Internal seminary CERTES

Study of the evolution of the energy performance of photovoltaic systems under different aging conditions

Pierre-Olivier LOGERAIS

Université Paris-Est Créteil, CERTES, IUT de Sénart-Fontainebleau, France

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Outline

I. Diversity of photovoltaic (PV) systems

II. Degradation of PV modules and approach

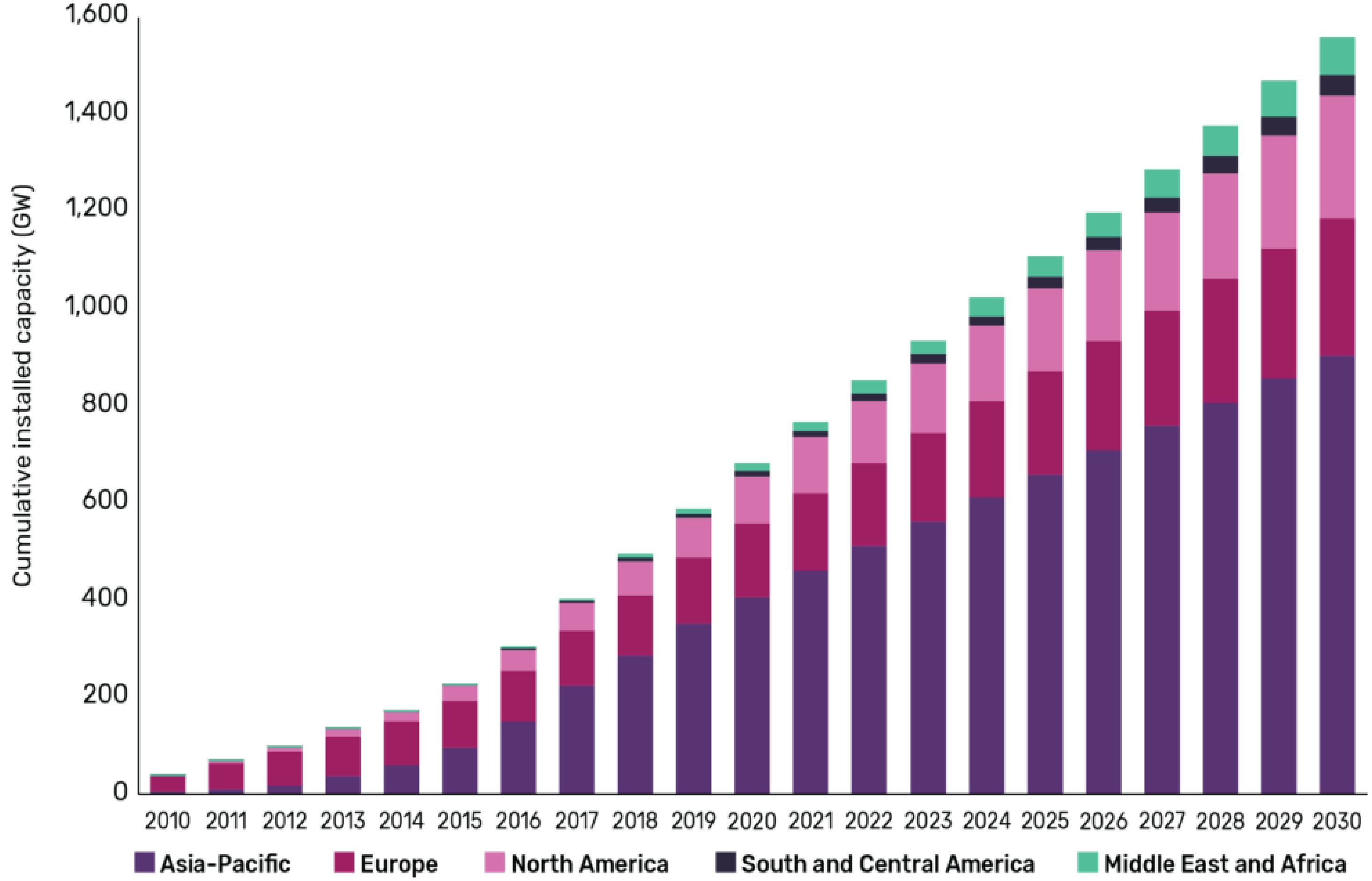
III. Four PhD studies supervised between 2014 and 2022

- PV plants of Sourdun (Île-de-France) and of Melouka (Algeria)
- UV accelerated test platform OSED-aging
- Model of a PV grid-connected system
- Model of a GaAs solar cell in outer space

IV. Conclusion and perspectives

I. Diversity of photovoltaic systems

Cumulative global solar PV installed capacity by region 2010-2030



Source: GlobalData Power Intelligence Center

I. Diversity of photovoltaic systems

PV grid-connected systems

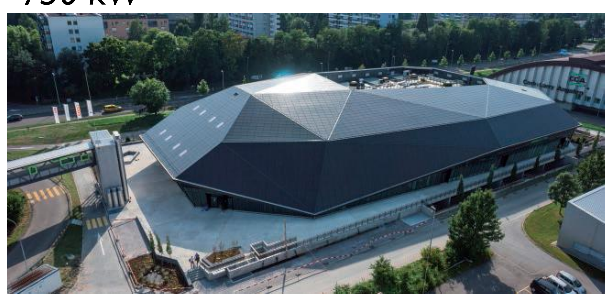
Integration of three PV façades
Building of the Tourist Office in Alès, France
9,5 kW

Rooftop photovoltaic plant
La Haye-les-Roses, Val de Marne, Paris, France
4,3 MW

Power plants
Copper Mountain Solar Facility in Nevada, USA
458 MW

The world's first **solar road**
Tourouvre-au-Perche in Normandy, France

Full roof BIPV
Umwelt arena Spreitenbach, Zurich, Switzerland
750 kW



Floating solar PV
O'MEGA1 project, Piolenc, Vaucluse, France
17 MW

I. Diversity of photovoltaic systems

Autonomous system

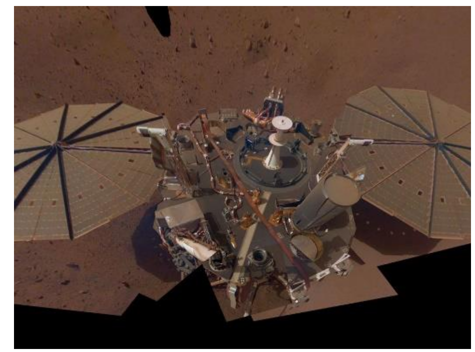
Solar water pump
900 W

Sign board
~ 100 W

Helios solar plane
~ 35 kW

Jason-1 satellite
Earth observing system, 2001
500 W

InSight probe on Mars
Geology, 2019
600 W

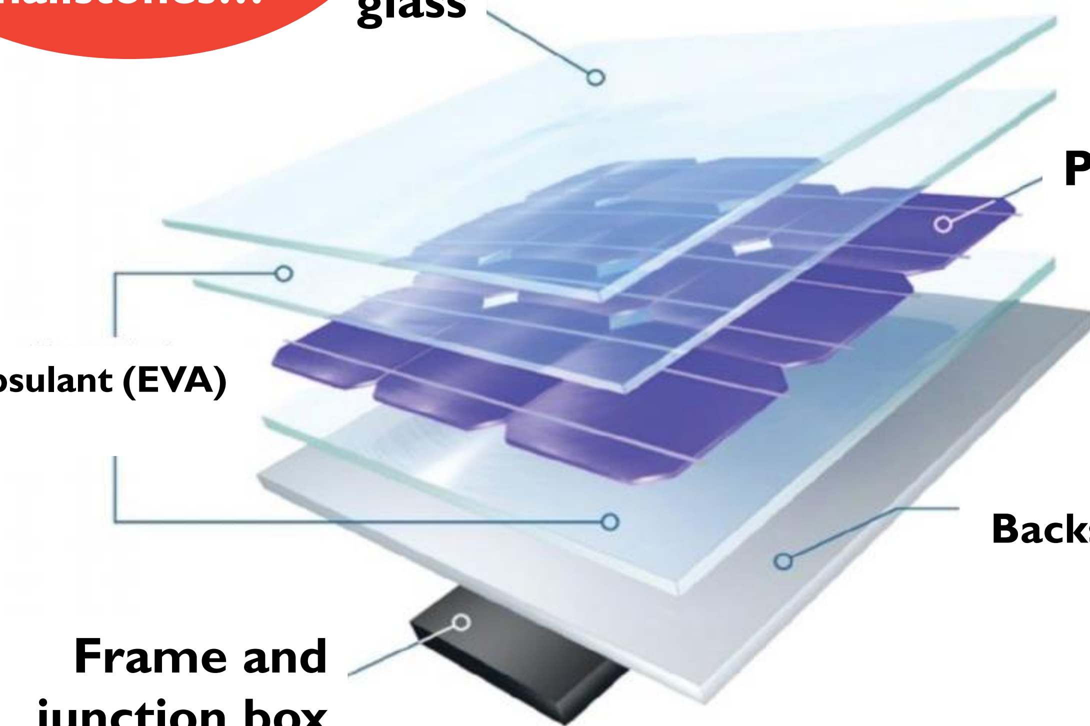


Rovers on Mars
Sojourner mission 1996
450 W

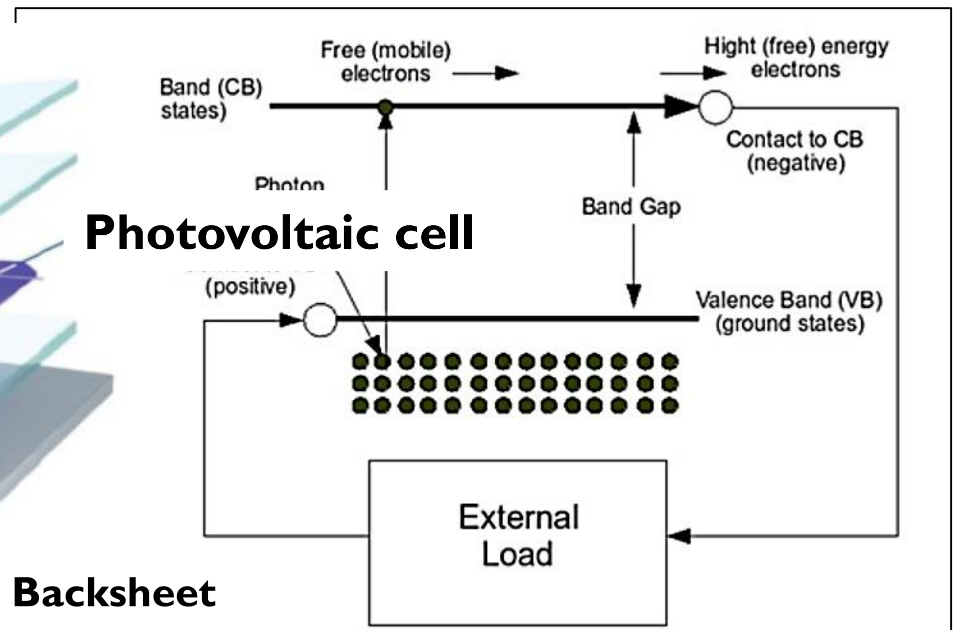
II. Degradation of PV modules

Irradiance T°, wind speed, snow, sand, hailstones…

Encapsulation of the PV cell



PV conversion of Si cell



Effiencies 18%–22% under STC

Degradation modes : optical parts

Soiling

Yellowing (browning)

Glass cracks

Delamination

Sealing problems (moisture ingress)

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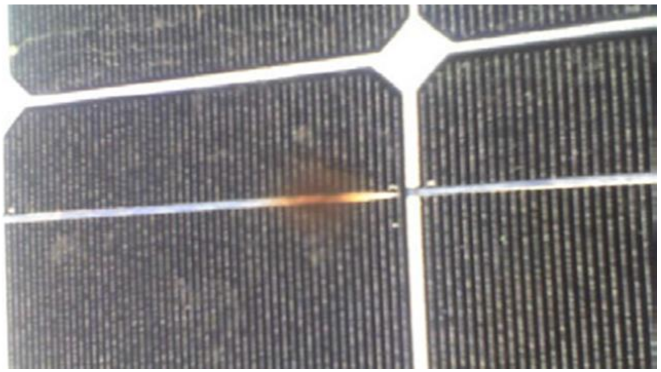
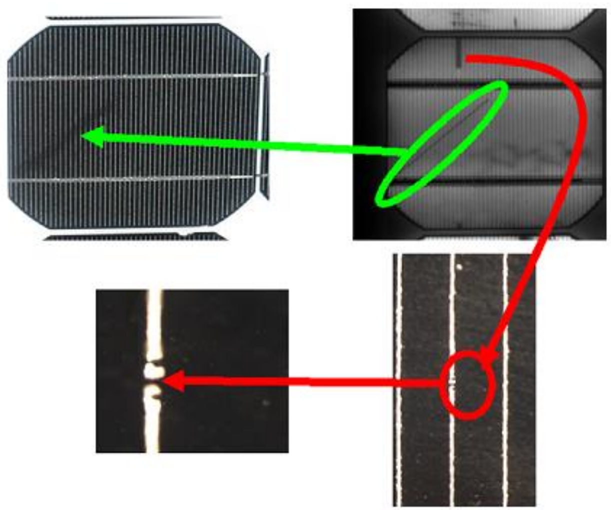
Degradation modes : electrical parts

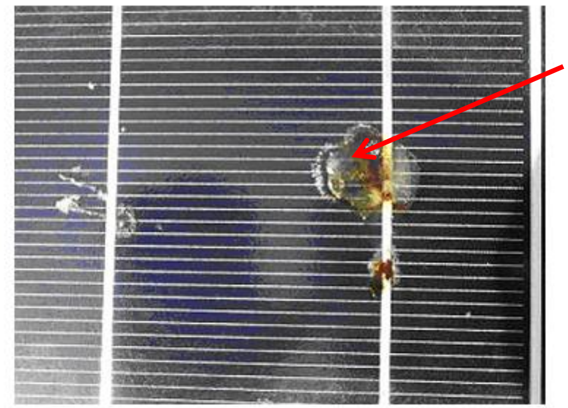
Corrosion



Microcracks
(electroluminescence)

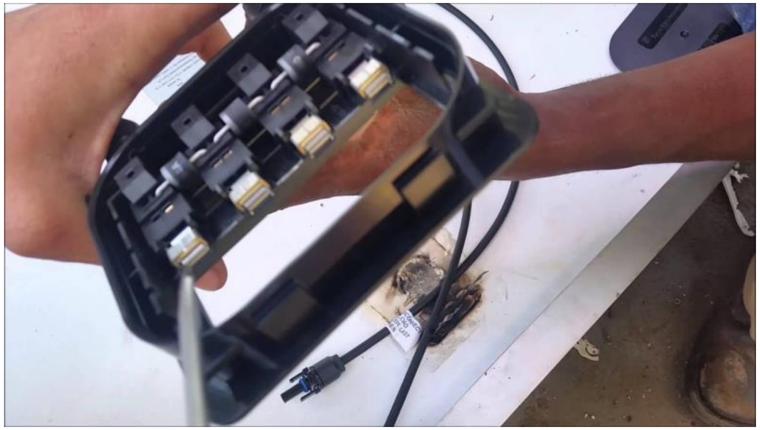


Hot spots
(IR thermography)



Degradation modes : electrical parts

Junction box replacement



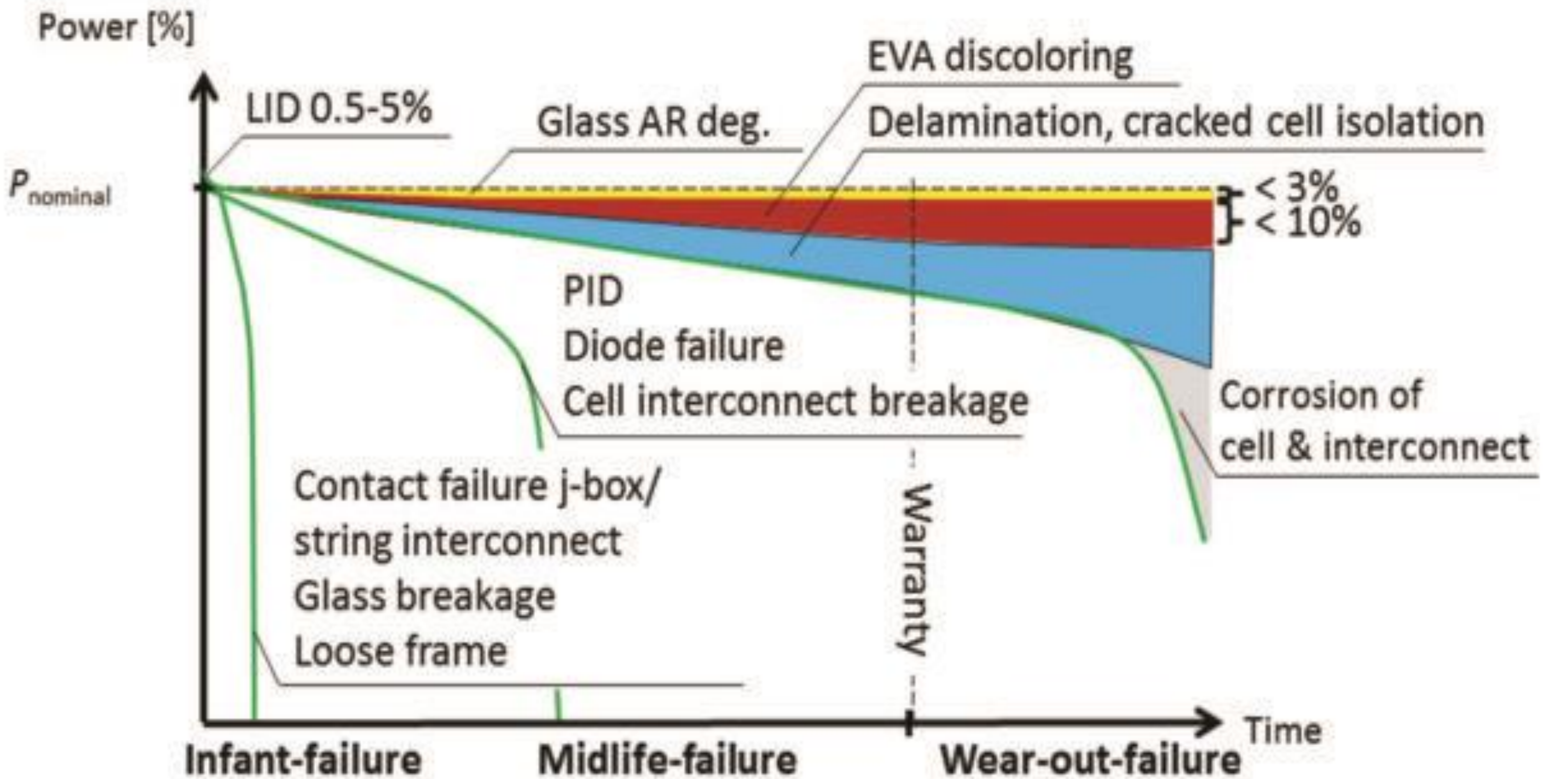
Mechanical load (snow, hail)

Detachment of the frame

II. Degradation of PV modules

Scenarios for wafer-based crystalline photovoltaic modules

LID – light-induced degradation ; PID – potential induced degradation
EVA – ethylene vinyl acetate ; j-box – junction box



Review of Failures of Photovoltaic Modules, IEA, Report IEA-PVPS T13-01:2014

II. Degradation of PV modules

Key benefits of environment-specific degradation rates

Technical benefits

- Performance closer to current technological conversion limit
- Fitting of PV cell technology to operation environment from the start
- Easy repowering of PV plants
- Reliability and durability of PV materials
- Preventive maintenance

Economical benefits

- Cumulative yield increase over lifetime
- Dependability of ROI
- Reduced maintenance costs
- Low-energy (lower carbon footprint)

II. Degradation of PV modules

Quantifying the impact of aging on performance

Irradiance (location, day), temperature, wind
PV module nominal values (STC) : I_{sc}, V_{oc}, P_{max}

Structural analysis of the degradation mode

PV system model
Data-based equation
Equivalent circuit
Finite element

Degradation law in the harsh environment

Validation

Sensitivity analysis

Performance evolution
I-V and P-V characteristics
P_{max} and P_{mean} degradation rates
Power production (day)

III. Studied systems

Photovoltaic system	Power scale	Environment	PV system model	Aging law	Validation	Sensible parameter	Knowledge
Plant Sourdun (France)	MW	temperate climate	Data-based equation from IEC 61724 analysis	PR degradation rate	Difference vs. real production < 1%	Irradiance and temperature	Relation $E_{out} = f(G)$
Plant Melouka (Algeria)	MW	Desert	Equation based on in-situ I-V measurement	P_{max} degradation rate	Degradation rates in literature	Observed degradation modes	Degradation rate of 1.22%/year
PV conversion line (MPPT + passive filter)	kW	Hot temperate climate	Equivalent circuit	Transmissivity $\tau(t)$ Resistances $R_i(t)$	Degradation rates in literature	Electrical resistances	30% power reduction after 20 years
Supercapacitor storage PV energy	100 W	temperate climate	Equivalent circuit	Transmissivity $\tau(t)$ Resistances $R_i(t)$ Capacitances $C_i(t)$	Outdoor measurement on a test bench	Capacitance of aged supercapacitors	Charge/discharge dynamics
Mono-Si PV panel with load in DH conditions	100 W	Damp heat	Equivalent circuit	Transmissivity $\tau(t)$ Resistances $R_i(t)$	Agreement with the case of Miami, USA	Optical degradations	Energy production projection for 25 years
PV cell with cracked Si cell	10 W	Snow	Physical-based equation	Inactive area	Agreement with values in the literature	Cracked surface	Energy loss over one given day
GaAs, InP junctions in space	W	Electron and proton irradiations in outer space	Finite element	Hole and electron traps Dose of particles	Agreement with DLTS measurements and satellite mission results	Recombination centers	Degradation of P_{max} and efficiency over time

III. Studied systems
PV plant of Sourdun (i)

In the Seine-et-Marne area
4,5 MWp
12 acres of land
p-Si modules
temperate climate

In service since March 2012
Exploited by the Générale du solaire

III. Studied systems
PV plant of Sourdun (ii)

Performance study from January 2012 up to December 2018:

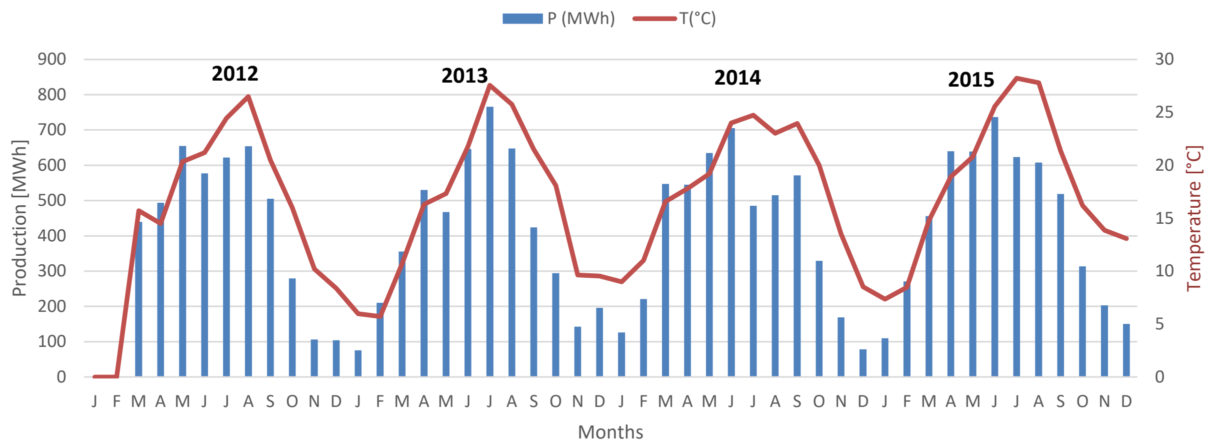
Monitored parameters: G, E, P, T_{mod}, T_a, v (timestep of 15 minutes)

Calculation of the **parameters specified by IEC 61724 standards (2017)** :

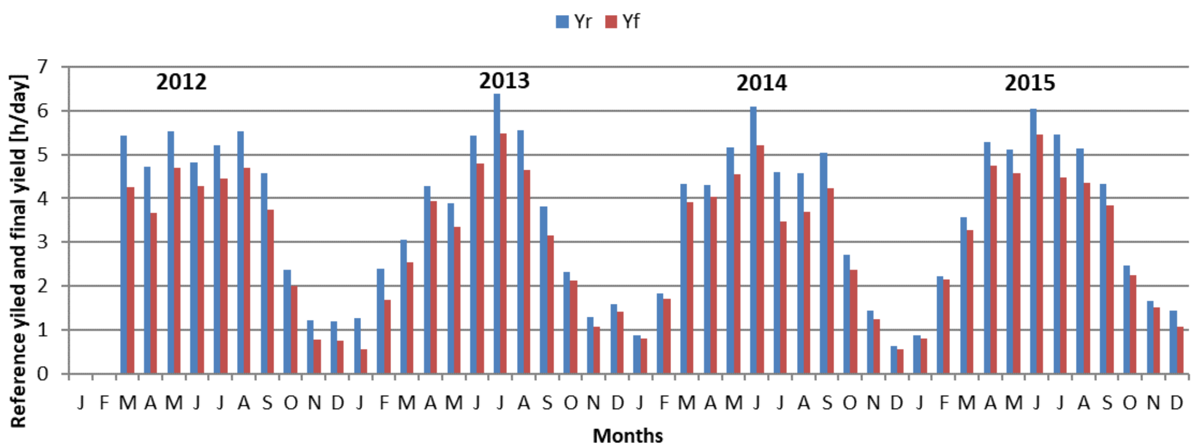
- reference yield: $Y_r = \left(\frac{H_t}{G_0}\right)$
- final yield: $Y_f = \left(\frac{E_{ac}}{P_0}\right)$
- availability: $D = 1 - \left(\frac{sum\left(DI \times TP\right)}{DPR}\right)$
- performance ratio: $PR = \left(\frac{Y_f}{Y_r}\right)$
- corrected performance ratio: $PR_C = \left(\frac{PR}{1+\alpha(Tm-Tn)}\right)$ **=> Degradation rate**

III. Studied systems
PV plant of Sourdun (iii)

Monthly evolution of production and ambient temperature

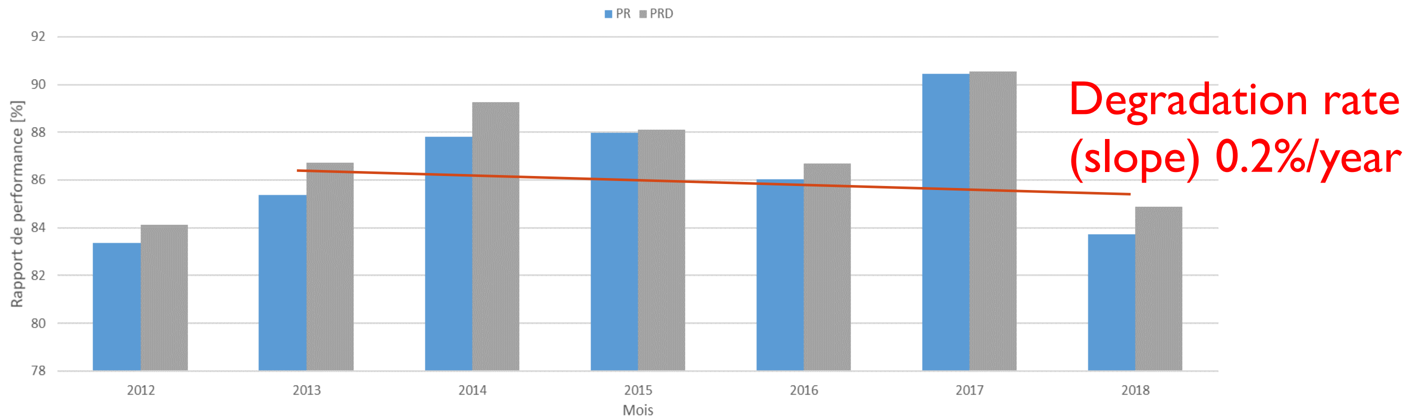


Monthly evolution of daily reference yield and final yield

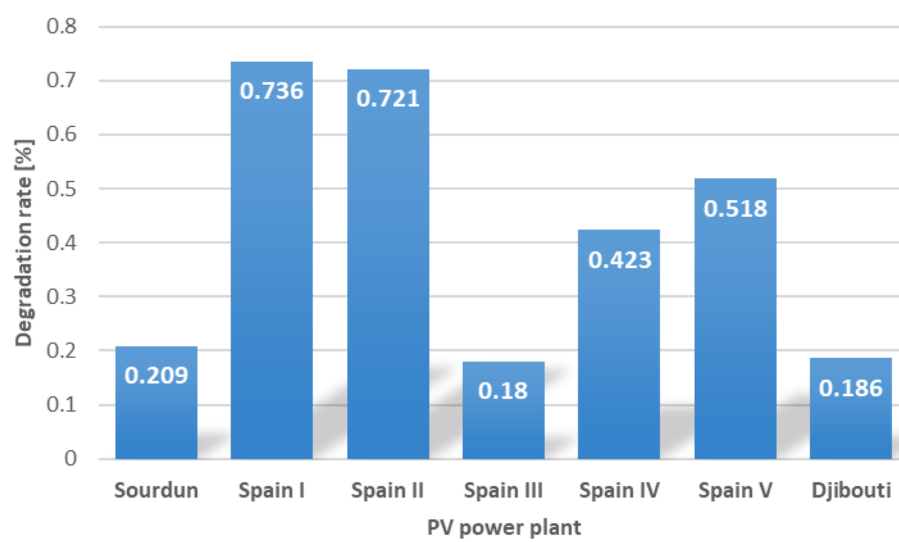


III. Studied systems
PV plant of Sourdun (iv)

Monthly evolution of production and ambient temperature.



Degradation rate regarding other PV installations studied within IEC 61724 standard.



M. Jed et al., Int. J. Sustainable Engineering, 14(6), 2021

III. Studied systems
Melouka PV installation (i)

Region of Adrar (Ageria)

30.24 kWp
864 PV Si-modules of type Belgosolar
48 strings of 18 modules
Inclination 17.5°
In service since 1985
Experimental studied with the CDER

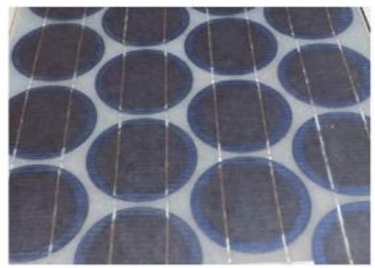
III. Studied systems
Melouka PV installation (ii)

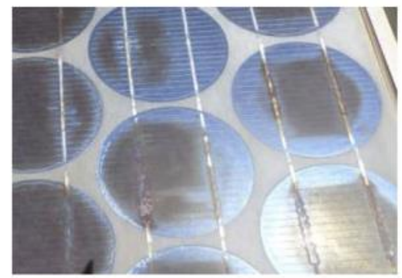
Degradations observed during the survey of photovoltaic modules of the site after 28 years in operation.

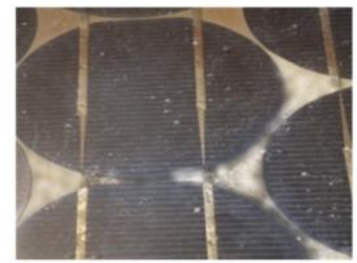

M01: Dark brown discoloration of EVA encapsulant


M02: Broken front glass


M03: Abrasion of glass


M04: Higher degree of browning of cells


M05: Reddish discoloration on front grid fingers


M06: Delamination of encapsulant


M07: Yellowing of encapsulant


M08: Hot spots in the area of the cells


M09: Thermal shocks

F. Bandou et al., IJHE, 14(6), 2021

III. Studied systems
Melouka PV installation (iii)

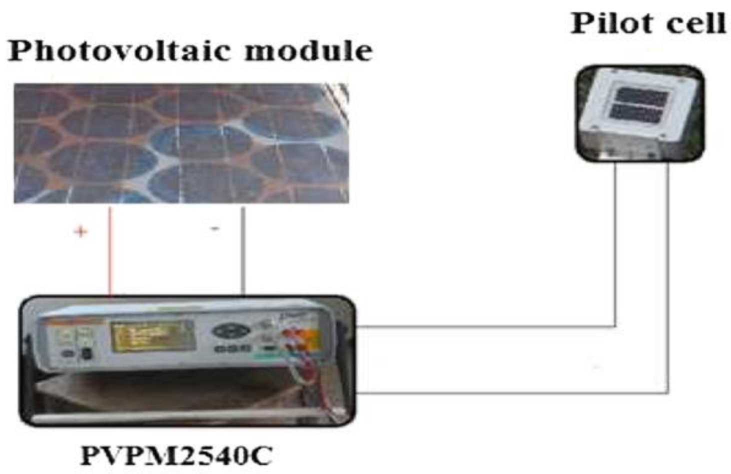
In-situ measurements of I-V curves after 27 years in operation:

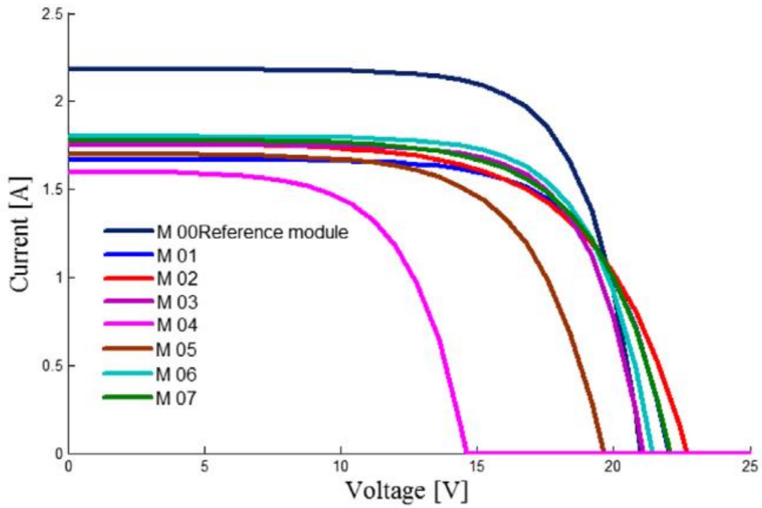
STC translation equations using IEC 60891 translation procedure:

$$I_{max,STC} = I_{max,mes}\left(\frac{G_{STC}}{G_{mes}}\right) + \alpha(T_{mod} - T_{STC})$$

$$V_{max,STC} = V_{max,mes} - \beta(T_{STC} - T_{mod})$$

$$P_{max,STC} = I_{max,STC} \times V_{max,STC}$$





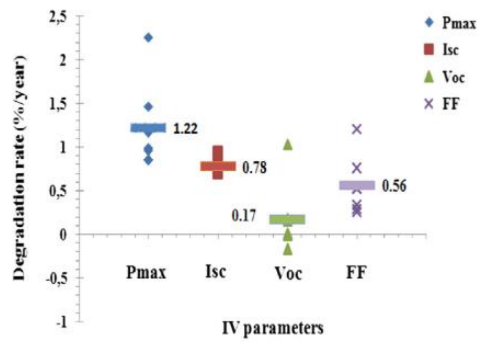
I-V characteristic curves of the M01-M07 modules tested outdoor translated to standard test conditions (1000 W/m^2, AM1.5 and cell temperature 25°C).

III. Studied systems
Melouka PV installation (iv)

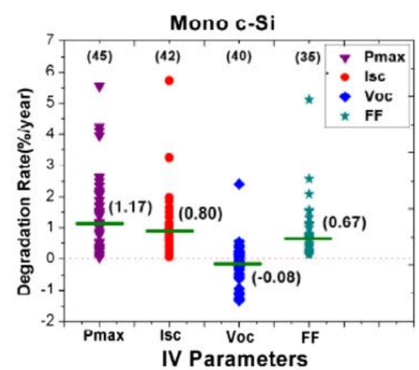
Degradation rate of the maximum power:

Module	Uncertainties				$P_{max} \pm u(P_{max})$ (W)	$R_D \pm u(R_D)$ for P_{max} (%/year)
	Current $u(I_{max})$	Voltage $u(V_{max})$	Irradiance $u(G_{mes})$	Temperature $u(T_{mod})$		
M01	0.09	0.05	0.45	0.26	23.54 ± 1.09	1.17 ± 0.04
M02	0.01	0.04	1.47	0.63	25.56 ± 0.64	0.96 ± 0.03
M03	0.01	0.25	0.60	0.35	26.56 ± 0.85	0.86 ± 0.02
M04	0.03	0.57	5.76	1.32	12.88 ± 1.42	2.26 ± 0.08
M05	0.03	0.03	0.46	0.43	20.58 ± 0.58	1.74 ± 0.06
M06	0.05	0.034	4.58	0.41	25.31 ± 0.53	0.99 ± 0.03
M07	0.012	0.08	0.71	0.16	26.68 ± 0.68	0.85 ± 0.03
Mean values					23.02 ± 0.83	1.22 ± 0.04

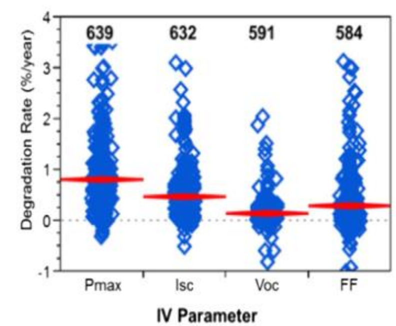
Comparative results of yearly degradation rates:



(a) : Results provided by our study.



(b) : Results provided by Dubey et al., 2014



(c) : Results provided by Jordan et al., 2012

F. Bandou et al., IJHE, 40, 2015

III. Studied systems
UV accelerated test (i)

OSED-aging platform (Sénart)

The UV chamber

- Brand : INVE 2000, Helios Quartz
- Chamber temperature at $50°C \pm 5°C$
- 500 W medium-pressure mercury UV lamp
- Incident irradiance fixed at $600\ W/m^2$ in the wavelength range $[250 - 400\ nm]$.

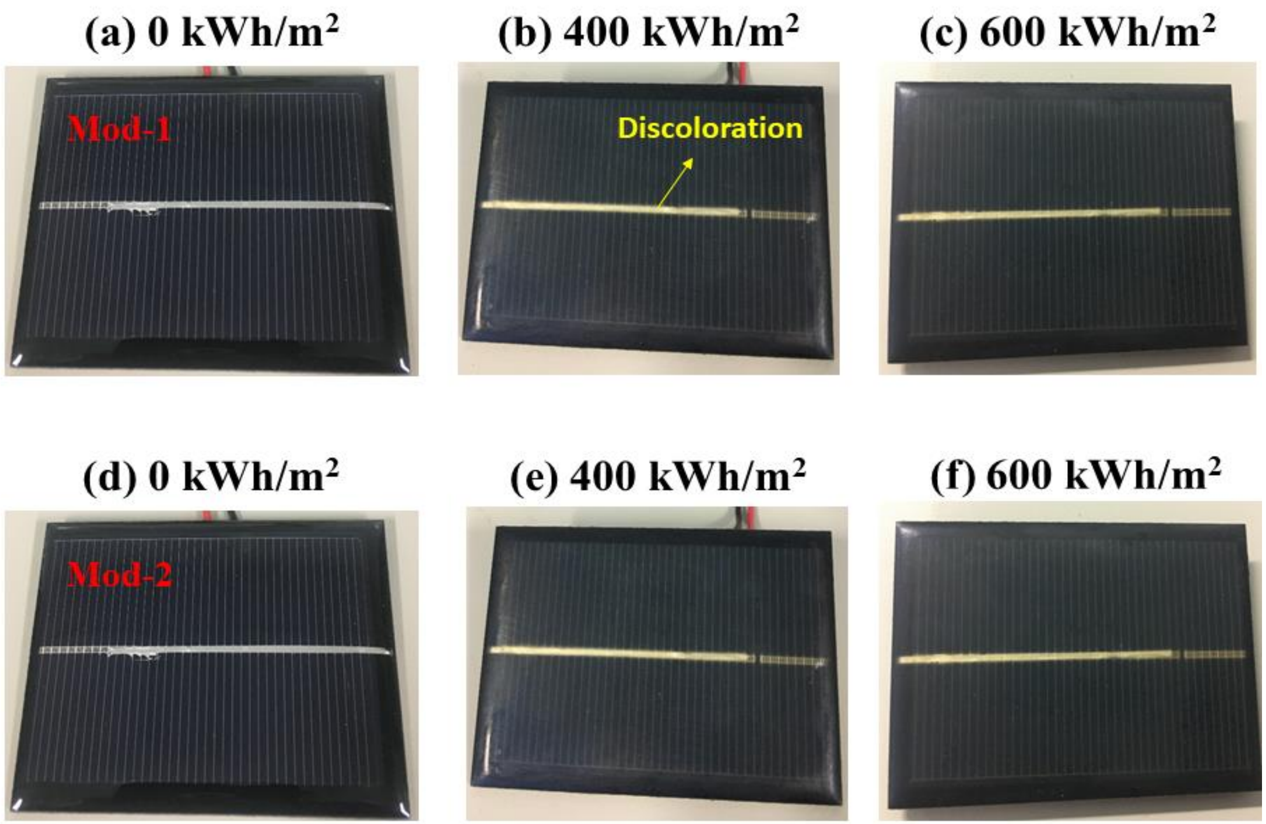
The solar simulator

- Brand : SolarLight type LS1000-6S
- Class-A for the spectral match and temporal instability classification ($\pm$ 5 %)
- Class-B for the irradiance uniformity ($\pm$ 10 %)
- Source is a 1000 W xenon lamp with an AM 1.5G filter.
- Temperature-controlled vacuum to maintain STC conditions

III. Studied systems
UV accelerated test (ii)

<u>UV test applied to samples encapsulated crystalline-Si PV cells with progressive UV doses</u>

(indoor temperature 50°C)



Presented by V. R. Posa et al.. JNPV conference, 2020

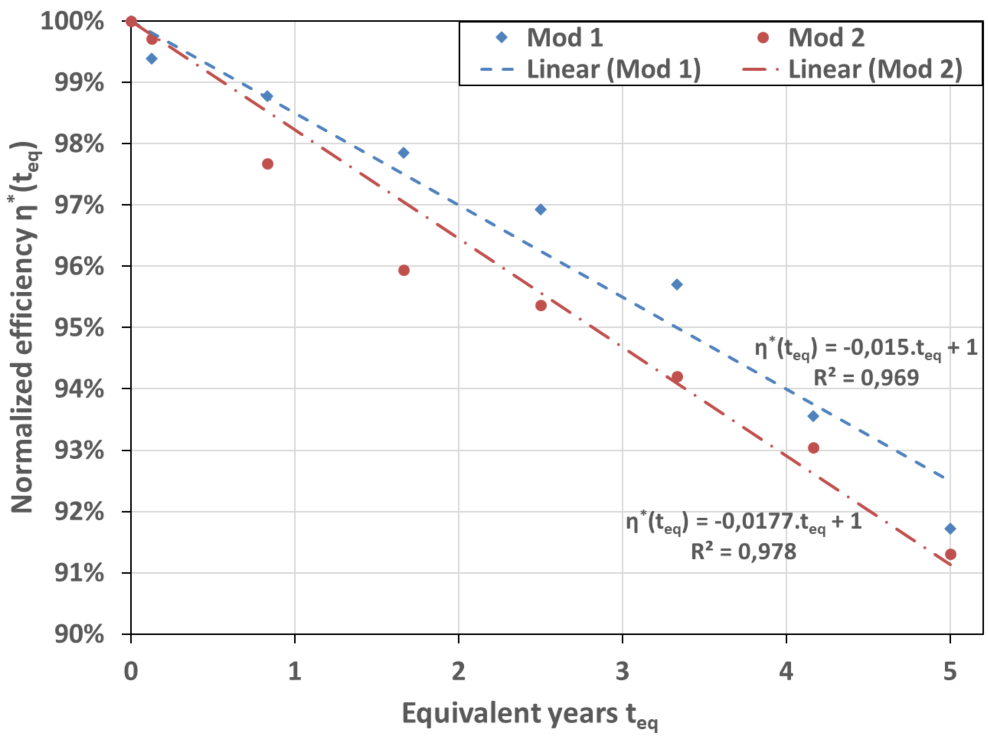
III. Studied systems
UV accelerated test (iii)

Degradation equivalent relation

Outdoor UV dose of 120 kWh/m² ⇔ 1 year exposure in PV modules operating in the desert environment *(M. Koehl, Proc. of SPIE, 7412, 2009)* => Test time in equivalent years

Normalized efficiency:

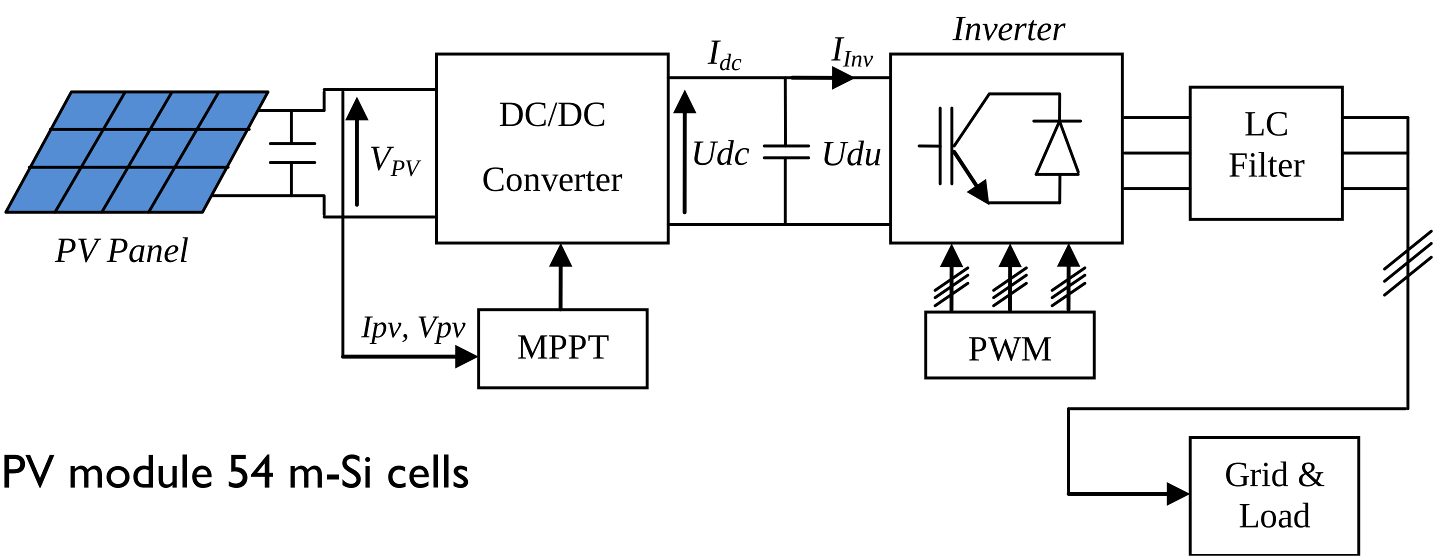
$$\eta^*(t_{eq}) = \frac{\eta(t_{eq})}{\eta(t=0)}$$



Degradation rate 1.65%/year

III. Studied systems
Grid-connected PV module (i)

Modeled photovoltaic conversion line



KC200GT PV module 54 m-Si cells

MPPT: P&O: Perturb and Observe

Passive LC filter

=> Matlab/Simulink model

Sizing of the system
A. Azizi et al.. Solar Energy, 174, 2018

III. Studied systems
Grid-connected PV module (ii)

Hybrid detection method introducing aging laws

MPP Tracking: time t <<T (inter-annual time)

Aging laws:

85°C/85% RH damp Heat on c-Si modules

Equivalent time: 1000 hours test time ⇔ 20 years of outdoor exposure *(IEC 61215 standards, 2016)*

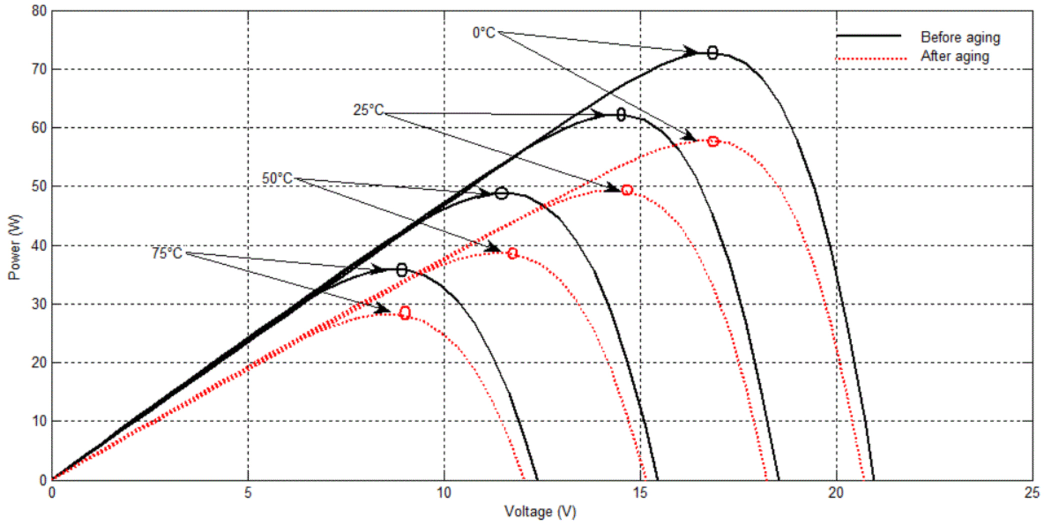
- ***Linear reduction of the transmissivity*** $\boldsymbol{\tau}$ (glass optical losses and encapsulating losses): $\tau(T) = \tau_0(-\alpha_{opt}.T + 100\%)$ $\alpha_{opt} = 0.6\ \%/year$ *(King at al., 2000)*

- ***Linear augmentation of the series resistance*** $\boldsymbol{R_s}$ (deterioration of electrical parts): $R_s(T) = R_{s0}(+\alpha_{R_s}.T + 100\%)$ $\alpha_{R_s} = 0.23\ \%/year$ *(Hulkoff, 2009)*

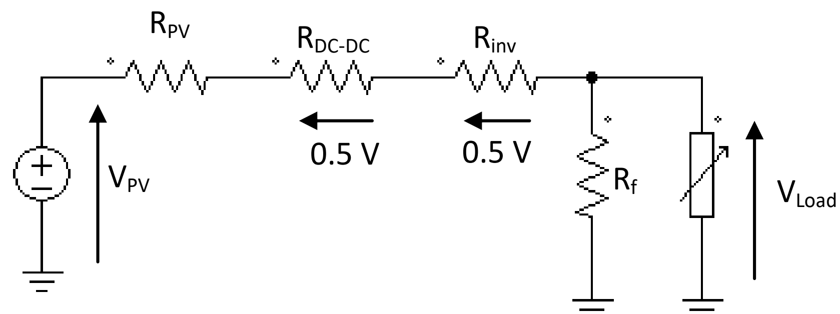
A. Azizi et al.. Solar Energy, 174, 2018

Outcomes

Impact of aging with influence of the temperature P-V characteristics after 20 years.



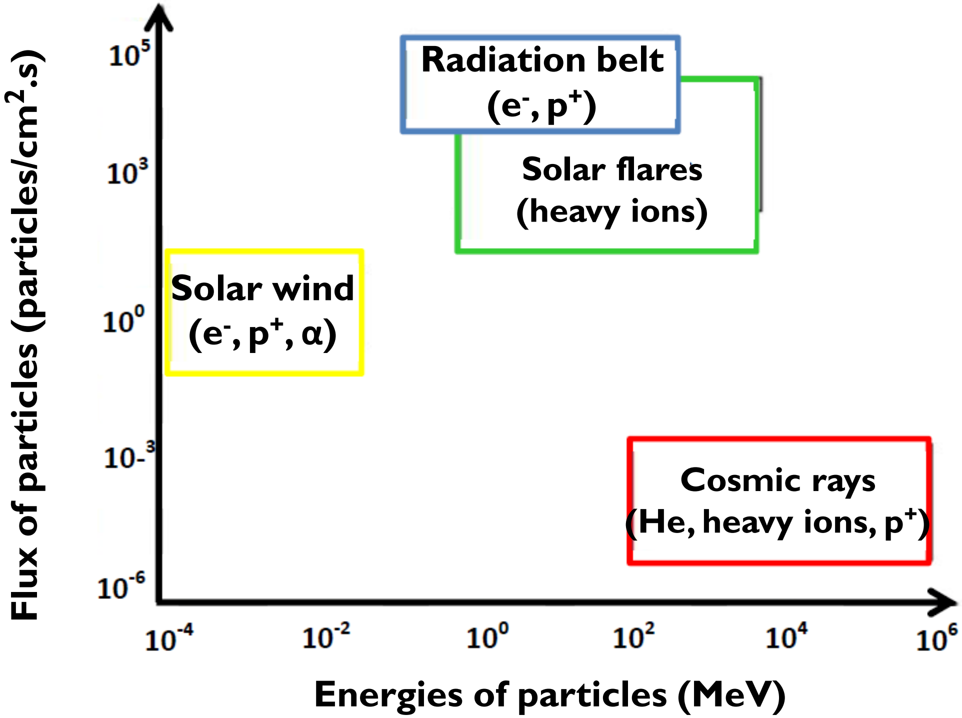
Equivalent circuit of the photovoltaic system with aging resistances



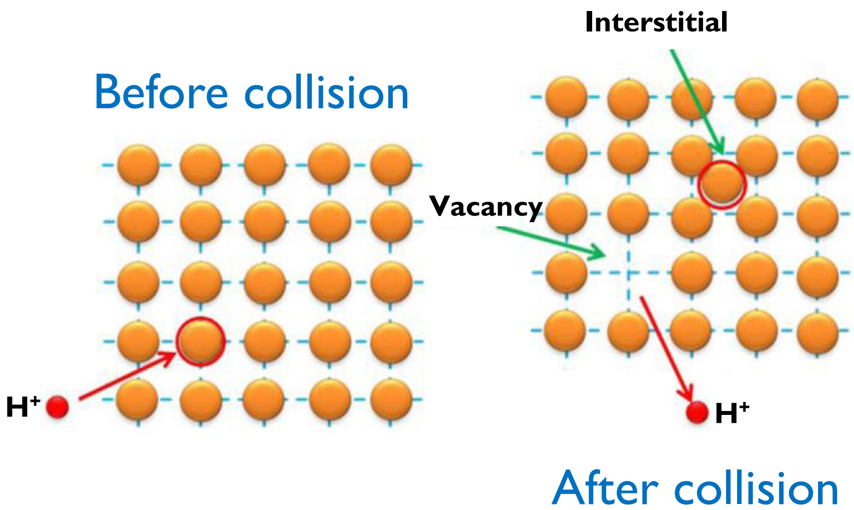
A. Azizi et al.. Solar Energy, 174, 2018

III. Studied systems
GaAs solar cell in space (i)

Flux and energies of particles



Displacement of an atom by a proton

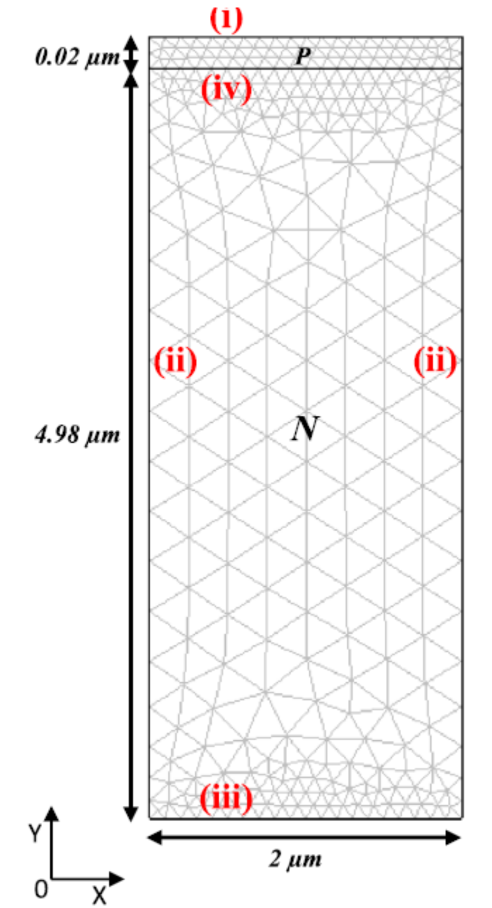


Consequences

- Trapping of carriers
- Deep level defects
- Generation of electron-hole pairs
- Recombinations
- Doping compensation
- Tunnel effect

III. Studied systems
GaAs solar cell in space (ii)

Modeling of the PN junction



Poisson's continuity equations:

$$\begin{cases} -\nabla.(\varepsilon.\nabla\psi) = q(p-n+N) \\ \dfrac{dJ_n}{d\,x} = -q(G_{opt}-R_{SRH}) \\ \dfrac{dJ_p}{d\,x} = q(G_{opt}-R_{SRH}) \end{cases}$$

Optical generation:

$G_{opt} = (1-R).\alpha(\lambda).\phi\exp(-\alpha(\lambda).x)$ with an absorption coefficient :

$$\alpha(\lambda) = K_{abs}.\sqrt{\frac{1{,}24}{\lambda[\mu m]} - E_g}$$

Shockley-Read-Hall recombination: $R_{SRH} = \sum_{j=1}^{m} \frac{n.p - {n_i}^2}{\tau_p.(n+n_t) + \tau_n(p+p_t)}$

Lifetime of electrons and holes: $\frac{1}{\tau_{n/p}} = \frac{1}{\tau_{0_{n/p}}} + \frac{1}{\tau_{rad_{n/p}}} + N_t\sigma_{n/p}v_{th_{n/p}}$

in which the trap concentration is associated to the recombination centers k and to the fluence φ : $N_t = k.\varphi$

III. Studied systems
GaAs solar cell in space (iii)

Aging properties

Parameters of the considered mission

Duration	15 years
Satellite power consumption	15 kW
Electron radiation/year/cm² (1 MeV) R_{radE}	1.4×10^{13}
Proton radiation/year/cm² (10 MeV) R_{radP}	2.3×10^{10}

Characteristics of electron and hole traps observed for 1 MeV electron irradiated GaAs solar cells

Electron fluence (e/cm2)	Electron traps			Hole traps		
	E	E_t (eV)	N_t (cm^{-3})	H	E_t (eV)	N_t (cm^{-3})
10^{14}	E1	Ec-0.14	$1.8\ 10^{13}$	H1	Ev+0.71	$3\ 10^{12}$
	E2	Ec-0.41	$8.2\ 10^{12}$			
	E3	Ec-0.71	$3\ 10^{10}$[a]			
	E4	Ec-0.90	$8.8\ 10^{11}$			
10^{15}				H1	Ev+0.13	$2.2\ 10^{14}$
	E2	Ec-0.41	$2.1\ 10^{14}$	H2	Ev+0.29	$4\ 10^{14}$
	E3	Ec-0.71	$1.7\ 10^{13}$	H3	Ev+0.35	$8\ 10^{13}$
	E4	Ec-0.90	$2.8\ 10^{13}$	H4	Ev+0.71	$6.4\ 10^{13}$
5.10^{15}				H1	Ev+0.13	$8.9\ 10^{14}$
	E2	Ec-0.41	$4.5\ 10^{14}$	H2	Ev+0.29	$1.5\ 10^{15}$
	E3	Ec-0.71	$3.2\ 10^{13}$	H3	Ev+0.35	$1\ 10^{15}$
	E4	Ec-0.90	$5\ 10^{15}$	H4	Ev+0.71	$1.9\ 10^{14}$
10^{16}				H1	Ev+0.13	$8.4\ 10^{14}$
	E2	Ec-0.41	$8.8\ 10^{13}$	H2	Ev+0.29	$1.6\ 10^{15}$
	E3	Ec-0.71	$5\ 10^{13}$	H3	Ev+0.35	$1\ 10^{15}$
	E4	Ec-0.90	$6.5\ 10^{13}$	H4	Ev+0.71	$2.7\ 10^{14}$

Bourgoin, Zazoui, Semicond Sci Technol 2002;17:453-60.

III. Studied systems
GaAs solar cell in space (iv)

Aging law

Irradiation data and defects engendered for the GEO mission (*Habraken et al. 2001*)
Log formalism of the efficiency decay (*La Roche et al. 1993; Yamaguchi 2001*).

The cumulated dose D_{grd} (in particles/cm^2) :

$$D_{grd} = T.\, log\, (R_{rad} + \varphi)$$

where

R_{rad} : irradiation rate of the electrons (or protons)
T : time in year
φ : fluence linked to the introduction rate of the recombination centers k and to the trap concentration: $N_t = k.\varphi$

H. Mazouz et al., IEEE JPV, 9(6), 2019

III. Studied systems
GaAs solar cell in space (v)

- **Validation without irradiation**

Output parameters	2D simulation	Experiment [Liou 1994]	1D simulation [Laiadi 2008]	2D simulation [Elahidoost 2012]
J_{cc} (mA/cm²)	28,58	32,37	23,86	24,08
V_{co} (V)	0,977	1,017	1,01	0,95
FF	0,884	0,815	0,88	0,839
η (%)	18,30	19,9	15,60	14,1

- **Validation under electron irradiation**

Fluence (e.cm⁻²)	Before irradiation	$\varphi = 10^{14}$			$\varphi = 10^{15}$			$\varphi = 5.10^{15}$			$\varphi = 10^{16}$		
		2D		1D	2D		1D	2D		1D	2D		1D
		modele	ref. [Elahidoost 2012]	ref. [Laiadi 2008]	modele	ref. [Elahidoost 2012]	ref. [Laiadi 2008]	modele	ref. [Elahidoost 2012]	ref. [Laiadi 2008]	modele	ref. [Elahidoost 2012]	ref. [Laiadi 2008]
J_{cc} (mA.cm⁻²)	28,58	25,22	23,81	22,27	17,11	21,63	21,63	15,63	16,95	17,04	11,24	12,26	14,362
V_{oc} (V)	0,977	0,969	0,94	0,88	0,958	0,92	0,92	0,897	0,895	0,706	0, 886	0,87	0,678
FF	0,884	0,890	0,840	0,796	0,892	0,841	0,841	0,887	0,830	0,751	0,889	0,817	0,730
η (%)	18,30	16,12	13,9	11,5	10,84	12,35	12,35	9,21	9,375	6,60	6,56	6,4	5,23

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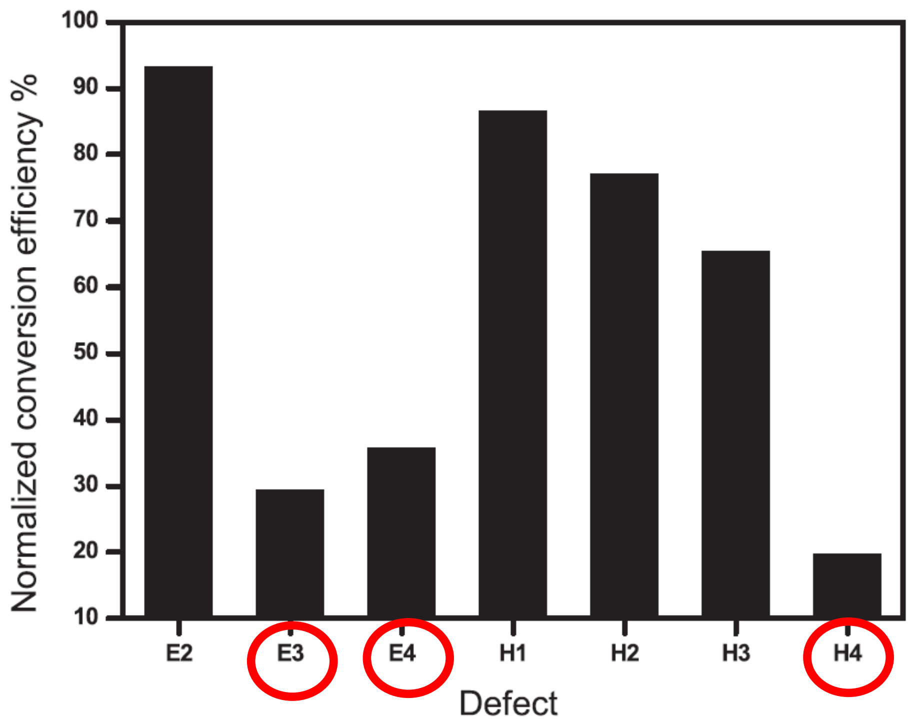
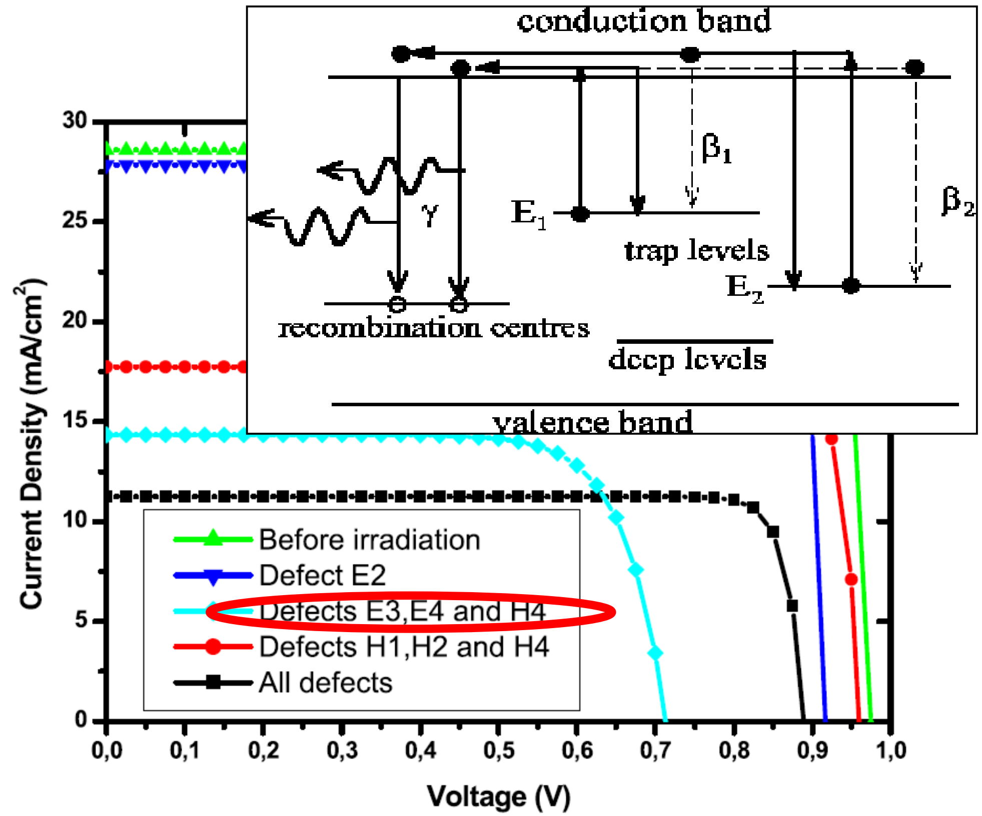
III. Studied systems
GaAs solar cell in space (vi)

Sensitivity analysis

Normalized conversion efficiency for the various defects



J(V) characteristics as a function of defect level for the electron fluence of 10^{16} e/cm^2

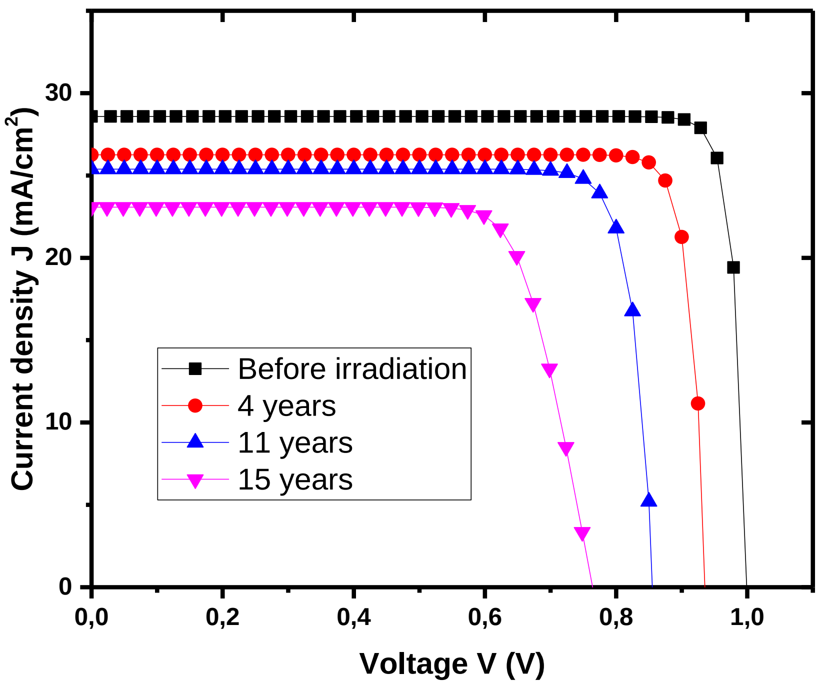


H. Mazouz et al., IJHE, 40, 2015.

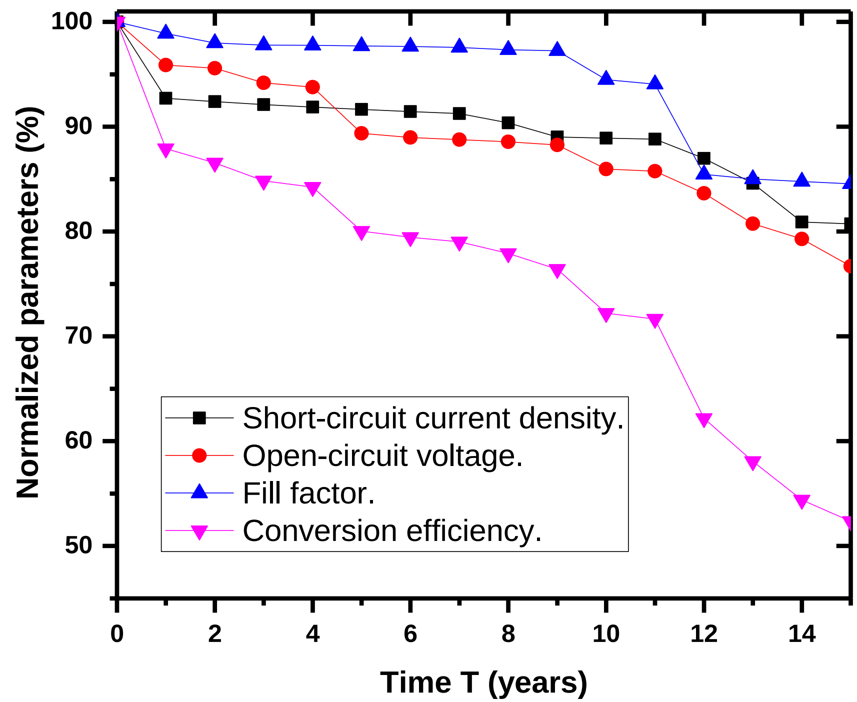
GaAs solar cell in space (vii)

Degradation of the performance in outer space

Evolution of the J(V) characteristic



Normalized conversion efficiency degradation with the other simulated output parameters



H. Mazouz et al.. IEEE JPV, 9(6), 2019

IV. Conclusion and perspectives

- **Multi-scale approach W → kW → MW** for fitting one PV technology module to one given environment at the CERTES laboratory

Accelerated test and sensitivity analysis on a prototype *OSED-aging platform* → Outdoor exposure *PV-Ecoclass platform* - - → PV plant

- **PhD students in progress**:
  - **Mohamed El Hacen JED**: defense on October 22th 2022
  - **Julia VINCENT:** sequential accelerated tests on Si PV cells by Slite-Source
  - **Islem BOUJLEL**: sensitivity analysis and energy performance of PV modules, aging of temperature coefficients

- **Projects and collaborations:** ANAPHORE (OSU-Efluve), TotalEnergies, CERD Djibouti, EMSI (Morocco)

Thank you for your attention