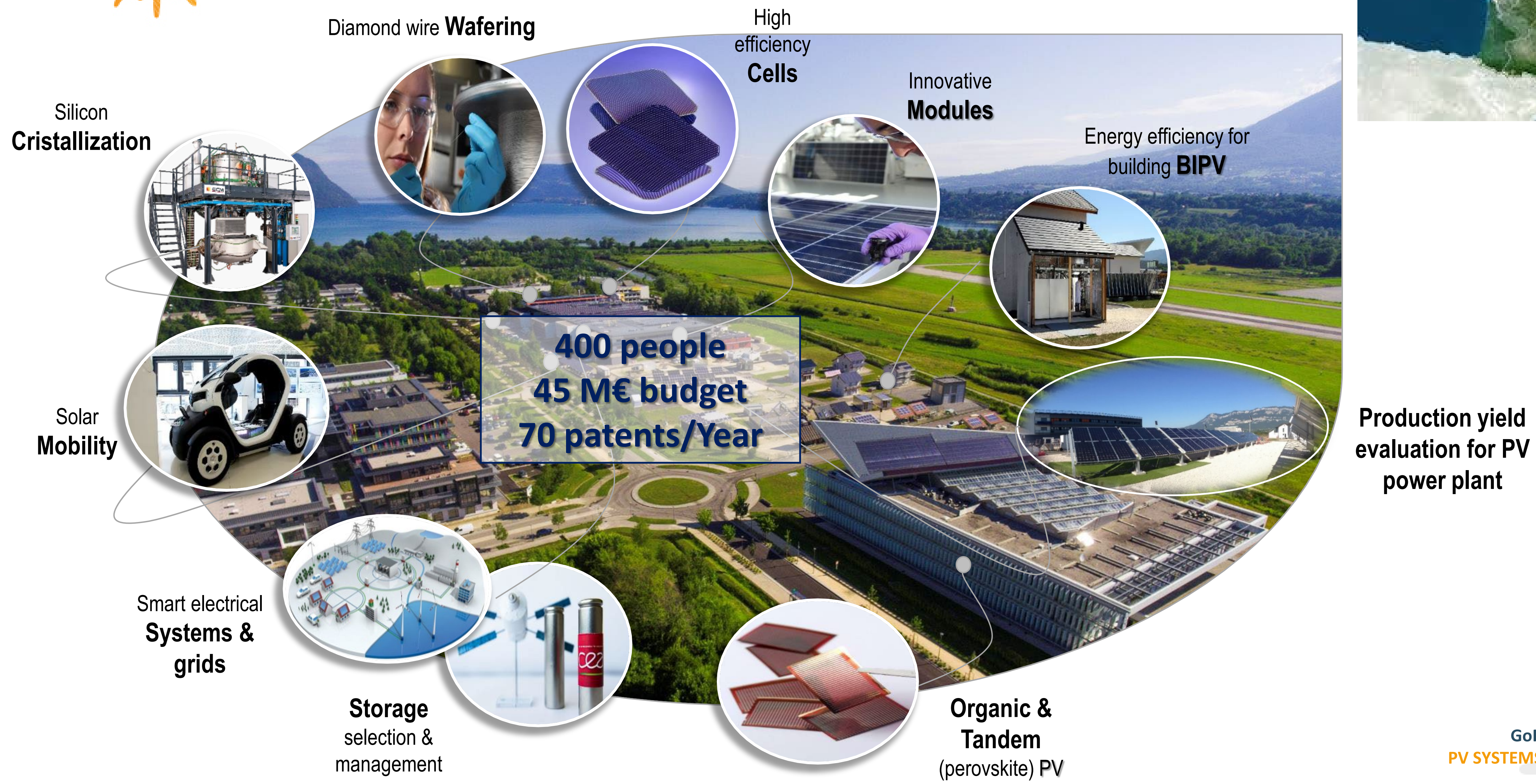
NEW ENERGY & NANOMATERIALS

• From research to industry





• CEA-INES Fact & Figures



• INES platforms overviews


G5-G6 DSS

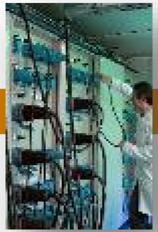

DW Wafering


Characterization


Cell pilot line for high efficiency solar cells


15 MW Module Line


Reliability and bankability test platform


Smart Grid


Charging station


Storage – Testing stations


Electrical cars


Nano-characterization


Batteries


Building platform


e-Plateform

• PV modules characterization

Objectives :

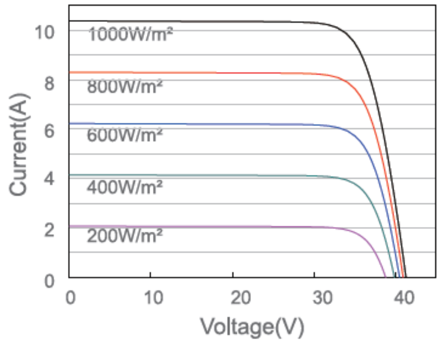
- What is obtained.
- What is a sun simulator made of.
- Identify important parameters to make a good indoor measurement.
- What are the limits of the label.
- How to relate the label to outdoor conditions.

• Datasheet information

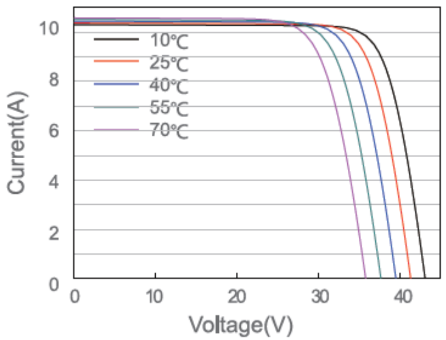
ELECTRICAL PARAMETERS AT STC

TYPE	JAM60S10 -330/MR	JAM60S10 -335/MR	JAM60S10 -340/MR	JAM60S10 -345/MR	JAM60S10 -350/MR
Rated Maximum Power(Pmax) [W]	330	335	340	345	350
Open Circuit Voltage(Voc) [V]	41.08	41.32	41.55	41.76	42.02
Maximum Power Voltage(Vmp) [V]	34.24	34.48	34.73	34.99	35.25
Short Circuit Current(Isc) [A]	10.30	10.38	10.46	10.54	10.62
Maximum Power Current(Imp) [A]	9.64	9.72	9.79	9.86	9.93
Module Efficiency [%]	19.6	19.9	20.2	20.5	20.8
Power Tolerance	0~+5W				
Temperature Coefficient of Isc(α_Isc)	+0.044%/°C				
Temperature Coefficient of Voc(β_Voc)	-0.272%/°C				
Temperature Coefficient of Pmax(γ_Pmp)	-0.350%/°C				
STC	Irradiance 1000W/m², cell temperature 25°C, AM1.5G				

Current-Voltage Curve JAM60S10-335/MR



Current-Voltage Curve JAM60S10-335/MR

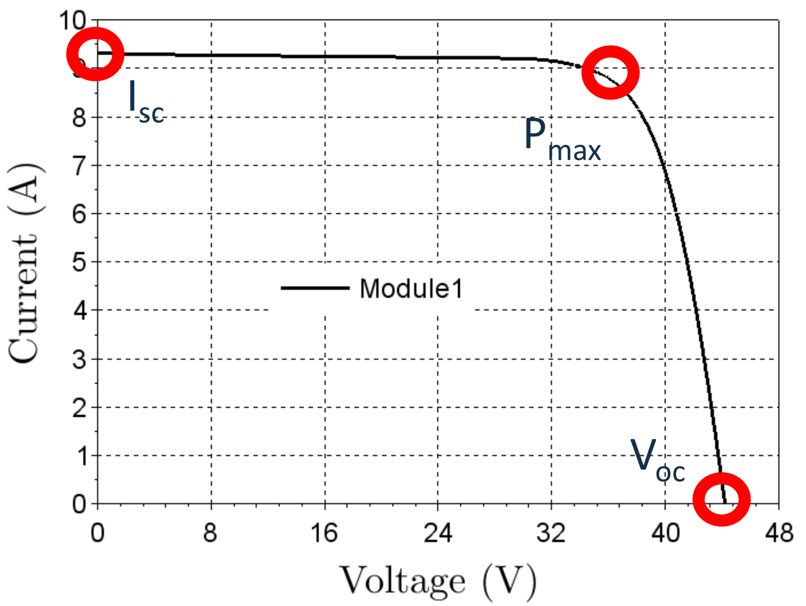


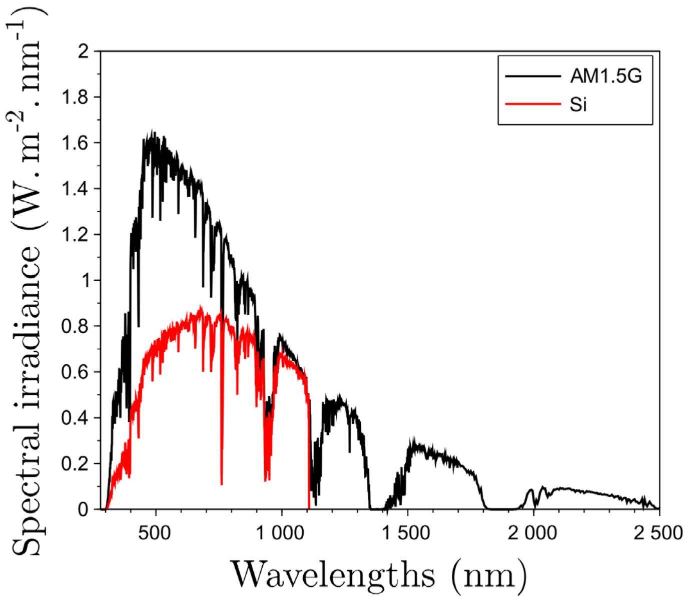
How is it obtained ?

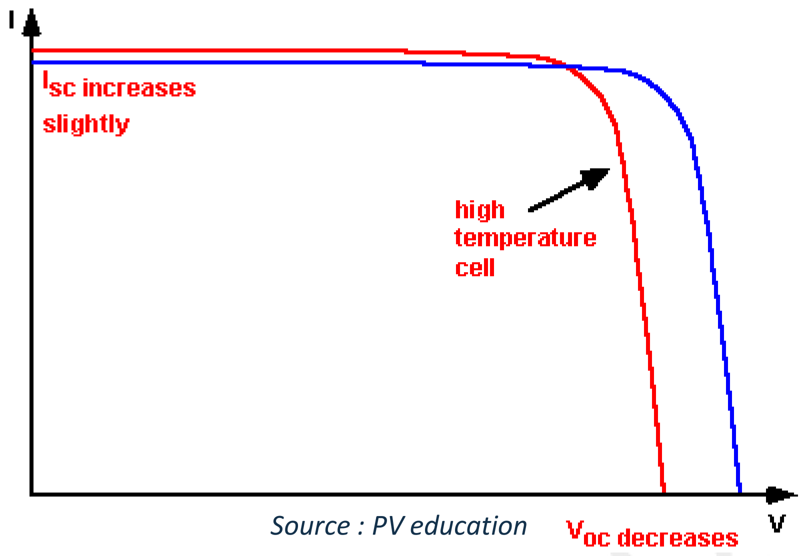
Measurand and results

IV curve
Spectrum
Spatial distribution
Temperature

Measurand = produced current by a PV module as a function of the load resistance connected under an homogenous 1000 W/m² irradiance on the whole surface with a spectral distribution defined according to the AM1.5G spectrum at a 25°C module temperature







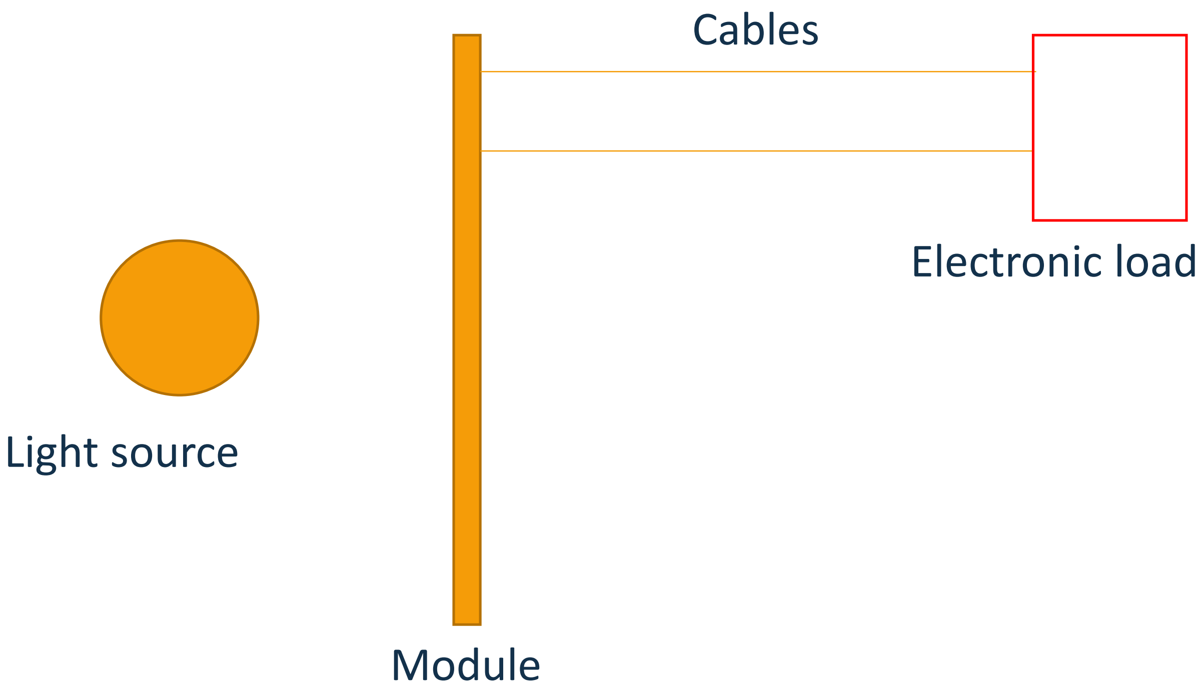
Source : PV education

Result of a measurement = IV curve

Standard test conditions (STC) = 1000W/m², 25°C and AM1.5G

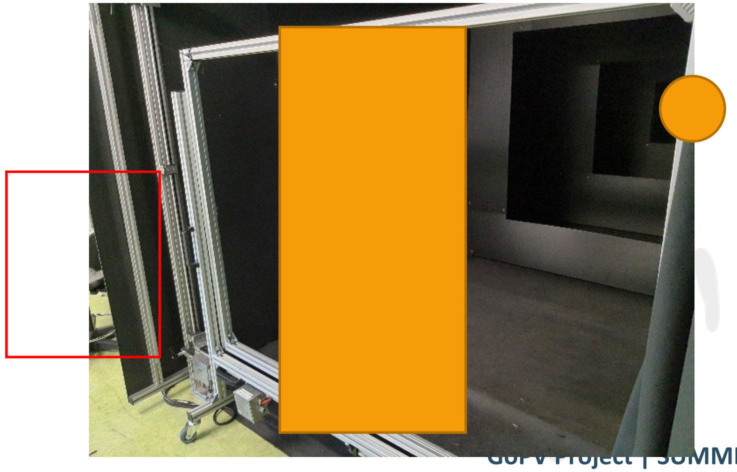
• Sun simulator

What do we need to obtain the IV curve of a PV module?



Examples of two sun simulators

SPIRE



PASAN

• Calibration

How to be sure that the irradiance is 1000W/m²?

- Buy a golden module.
- Put the golden module on the simulator.
- Set the power supply of the lamps to obtain the Isc given by the certificat of the golden module.
- Measure at the same time the current of silver cells on the simulator.
- Obtain an irradiance assessment for each flash thanks to the silver cells.

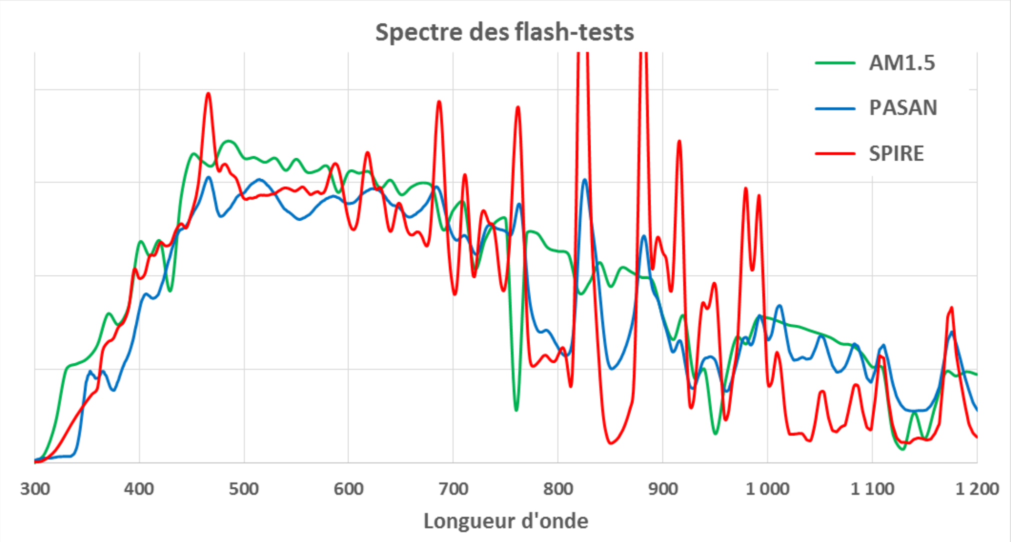
Calibration and follow up of the equipment are essential for its good use.

Simulators classes

IEC 60904-9 : demands for the use of sun simulators (last update november 2020)

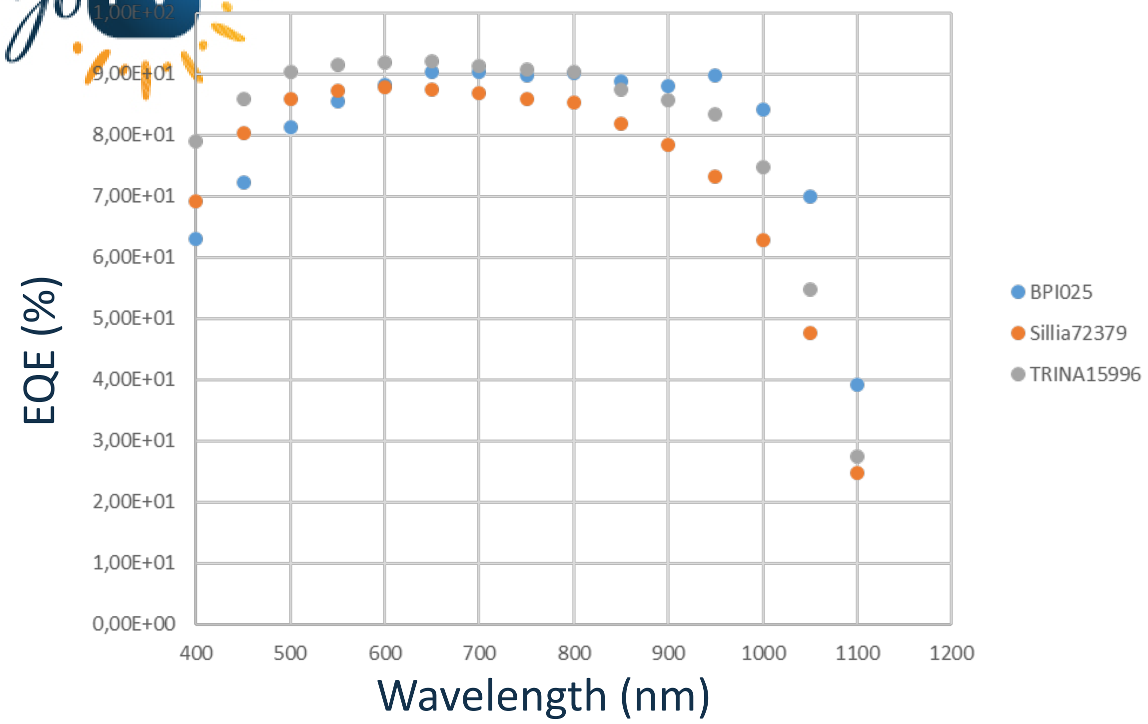
Classifications	Spectral match to all intervals specified in Table 1 or Table 2	Spatial non-uniformity of irradiance %	Temporal instability	
			Short term instability of irradiance STI %	Long term instability of irradiance LTI %
A+	0,875 to 1,125	1	0,25	1
A	0,75 to 1,25	2	0,5	2
B	0,6 to 1,4	5	2	5
C	0,4 to 2,0	10	10	10

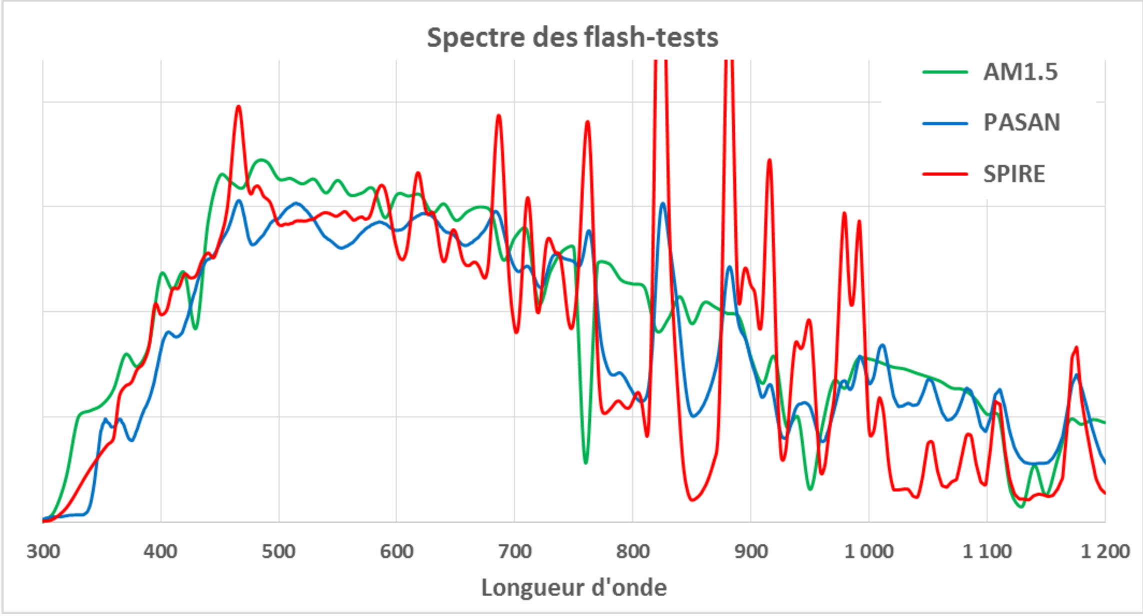
Spectral distribution



	Wavelength range nm	Percentage of total irradiance in the wavelength range 300 nm to 1 200 nm %	Cumulative integrated irradiance %
1	300 to 470	16,61	16,61
2	470 to 561	16,74	33,35
3	561 to 657	16,67	50,02
4	657 to 772	16,63	66,65
5	772 to 919	16,66	83,31
6	919 to 1 200	16,69	100,00

Why spectal distribution is important?





Spectral Mismatch (SMM)

$$SMM_{ij} = \frac{\int E_{ref}(\lambda)\cdot S_i(\lambda)\cdot d\lambda \int E_{sim}(\lambda)\cdot S_j(\lambda)\cdot d\lambda}{\int E_{sim}(\lambda)\cdot S_i(\lambda)\cdot d\lambda \int E_{ref}(\lambda)\cdot S_j(\lambda)\cdot d\lambda} \quad (i<j)$$

- I_{sc} of the golden module under the AM1.5G spectrum
- I_{sc} of the golden module under the simulator spectrum
- I_{sc} of the device under test under the simulator spectrum
- I_{sc} of the device under test under the AM1.5G spectrum

$E_{ref}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength λ, of the reference spectral irradiance distribution as given in IEC 60904-3;

$E_{sim}(\lambda)$ is the irradiance per unit bandwidth at a particular wavelength λ, of spectral irradiance distribution of the solar simulator at the time of measurement;

$S_i(\lambda)$ is the spectral responsivity of the device number i, where i is from 1 to n-1;

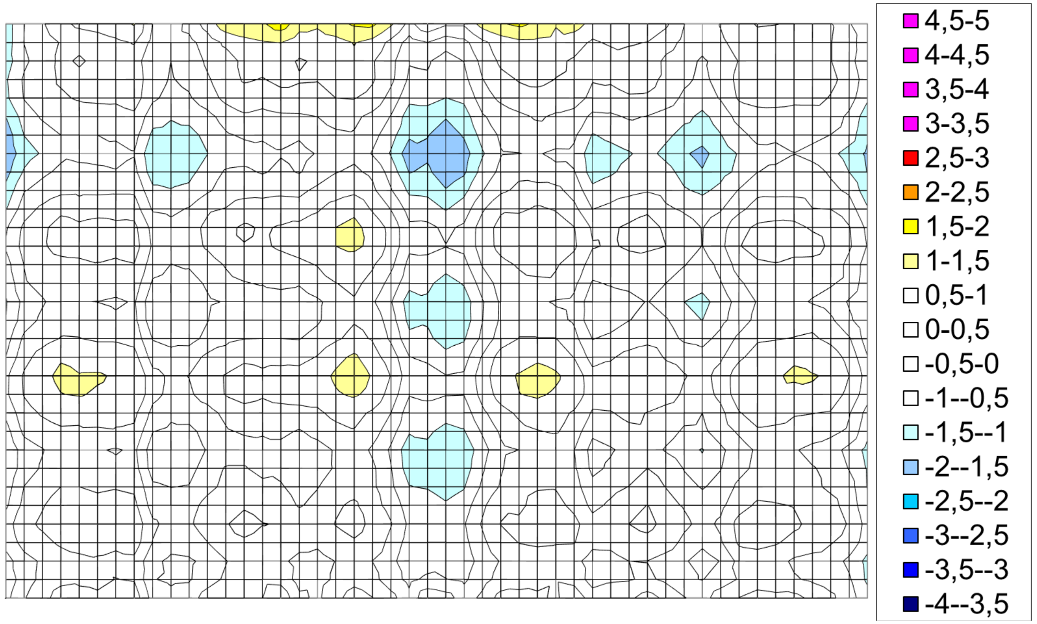
$S_j(\lambda)$ is the spectral responsivity of the device number j, where j is from 2 to n and $j > i$.

EQE ≠
Spectra ≠ → I_{sc} ≠

• Simulators classes

IEC 60904-9 : demands for the use of sun simulators (last update november 2020)

Spatial homogeneity



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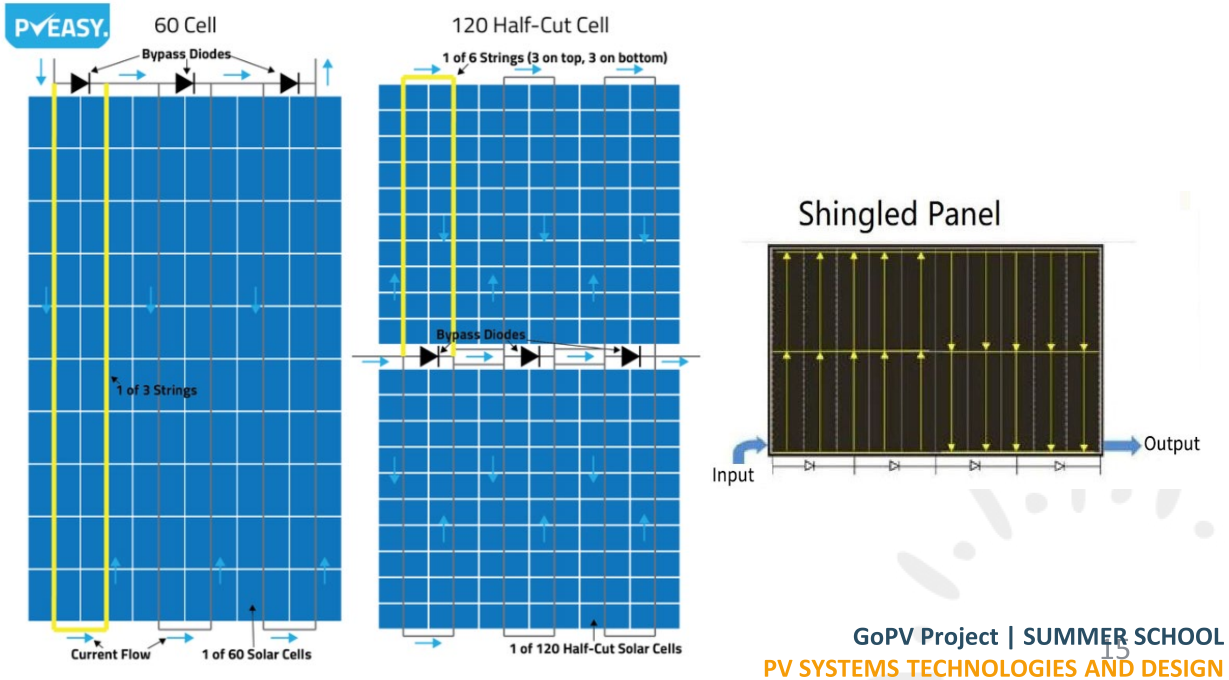
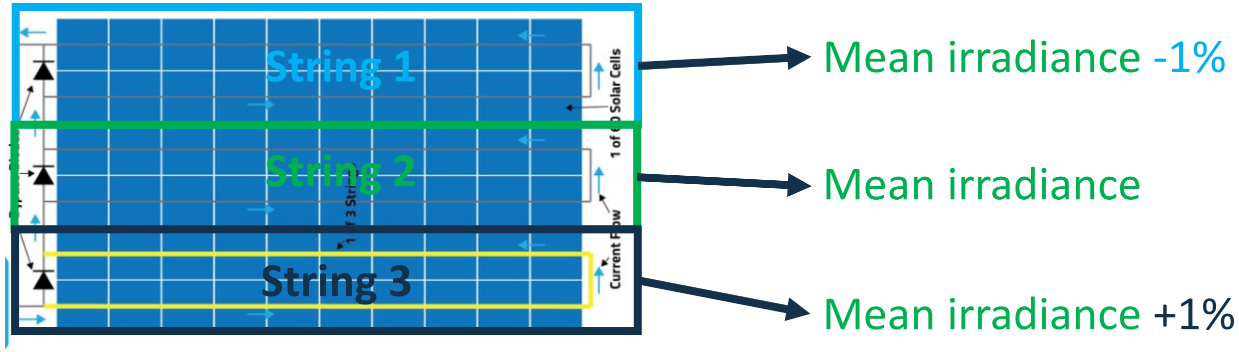
A	0,75 to 1,25	2	0,5	2
B	0,6 to 1,4	5	2	5
C	0,4 to 2,0	10	10	10

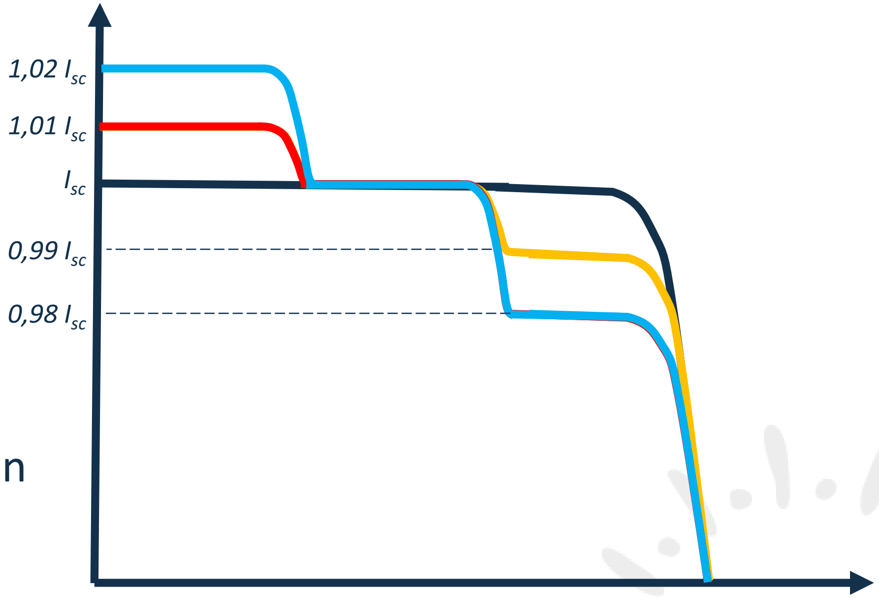


Always locate the modules at the same spot with the same rotation
Even more important with half cells and shingle

Why spatial homogeneity is important?

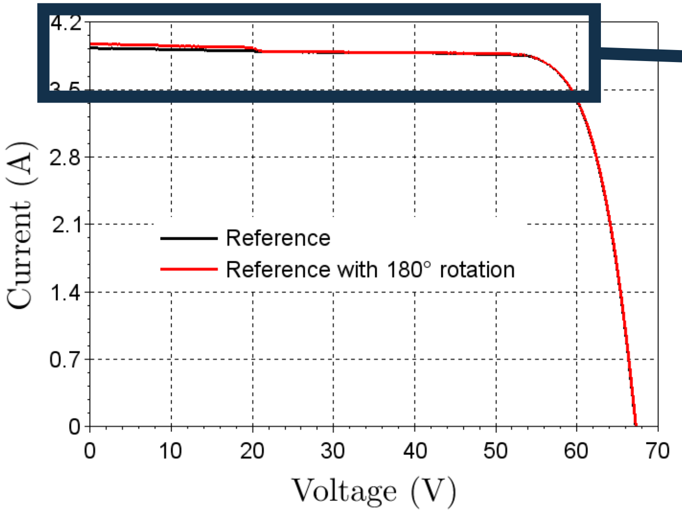


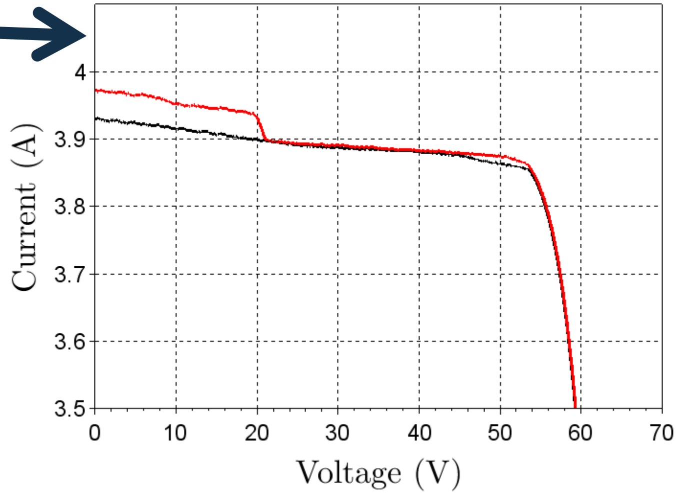
I_{sc}	Case 0
1	0,99
2	1
3	1,01



Case 0 = All the cells are completely the same
Case 1 = One string underperforming
Case 2 = One string underperforming + one string overperforming
Case 3 = One string underperforming + one string overperforming + 180° rotation

Rotation





Case	I_{sc} (A)	V_{oc} (V)	FF (%)	P_{max} (W)
2	3,930	67,27	80,35	212,39
3	3,971	67,28	79,60	212,68

Rotation of the modules can impact the measurement

• Simulators classes

IEC 60904-9 : demands for the use of sun simulators (last update november 2020)

Classifications	Spectral match to all intervals specified in Table 1 or Table 2	Spatial non-uniformity of irradiance %	Temporal instability	
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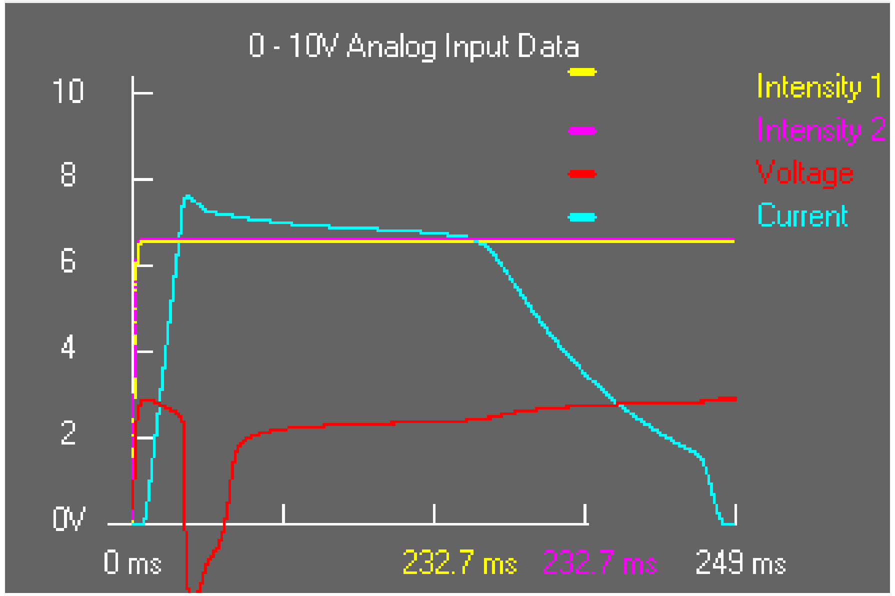
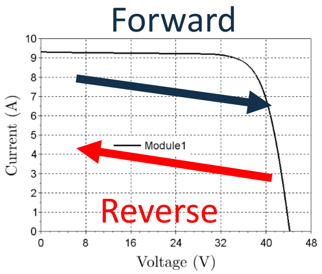
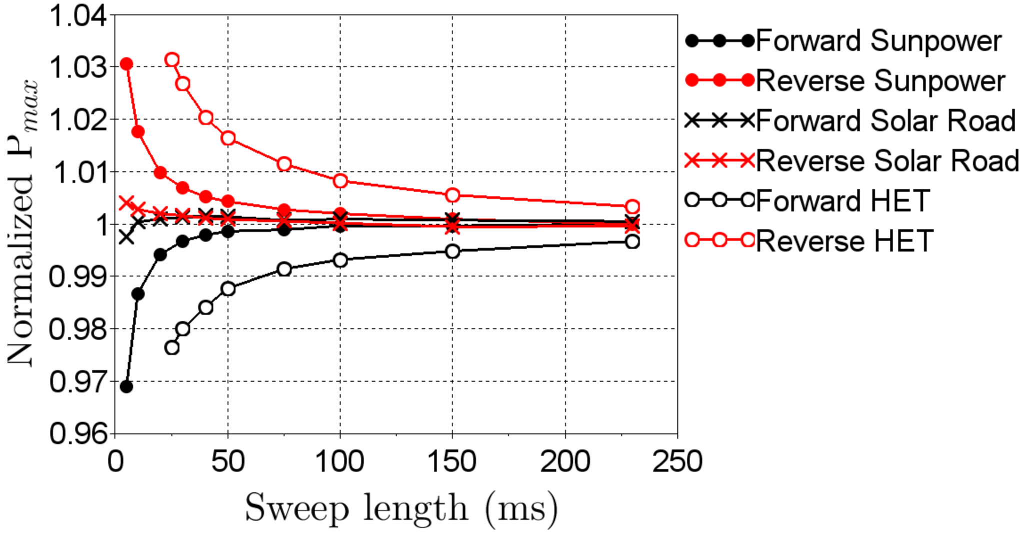
Temporal stability



Capacitive effects





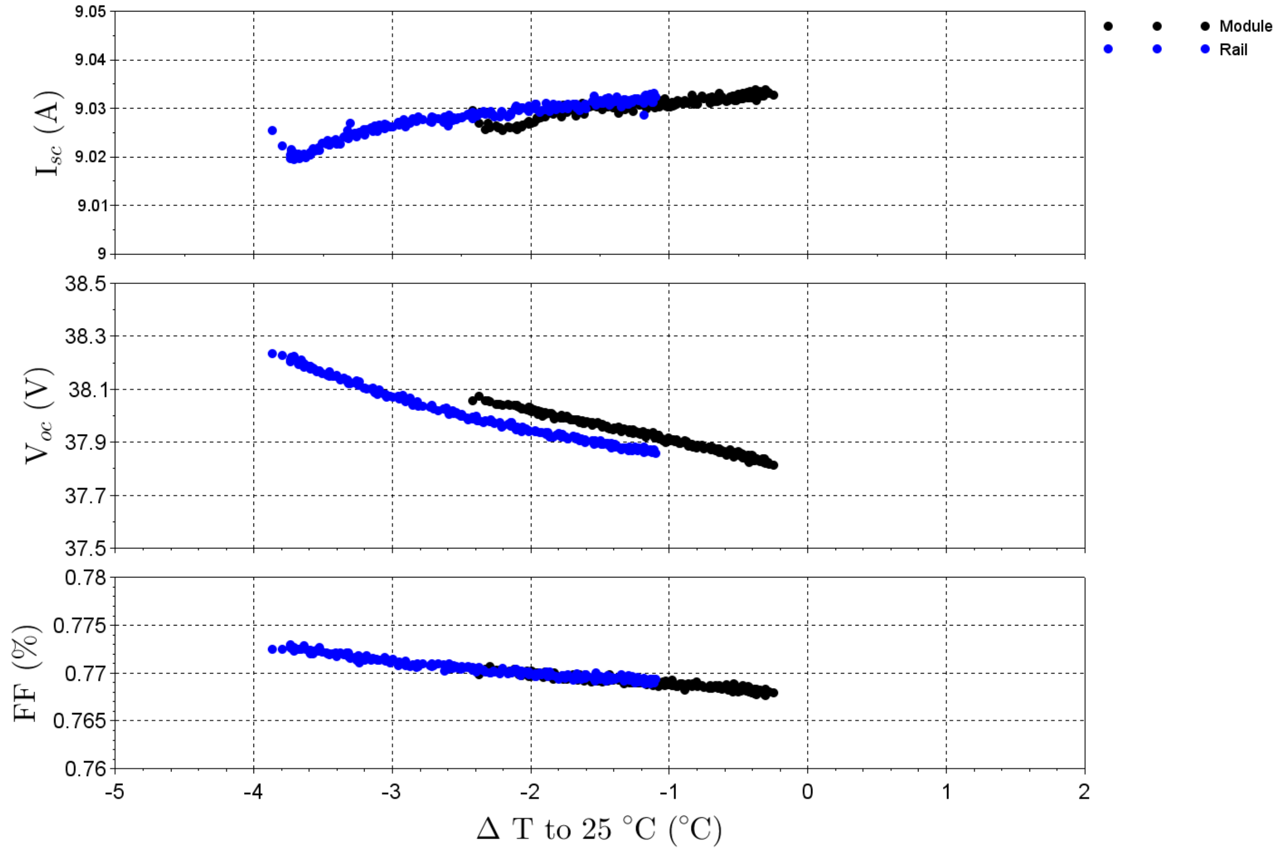
High performances modules can be capacitive.
It is important to minimize the capacitives effects.

Repeatability and reproducibility

	Nb mesures	I_{sc} (A)	V_{oc} (V)	FF (%)	P_{max} (W)	
Ref1	5	8,919±0,002	37,780±0,006	78,07±0,04	263,06±0,16	±0,06%
Ref2	5	5,887±0,001	14,282±0,003	72,28±0,06	60,77±0,05	±0,08%
Ref3	10	8,647±0,002	43,924±0,013	75,43±0,02	286,46±0,11	±0,04%

	SPIRE			PASAN			PASAN> SPIRE
	P_{max} forward (W)	P_{max} reverse (W)	Δ forward reverse (%)	P_{max} forward (W)	P_{max} reverse (W)	Δ forward reverse (%)	Δ forward (%)
Ref1	262,8	262,9	<0,1	262,4	263,7	+0,5	-0,2
Ref2	317,9	318,2	+0,1	321,7	324,8	+1,0	+1,2
Ref3	289,4	292,2	+1,0	291,2	302,2	+3,8	+0,6
Ref4	87,5	87,5	<0,1	89,0	90,0	+1,1	+1,7

Temperature



	Temperature increase
V_{oc}	↓
I_{sc}	↑
FF	↓
P_{max}	↓

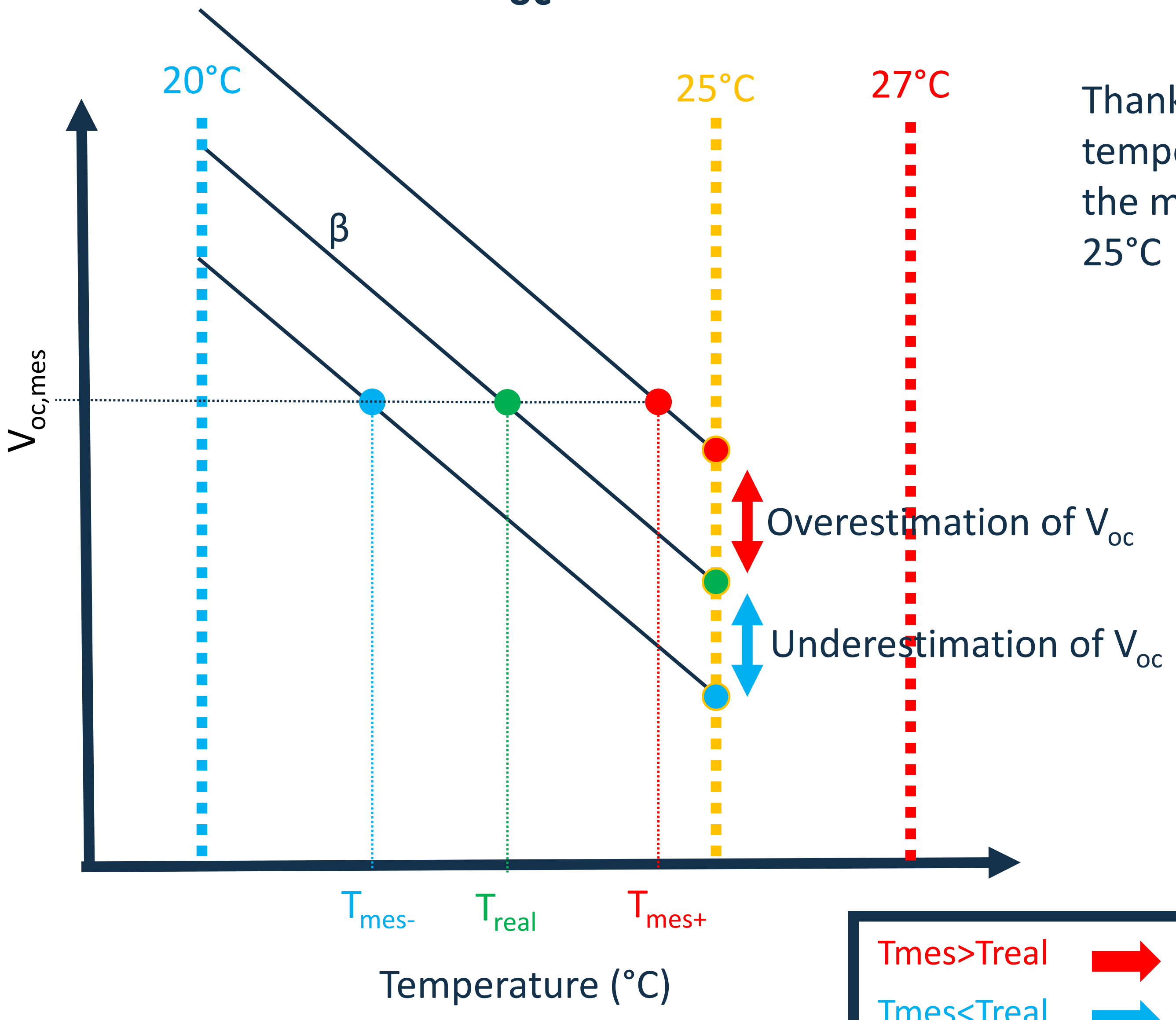
Do the measurement as close as possible to 25°C and make sure the device under test is really at this temperature.

How temperature impact V_{oc}

Standard test conditions =25°C

Indoor environment in between **20 et 27°C** depending on the seasons.
Intra-day variations occur.

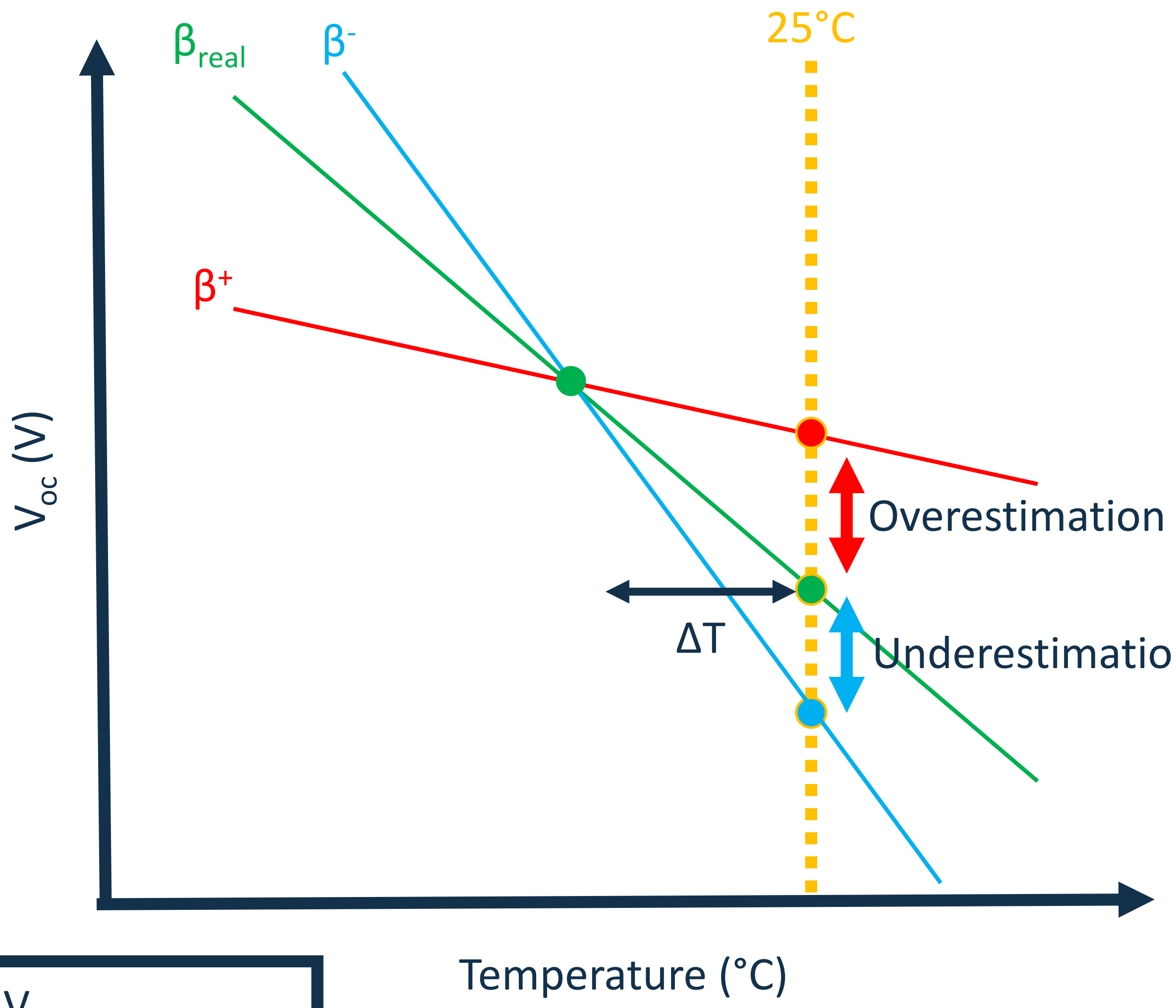
What is measured :
- A V_{oc} at the real module temperature, T_{real}
- A temperature which is not necessarily T_{real}



Thanks to the β temperature coefficient, the measure is corrected to 25°C

Tmes>Treal	→	Overestimation of V_{oc}
Tmes<Treal	→	Underestimation of V_{oc}

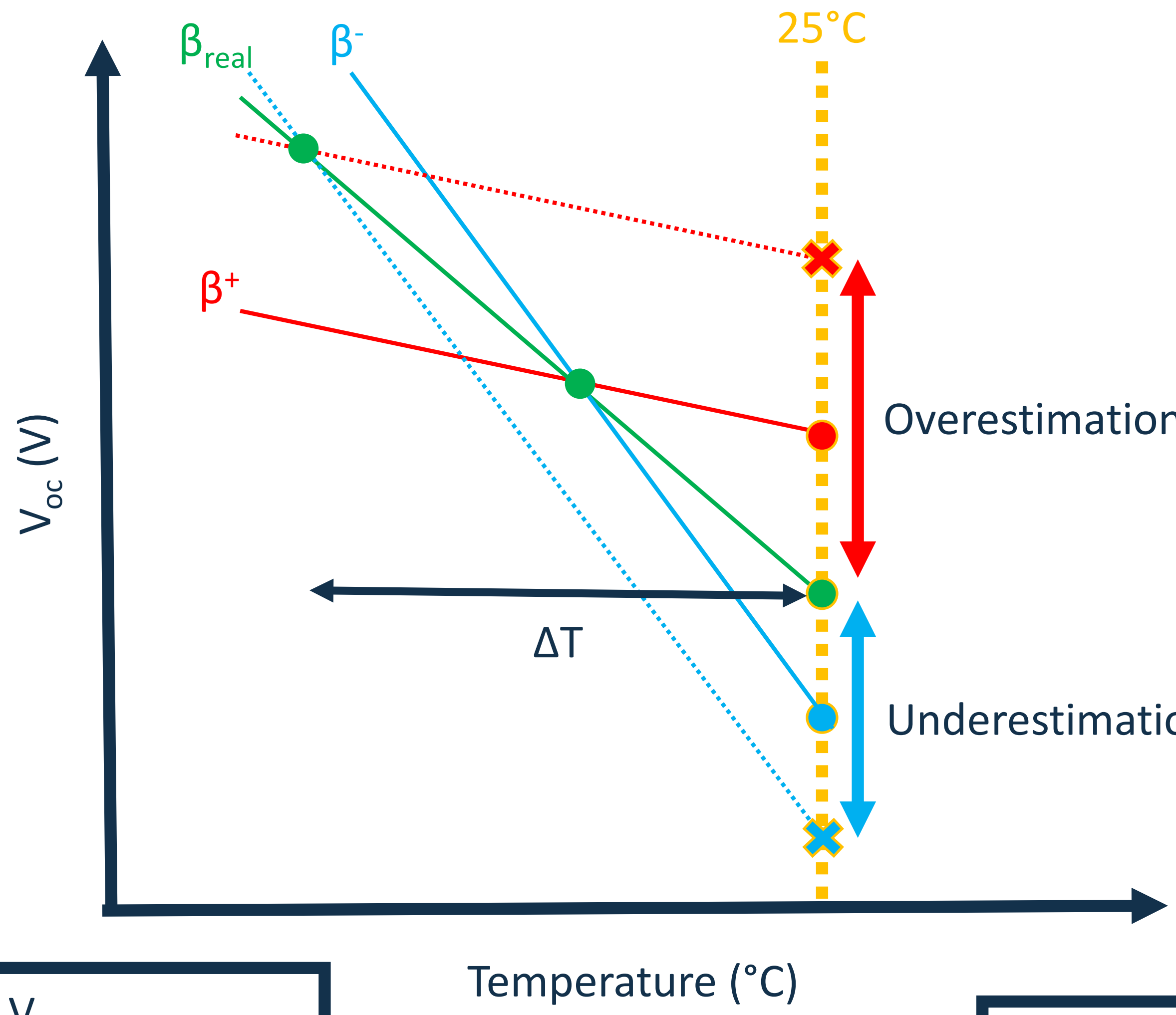
How temperature coefficients impact V_{oc}



β^+ → Overestimation of V_{oc}

β^- → Underestimation of V_{oc}

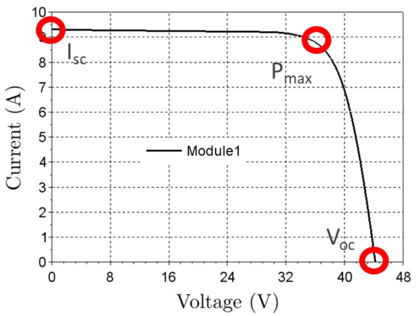
How temperature coefficients impact V_{oc}



β^+ → Overestimation of V_{oc}
β^- → Underestimation of V_{oc}

The larger ΔT, the more important the temperature coefficients are.

Sum up



- An IV curve => I_{sc}, V_{oc}, P_{max}, FF

Objectives :

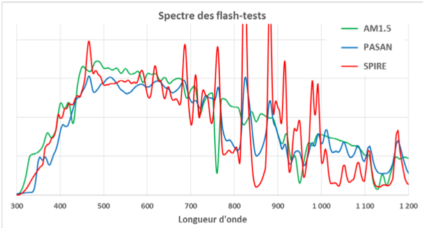
- What is obtained.

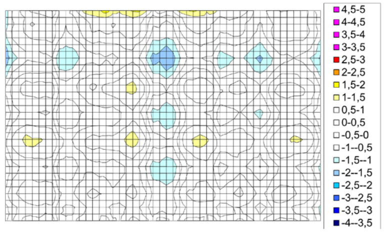
What is a sun simulator made of.

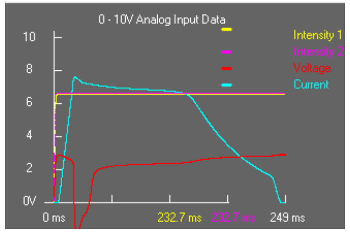
- A light source
- An electronic load

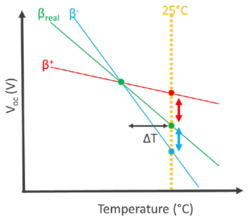
- Identify important parameters to make a good indoor measurement.

- The irradiance
- The spectral distribution
- The spatial homogeneity
- The temporal stability
- The temperature









- What are the limits of the label.

- Discrepancies between how is really done the measurement and the measurand are the first limit.
- STC are not outdoor conditions.

- How to relate the label to outdoor conditions.

• Outdoor conditions

Energy Science & Engineering

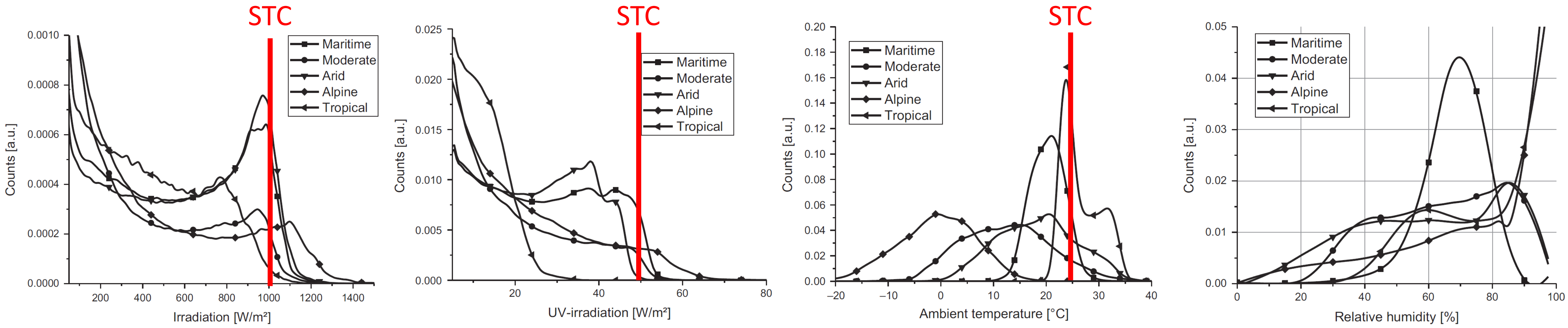
Open Access

RESEARCH ARTICLE

Categorization of weathering stresses for photovoltaic modules

Michael Koehl*, Markus Heck & Stefan Wiesmeier

Fraunhofer ISE, Heidenhofstr. 2, Freiburg 79110, Germany

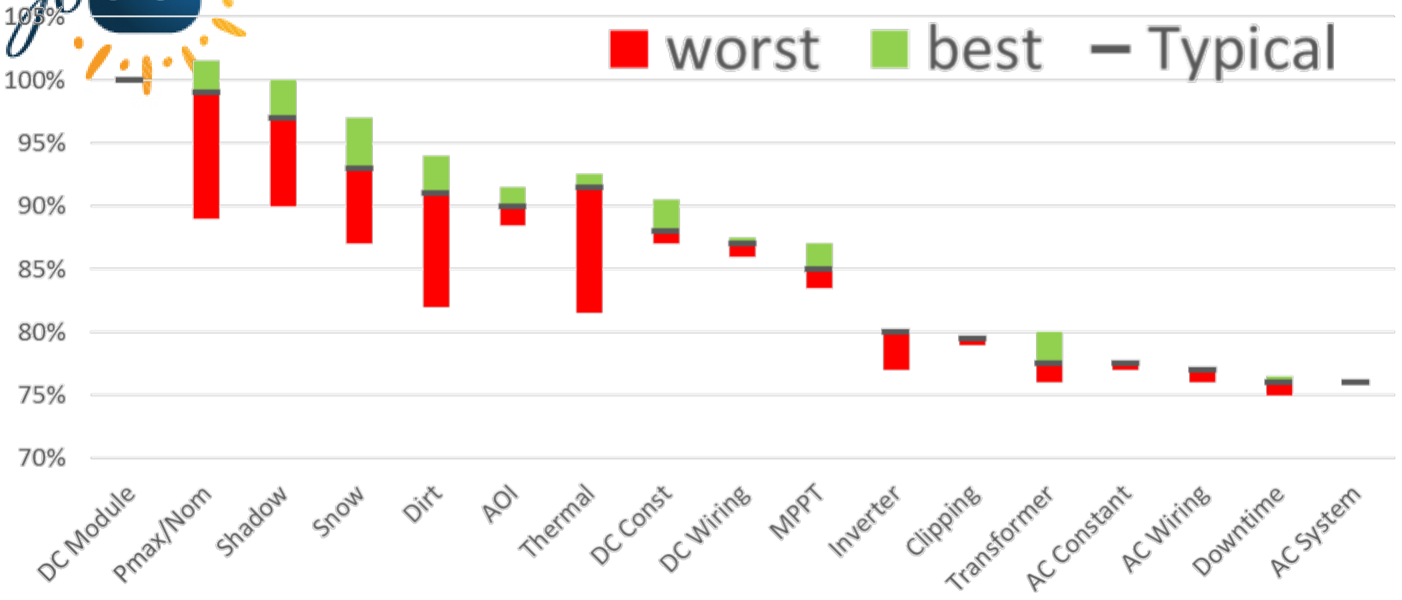


- Irradiances
- UV irradiances
- Temperatures
- Humidity

Impact

- Local performances
- Local ageing

• Energetic losses outdoor



S. Ransome, PVSEC, France, 2004

Same phenomena as for STC measurements.
Just worst conditions…
PR > 80% nowadays

Progress in PHOTOVOLTAICS

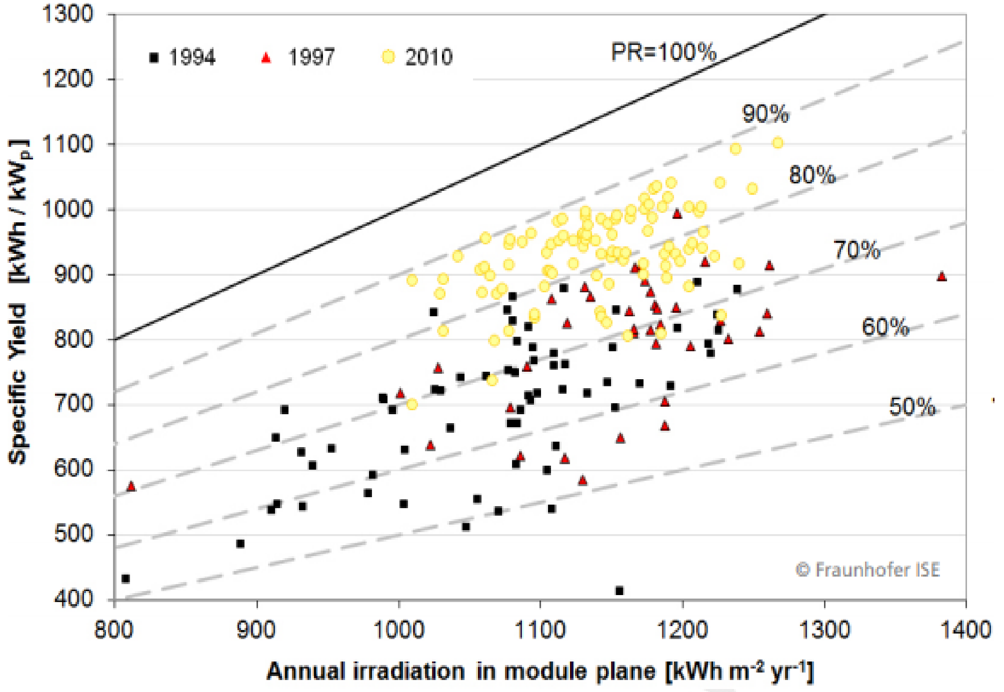
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2012; **20**:717–726
Published online 18 January 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1219

PAPER PRESENTED AT 26TH EU PVSEC, HAMBURG, GERMANY 2011

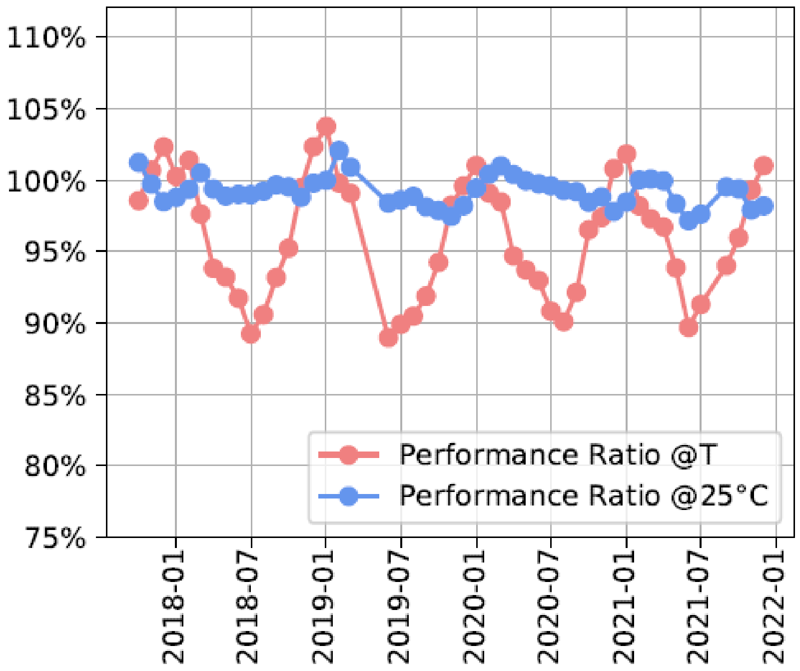
Performance ratio revisited: is PR > 90% realistic?

Nils H. Reich[1]*, Bjoern Mueller[1], Alfons Armbruster[1], Wilfried G. J. H. M. van Sark[2], Klaus Kiefer[1] and Christian Reise[1]

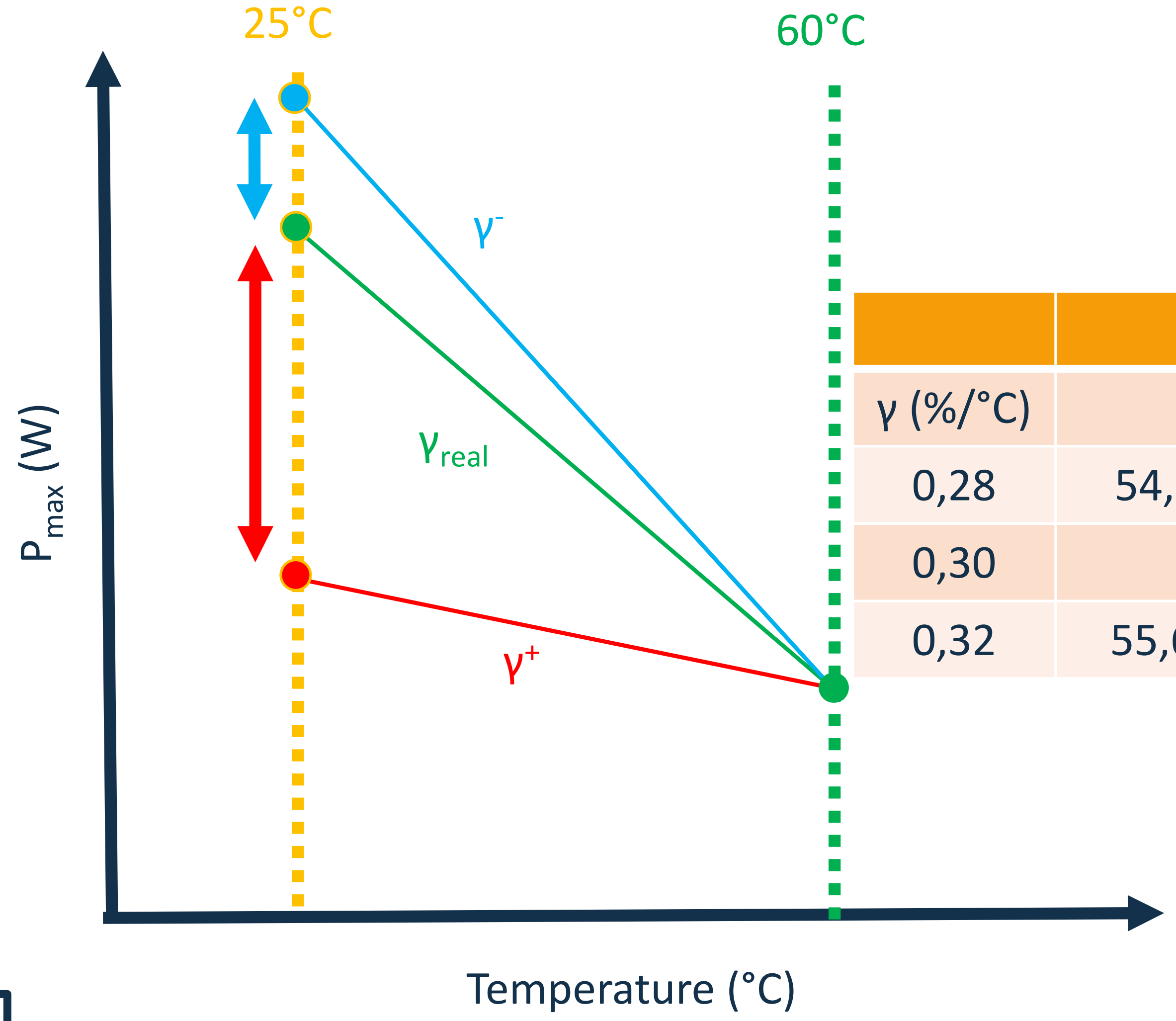
[1] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D-79110 Freiburg, Germany
[2] Science, Technology and Society, Utrecht University, Copernicus Institute, Budapestlaan 6, 3584 CD Utrecht, The Netherlands



• Temperature correction



Monitoring of PR and temperature corrected PR for a module installed at CEA INES



	P_{max} (W)	
γ (%/°C)	25°C	60°C
0,28	54,9 (-0,63%)	50
0,30	55,25	50
0,32	55,6 (+0,63%)	50

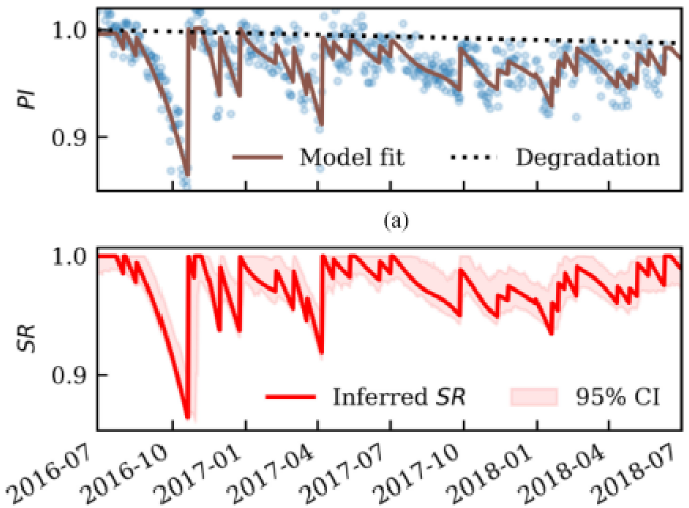
It is possible to normalize the monotoring to 25°C but it does not eradicate the noise/seasonality in the data

γ^+ → Underestimation of P_{max}
γ^- → Overestimation of P_{max}

Soiling

Combined Estimation of Degradation and Soiling Losses in Photovoltaic Systems

Åsmund Skomedal and Michael G. Deceglie



Olivares et al. (2021)

Micheli et al. (2021)

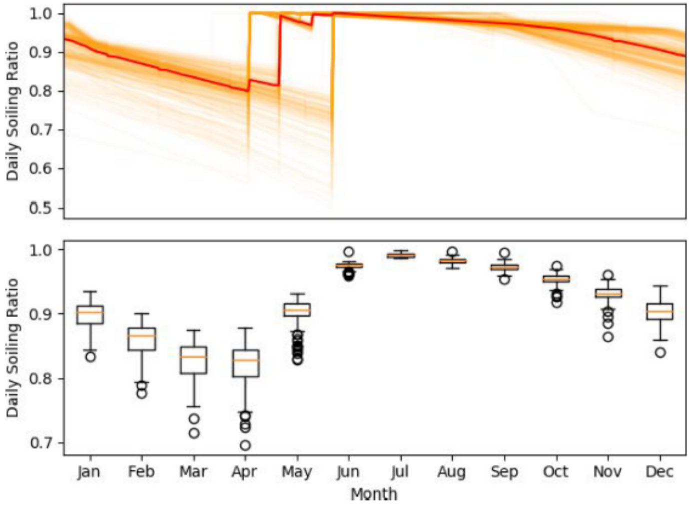


FIGURE 6 Three-year soiling profiles plotted over a 12-month period. Upper plot: soiling profiles. In red median of the soiling profiles. Lower plot: boxplots of the average daily soiling ratio in each month. The orange horizontal lines mark the medians, whereas the top and bottom limits of each box are the third and first quartile of the distribution (Q3 and Q1, respectively). The vertical lines in each boxplot are limited either by the lower or the upper whiskers (i.e., minimum and maximum values that are not outliers). The circles identify outliers, determined because outside of the Q1 − 1.5 * IQR to Q3 + 1.5 * IQR range, where IQR is calculated as Q3 − Q1

- Soiling reduces significantly the PR => cleaning methods are needed
- It depends on numerous environmental conditions (dust, birds, dew, wind…)

• Spectral impact

Renewable Energy 164 (2021) 1306–1319

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Spectral impact on PV in low-latitude sites: The case of southeastern Brazil

Guilherme Neves [a, b, *], Waldeir Vilela [a], Enio Pereira [b], Marcia Yamasoe [c], Gustavo Nofuentes [d, e]

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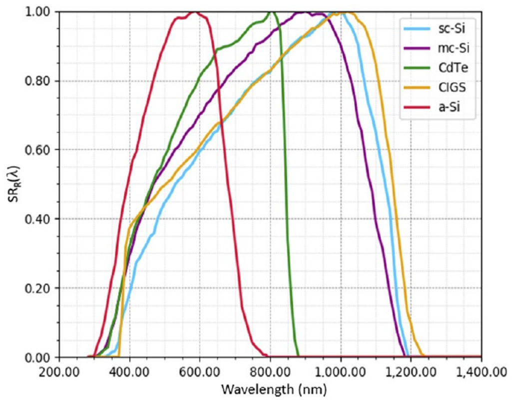
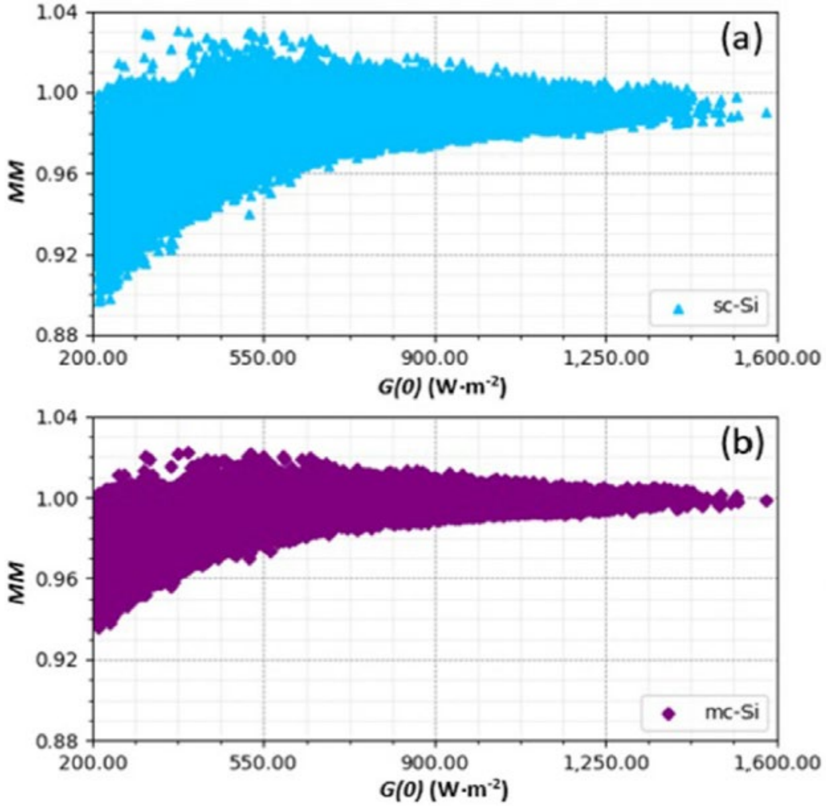
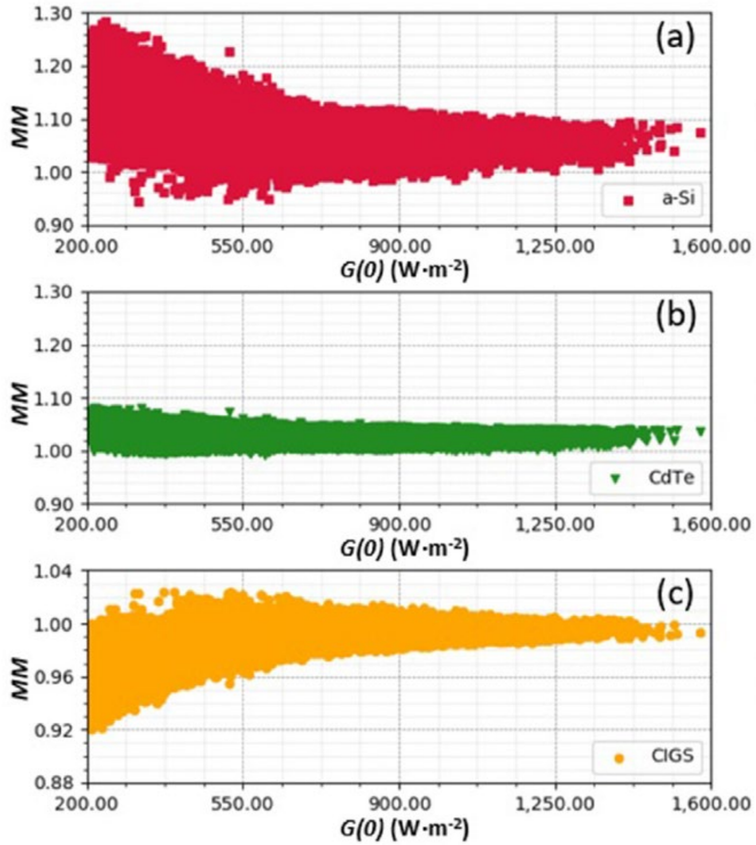
Typical Meteorological Year methodologies applied to solar spectral irradiance for PV applications

Jesús Polo [a, *], Miguel Alonso-Abella [a], Nuria Martín-Chivelet [a], Joaquín Alonso-Montesinos [b], Gabriel López [c], Aitor Marzo [d], Gustavo Nofuentes [e], Nieves Vela-Barrionuevo [a]

$$MM = \frac{\int E(\lambda) SR(\lambda) d\lambda}{\int E_{REF}(\lambda) SR(\lambda) d\lambda} \frac{\int E_{REF}(\lambda) SR_{REF}(\lambda) d\lambda}{\int E(\lambda) SR_{REF}(\lambda) d\lambda}$$







Mismatch factor (MM) is a function of :
- The incident spectrum
- The spectral response of the device under test
- The spectral response of the reference

• Spectral impact

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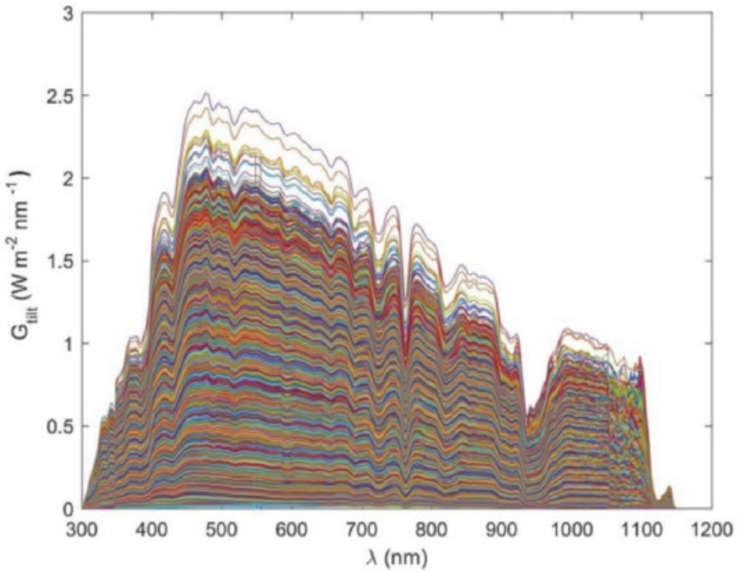
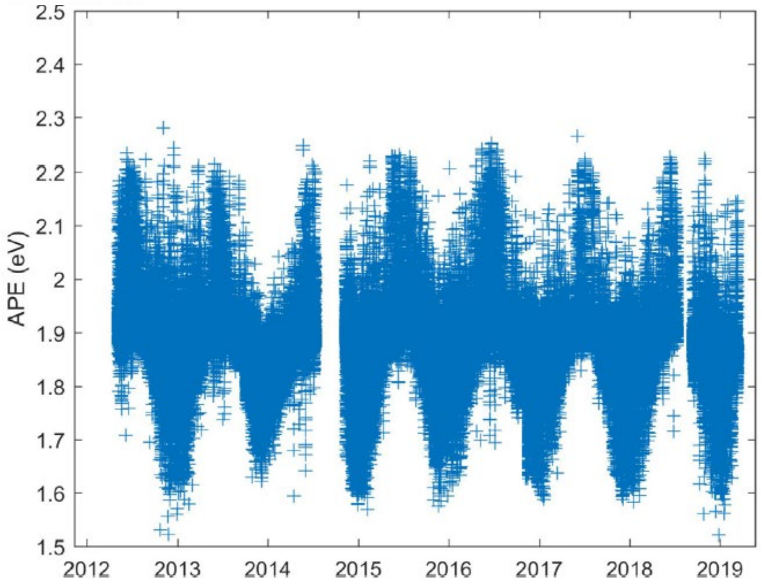
$$MM = \frac{\int E(\lambda) SR(\lambda) d\lambda}{\int E_{REF}(\lambda) SR(\lambda) d\lambda} \frac{\int E_{REF}(\lambda) SR_{REF}(\lambda) d\lambda}{\int E(\lambda) SR_{REF}(\lambda) d\lambda}$$

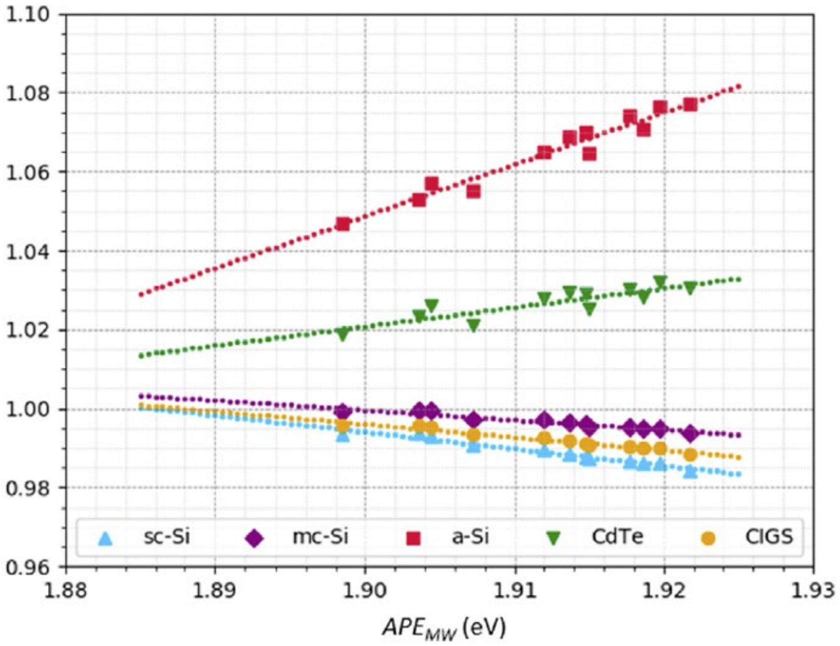
$$APE = \frac{\int_a^b E(\lambda) d\lambda}{\int_a^b \Phi_{ph}(\lambda) d\lambda}$$

where $E(\lambda)$ [W m^{-2}nm^{-1}] is the spectral irradiance, $\Phi_{ph}(\lambda)$ [m^{-2}·nm^{-1}·s^{-1}] is the spectral photon flux and a [nm] and b [nm]



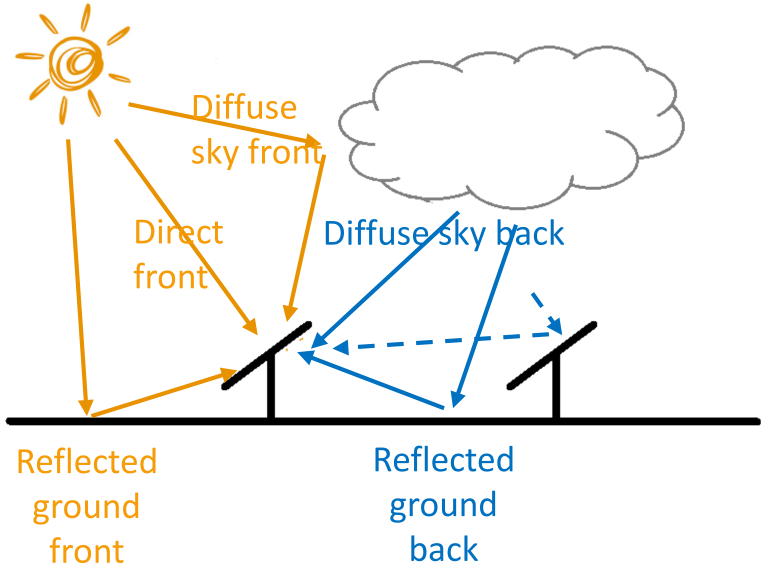


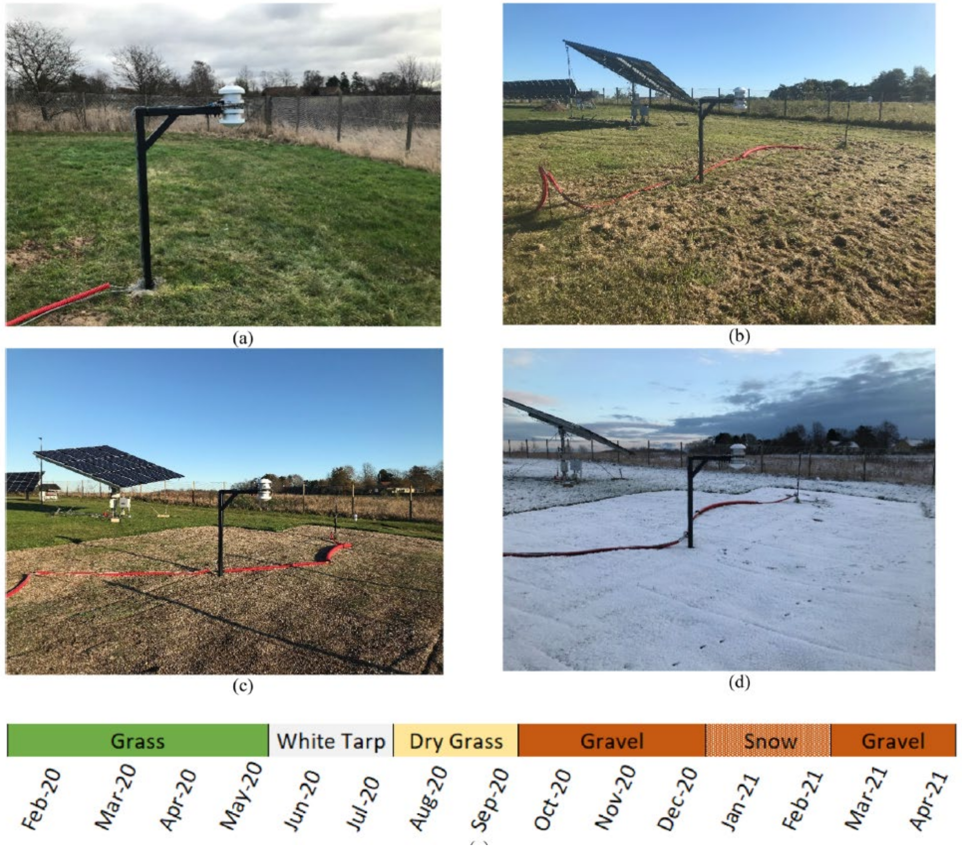
$$APE_{MW} = \frac{\sum_{i=1}^{n} APE_i \cdot G_i(0)}{\sum_{i=1}^{n} G_i(0)}$$



- Average photon energy (APE) varies depending on the location, the hour of the day and along the year.
- Mismatch factor could be seasonal.

Albedo





Riede-Lyngskaer et al. (2022)

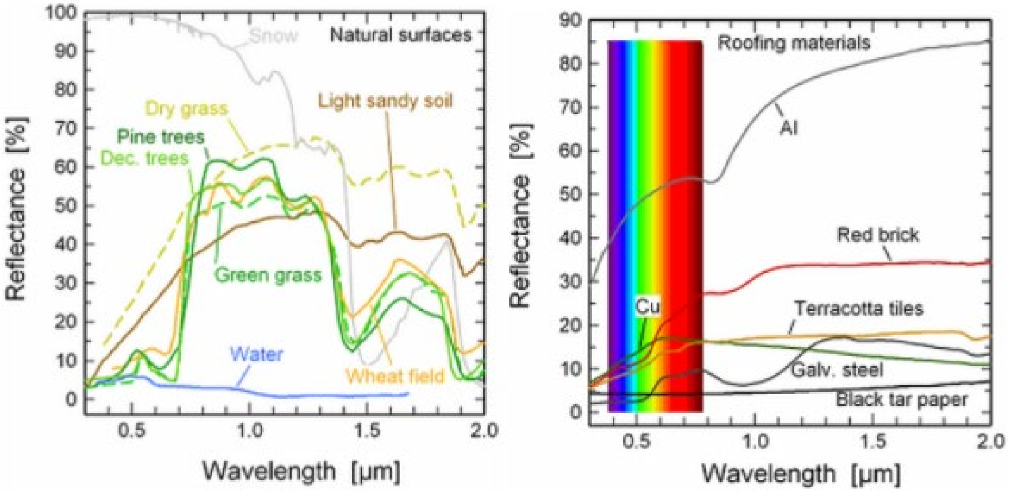


Figure: Reflectance vs wavelength for natural surfaces (left) and roofing materials (right).

- Albedo depends on the spectral reflection
- It can be seasonal

• Degradation vs weather

Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2016; **24**:978–989
Published online 7 February 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2744

RESEARCH ARTICLE

Compendium of photovoltaic degradation rates

Dirk C. Jordan[1]*, Sarah R. Kurtz[1], Kaitlyn VanSant[2] and Jeff Newmiller[3]

1 National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401, USA
2 Colorado School of Mines, 1500 Illinois Street, Golden, CO 8040, USA
3 DNV GL, 2420 Camino Ramon, Suite 300, San Ramon, CA 95483, USA

Table I. Summary of the median and mean degradation rate and the number of data points for various subsets of the aggregated data. 2+ indicates study types using two or more measurements and excludes systems with known start-up issues.

Technology	Study type	System/Module	Median	Mean	Data points
All data	All	All	0.90	0.93	11 029
x-Si	All	All	0.90	0.91	10 572
Thin-film	All	All	1.15	1.38	455
All	Median per study and system	All	0.82	1.09	312
All	2+ measurements	All	0.46	0.69	2792
All	1, outdoor IV	All	1.08	1.06	7238
All	1, indoor IV	All	0.64	0.77	963
All	High quality studies	All	0.49	0.66	2161
x-Si	Median per study and system	Modules	0.67	0.91	127
x-Si	Median per study and system	Systems	0.69	0.79	108
x-Si	High quality, all	Modules	0.40	0.51	1552
x-Si	High quality, all	Systems	0.64	0.81	384
x-Si	High quality, Median per study and system	Modules	0.55	0.59	61
x-Si	High quality, Median per study and system	Systems	0.61	0.69	71
x-Si	High quality, desert	All	0.71	1.19	42
x-Si	High quality, hot and humid	All	0.60	0.80	683
x-Si	High quality, moderate	All	0.42	0.57	1396
x-Si	High quality, snow	All	0.35	0.62	39

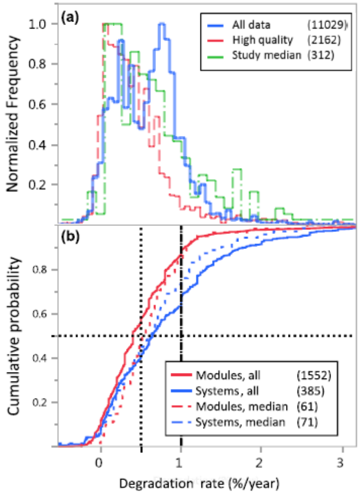
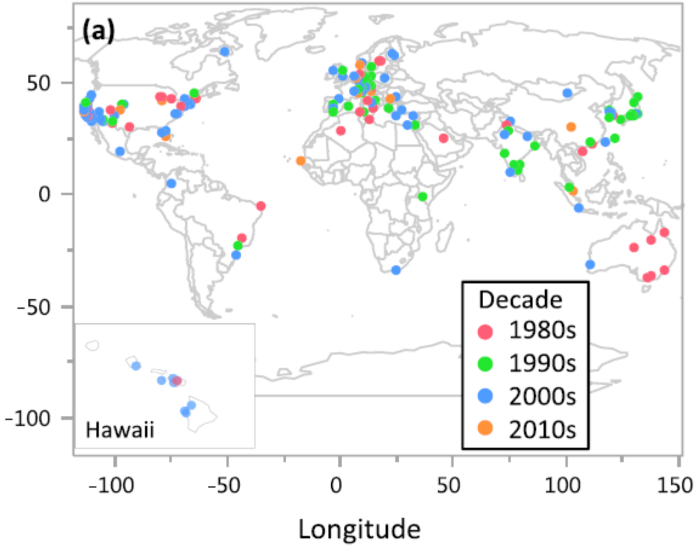
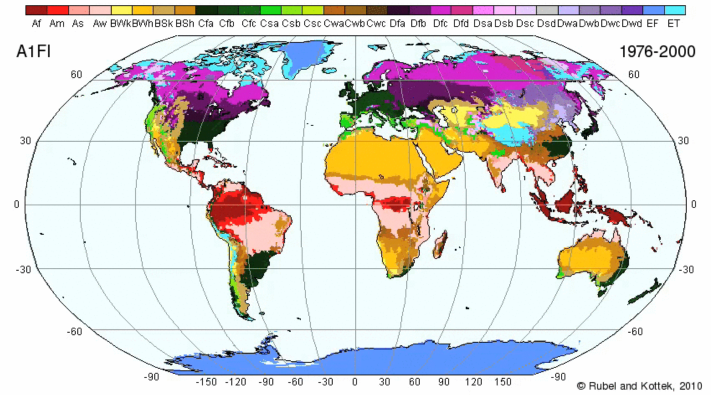


Figure 2. Histograms of all data, high quality data and the median per study and system presented as the normalized frequency (a). Cumulative distribution functions for high-quality x-Si systems and modules (b). The median is indicated by a dashed horizontal line; 0.5%/year and 1%/year degradation are indicated as a dashed and dash-dotted line, respectively. The number of data points for the respective subsets is given in parentheses.





http://koeppen-geiger.vu-wien.ac.at/

- Mean degradation rate around 0.5%/year
- Degradation rate depends on the weather conditions
- Koëppen-Geiger climates zones are heplful to define degradation areas

Published data on photovoltaic (PV) degradation measurements were aggregated and re-examined. The subject has seen an increased interest in recent years resulting in more than 11 000 degradation rates in almost 200 studies from 40 different countries.

Degradation vs weather

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 9, NO. 4, JULY 2019 1105

Modeling Outdoor Service Lifetime Prediction of PV Modules: Effects of Combined Climatic Stressors on PV Module Power Degradation

Ismail Kaaya, Michael Koehl, Amantin Panos Mehilli, Sidrach de Cardona Mariano, and Karl Anders Weiss

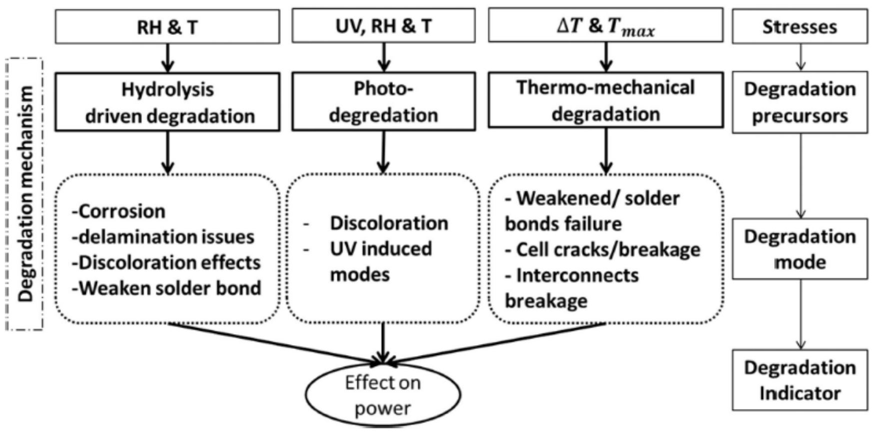


Fig. 1. Schematic diagram of the modeling hypotheses.

- Three general degradation mechanisms
  - Hydrolysis
  - Photodegradation
  - Thermomechanical degradation
- With the proposed model by Ascencio et al. we can assess the degradation rate all around the world for given parameters associated to one bill of materials

energies MDPI

Article

Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules

ulián Ascencio-Vásquez [1,*], Ismail Kaaya [2,3], Kristijan Brecl [1], Karl-Anders Weiss [2] and Marko Topič [1]

1 Faculty of Electrical Engineering, University of Ljubljana, Tržaška cesta 25, 1000 Ljubljana, Slovenia; kristijan.brecl@fe.uni-lj.si (K.B.); marko.topic@fe.uni-lj.si (M.T.)
2 Fraunhofer Institute of Solar Energy, Heidenhofstr. 2, 79110 Freiburg im Breisgau, Germany; ismail.kaaya@ise.fraunhofer.de (I.K.); karl-anders.weiss@ise.fraunhofer.de; (K.-A.W.)
3 School of Industrial Engineering, University of Malaga, 29016 Malaga, Andalucia, Spain
* Correspondence: julian.ascencio@fe.uni-lj.si

$$k_H = A_H \cdot rh_{eff}^{n} \cdot \exp\left(-\frac{E_H}{k_B \cdot T_m}\right), \quad (11)$$

$$k_P = A_P \cdot (UV_{dose})^X \cdot \left(1 + rh_{eff}^{n}\right) \cdot \exp\left(-\frac{E_P}{k_B \cdot T_m}\right), \quad (12)$$

$$k_{Tm} = A_{Tm} \cdot (\Delta T)^{\theta} \cdot C_N \cdot \exp\left(-\frac{E_{Tm}}{k_B \cdot T_U}\right), \quad (13)$$

$$k_T = A_N \prod_{i=1}^{n} (1 + k_i) - 1, \quad (14)$$

here the parameters are:

k_H: Hydrolysis degradation rate (%)
k_P: Photo-degradation rate (%)
k_{Tm}: Thermomechanical degradation rate (%)
k_T: Total degradation rate (%)
k_B: Boltzmann constant (8.62×10^{-5})
E_H: Activation Energy for Hydrolysis degradation (eV)
E_P: Activation Energy for Photo-degradation (eV)

E_{Tm}: Activation Energy for Thermomechanical degradation (eV)

A_H: Pre-exponential constant for Hydrolysis degradation

A_P: Pre-exponential constant for Photo-degradation
A_{Tm}: Pre-exponential constant for Thermomechanical degradation

rh_{eff}: effective relative humidity
UV_{dose}: integral UV dose (kW/m^2)
T_m: average module temperature
T_U: upper module temperature
T_L: lower module temperature
$\Delta T = T_U - T_L$: temperature difference
n: model parameter that indicates the impact of RH on power degradation.

X: model parameter that indicates the impact of UV dose on power degradation.
θ: model parameter that indicates the impact of ΔT on power degradation.
C_N: Cycling rate

A_N: normalization constant of the physical quantities (a^{-2}/%)

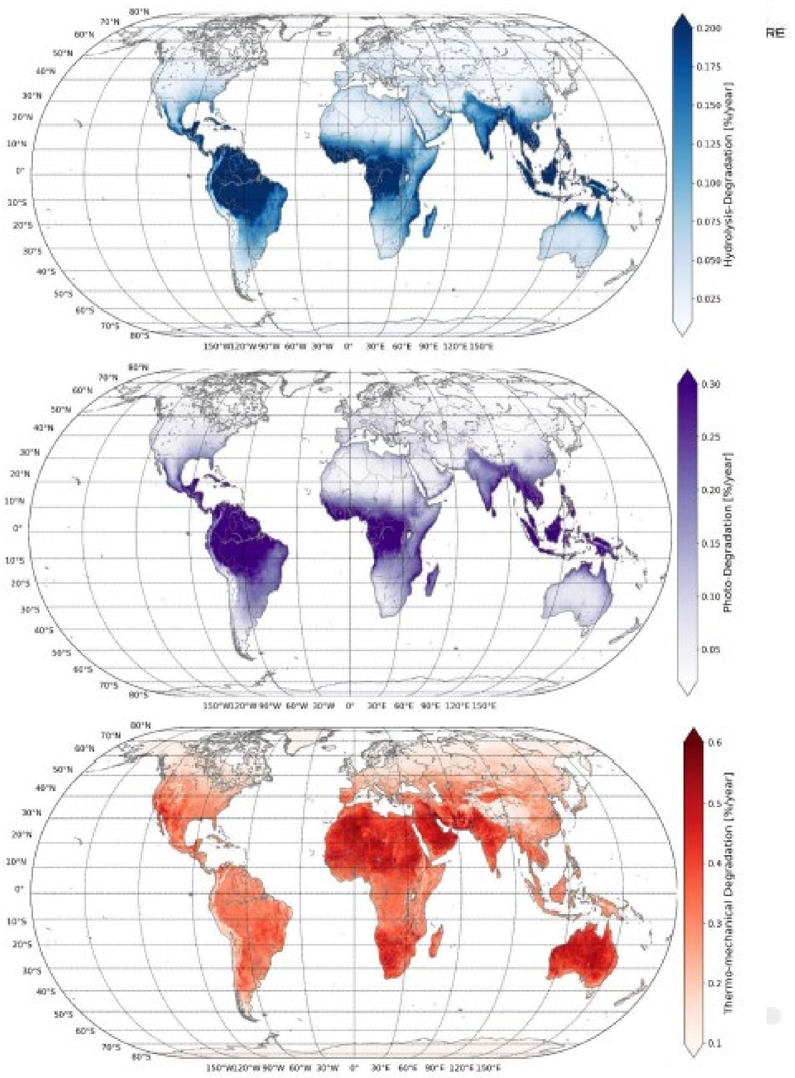


Figure A1. Global mapping of degradation mechanisms. **top** Hydrolysis-degradation, **middle** photo-degradation and **bottom** thermomechanical degradation.

PV SYSTEMS TECHNOLOGIES AND DESIGN

• Degradation vs weather

energies

MDPI

Article

Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules

Julián Ascencio-Vásquez [1,*], Ismail Kaaya [2,3], Kristijan Brecl [1], Karl-Anders Weiss [2] and Marko Topič [1]

1 Faculty of Electrical Engineering, University of Ljubljana, Tržaška cesta 25, 1000 Ljubljana, Slovenia; kristijan.brecl@fe.uni-lj.si (K.B.); marko.topic@fe.uni-lj.si (M.T.)
2 Fraunhofer Institute of Solar Energy, Heidenhofstr. 2, 79110 Freiburg im Breisgau, Germany; ismail.kaaya@ise.fraunhofer.de (I.K.); karl-anders.weiss@ise.fraunhofer.de; (K.-A.W.)
3 School of Industrial Engineering, University of Malaga, 29016 Malaga, Andalucia, Spain
* Correspondence: julian.ascencio@fe.uni-lj.si

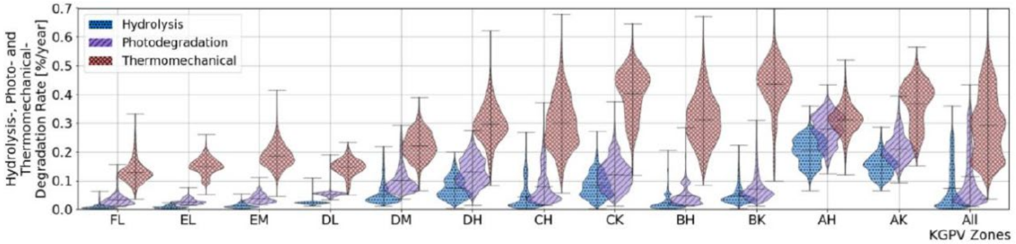


Figure 5. Spatial distribution of the degradation mechanisms in view of the Köppen-Geiger-Photovoltaic (KGPV) climate zones.

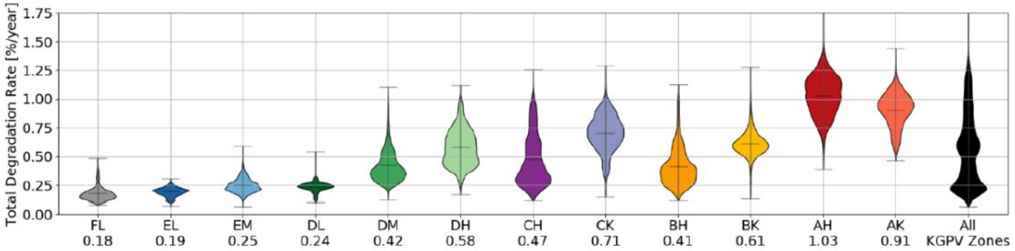


Figure 6. Spatial distribution of the total degradation rates in view of the KGPV climate zones. The average of total degradation rate per climate zone is indicated below each label in %/a.

Temperature-Precipitation (TP) Zones
A: Tropical climate
B: Desert climate
C: Steppe climate
E: Temperate climate
D: Cold climate
F: Polar climate

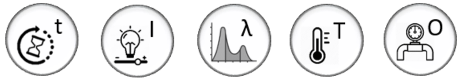
Irradiation (H) Zones
K: Very high irradiation
H: High irradiation
M: Medium irradiation
L: Low irradiation

- **High temperature causes**
  - High thermomecanichal degradation
  - Accelerated hydrolysis
  - Accelerated photodegradation
- **High humidity causes**
  - No significant impact on thermomecanichal
  - High hydrolysis
  - Accelerated photodegradation
- **High irradiance causes**
  - Accelerated thermomechanichal degradation
  - No significant impact on hydrolysis
  - High photodegradation

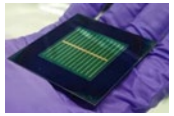
Reliability and durability

Floating

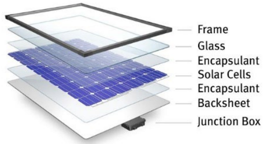
Desert



Tandem



Perovskite



Conditions

BOM

PID

SALT MIST

LID

Thermal cycles

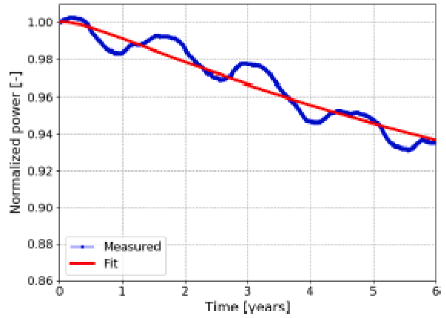
Humidity

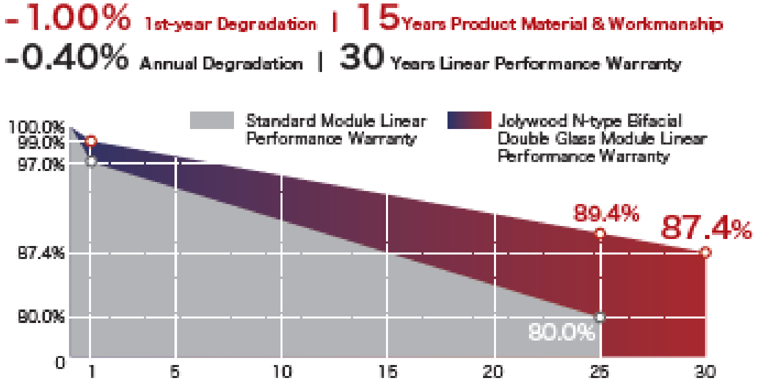
UV

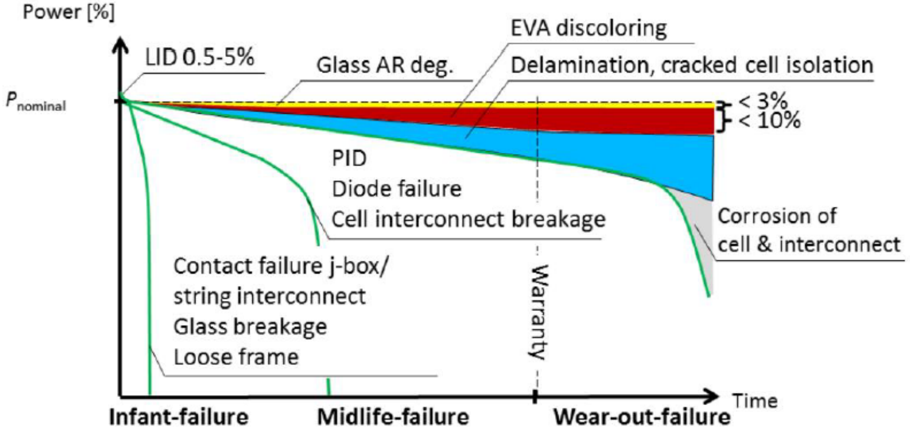
DML

Soiling

Performances pronostic







CHALLENGES

- ➢ Develop models for PV performances degradation in outdoor conditions
- ➢ Increase reliability for derisking PV investments
- ➢ Enhance durability for saving energy, materials and cost

• Climate change and production

Solar Energy 220 (2021) 671–679

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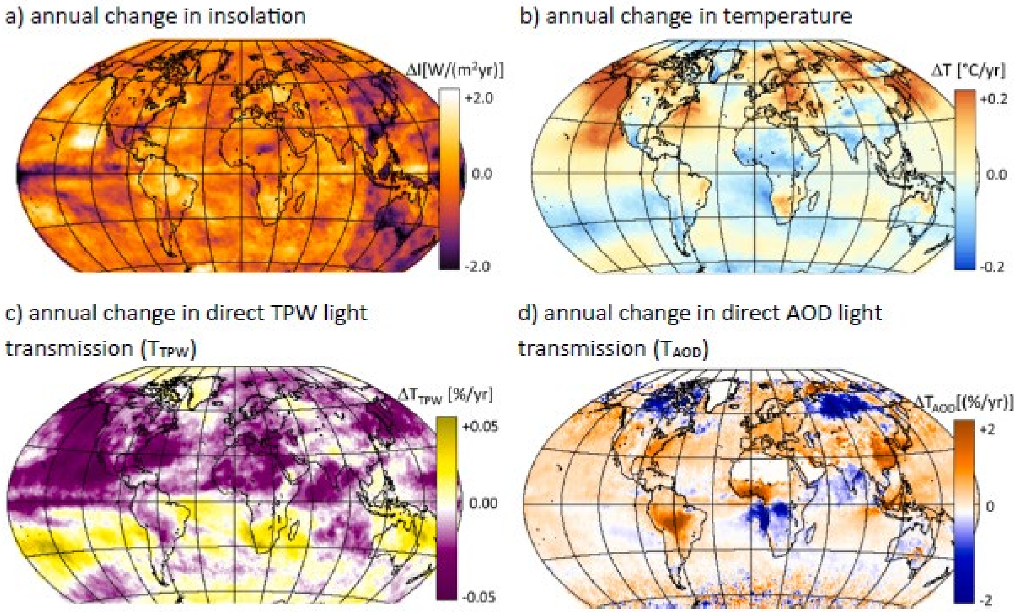
journal homepage: www.elsevier.com/locate/solener

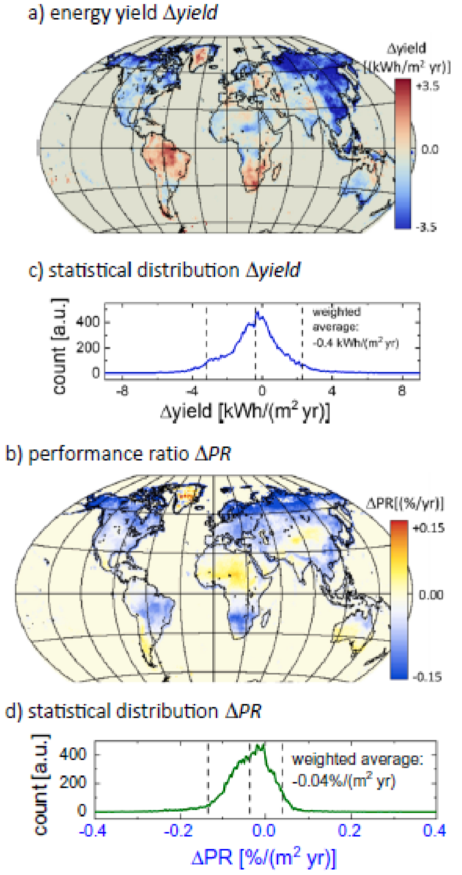
How changes in worldwide operating conditions affect solar cell performance

Ian Marius Peters [a,*], Tonio Buonassisi [b]

[a] Massachusetts Institute of Technology, United States

[b] Massachusetts Institute of Technology, Cambridge, MA 02139, USA





Global annual changes in average energy yield and PR in between 2006 and 2015

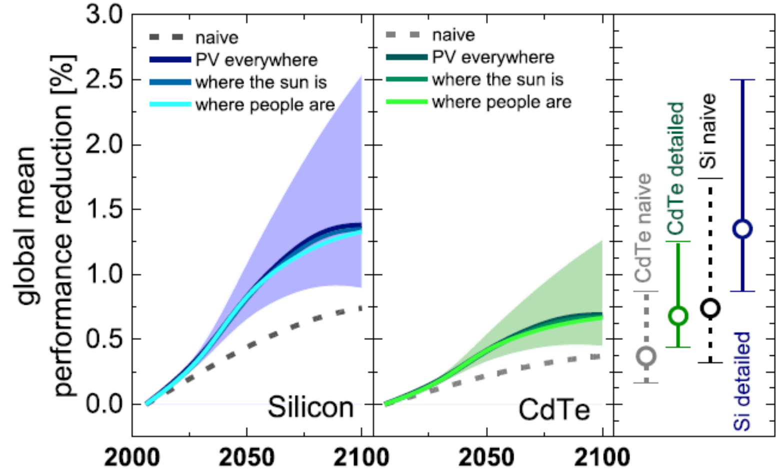
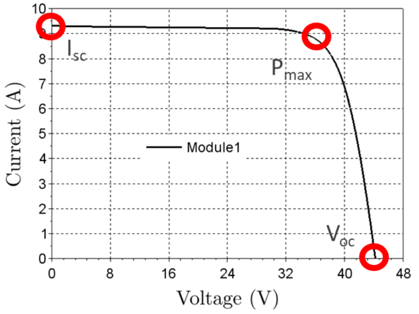
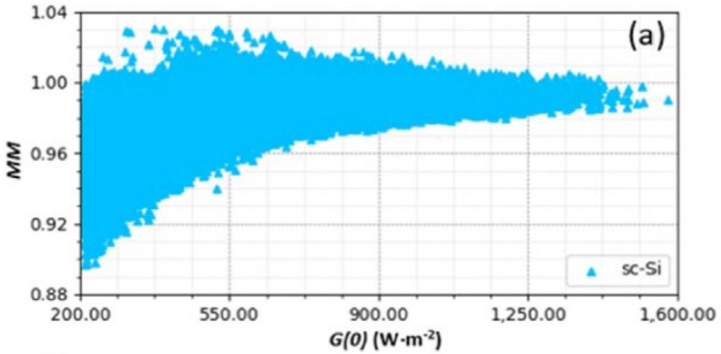


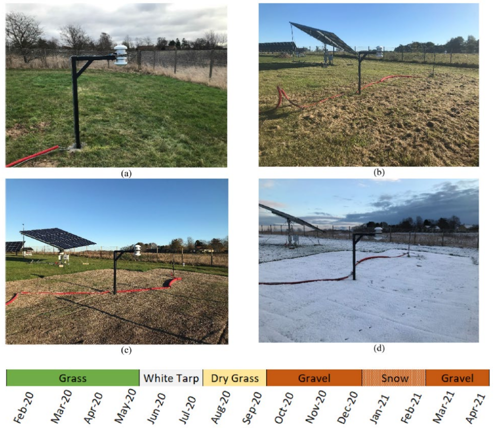
Fig. 6. Projected reduction in solar cell performance. In the leftmost part of the figure results for silicon (blue) are shown compared to the naïve baseline (black dashes). The middle part of the figure shows the same for CdTe (green and grey dashes). Lines correspond to the RCP 4.5 global warming scenario, shaded areas and bars in the rightmost figure mark the range of results for different IPCC projection (lower limit —RCP2.6, upper limit — RCP8.5). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- **Climate change causes variation of**
  - Temperatures
  - Precipitable water
  - Insolation (intensity and spectrum)
- **It will results in different conditions for the same installation in between the begin of life and the end of life of the installation**
- **It will lower the global performance of PV**

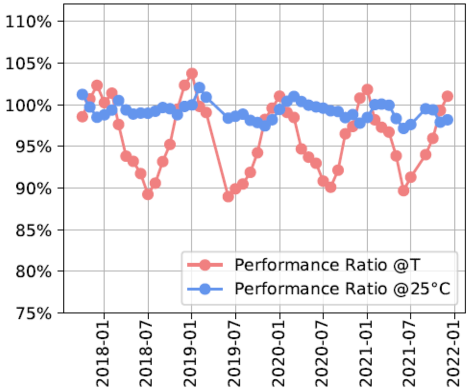
Conclusions

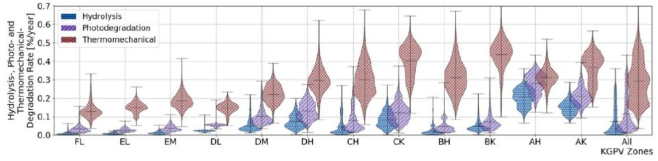






- **To characterize a module we use the IV curve:**
  - I_{sc}, V_{oc}, P_{max}, FF
- **Weather impacts IV curves:**
  - The irradiance (clouds, AM, Albedo)
  - The spectral distribution (clouds, AOI, SR, APE, Albedo)
  - The spatial homogeneity (snow, soiling, shadowing)
  - The temperature (ambiant temperature, wind, humidity)
- **Weather impacts the durability of the module**
  - Model each degradation mechanism for any outdoor conditions and any BOM





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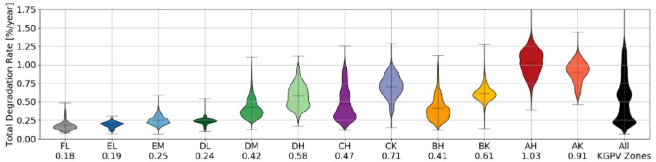

Figure 6. Spatial distribution of the total degradation rates in view of the KGPV climate zones. The average of total degradation rate per climate zone is indicated below each label in %/a.

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

Thank you for your attention!

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