CAN WE MAKE SOLAR PV MODULES THAT LAST 30+ YEARS?

IS THE INDUSTRY DOING IT?

01.12.2025

PV MODULETECH CONFERENCE EUROPE

A. Virtuani, H. Quest, E. Ozkalay, A. Gassner, G. Eder, G. Cattaneo, M. Despeisse, C. Ballif

Malaga, PV-ModuleTech Conference Europe
2-3 December 2025

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Mt Soleil (CH), since 1992

CSEM: at a glance

Public-private innovation center based in CH with international reach.

Solar PV: cells/modules, IPV products, polymer for PV compounding platform, advanced monitoring, grid-integration …..

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Gonghe (CN) 2,200 MW_{AC} (-)

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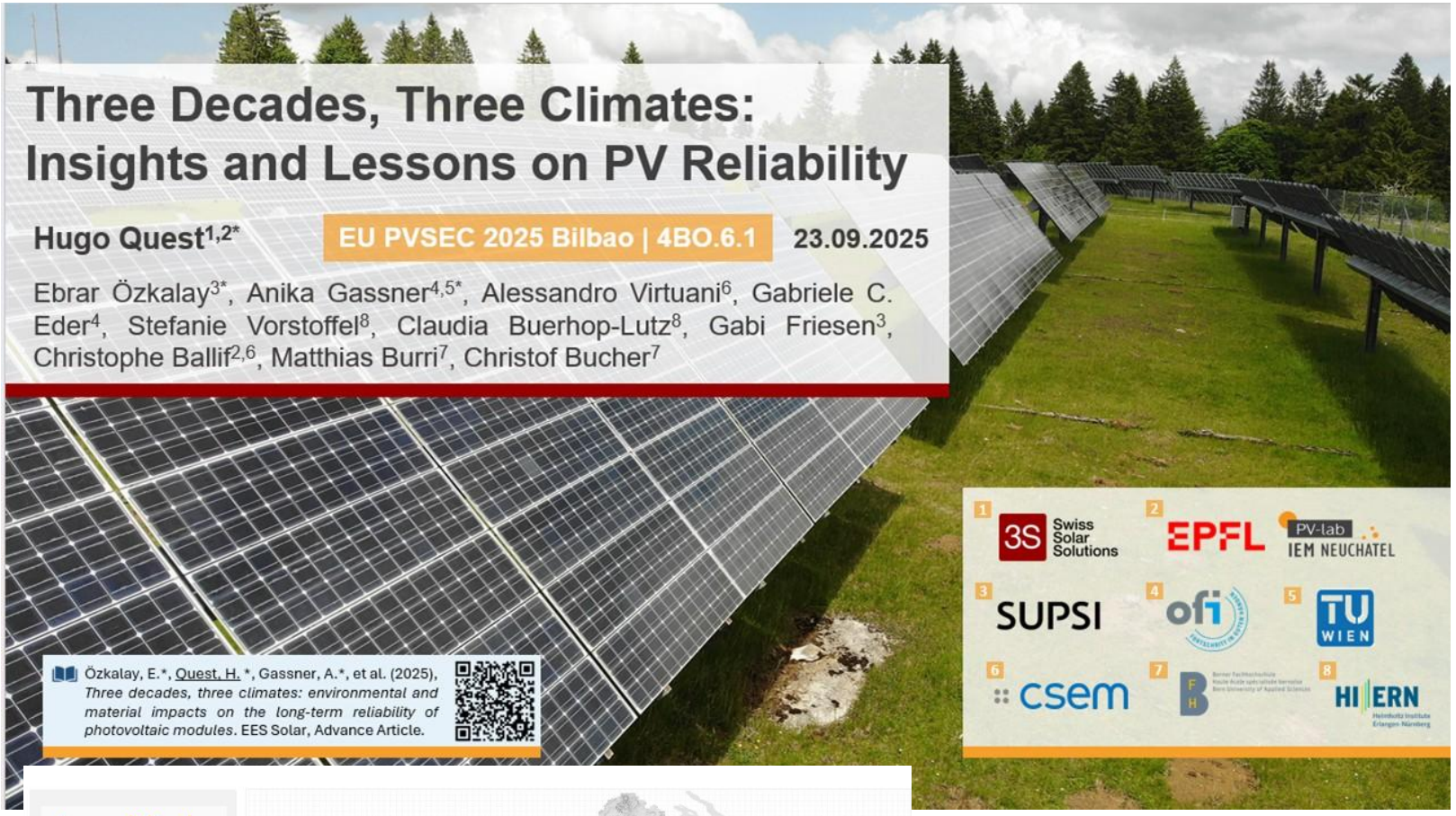
A FEW CONCEPTS

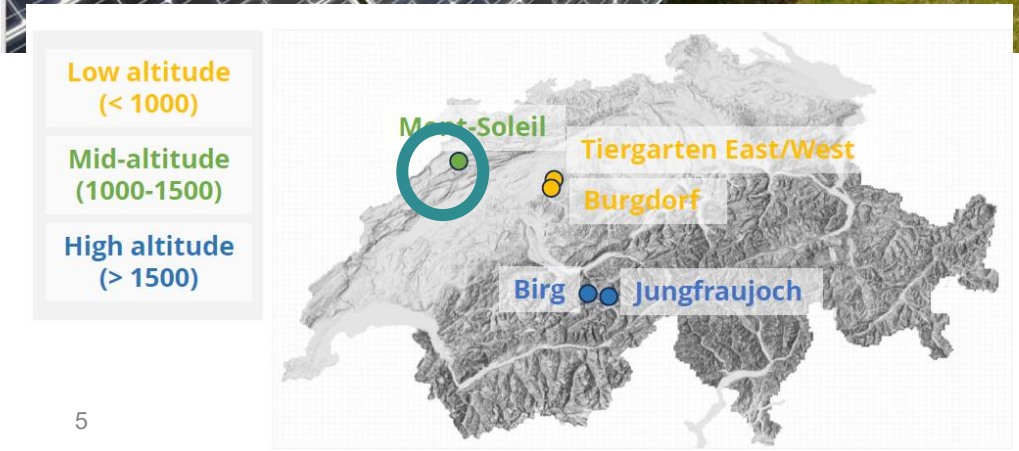
a) **Reliability matters**: impact on PV project profitability, LCOE, C-footprint, etc.
b) Lifetime of PV system often equated to lifetime of solar panels
c) **Business plans** assumptions for module/system long-term performance:
linear degradation, -0.5 %/y performance loss rates (PLR)
a) PV module performance warranties: 25 to 30 years

- Warranties based on: assumptions, IEC testing (extended testing, ….)
- IEC testing is «qualification» testing, not life-time testing (!!!)
- Arbitrary definition of «lifetime»: 80% of initial nameplate power

MONT-SOLEIL PV SYSTEM (500 KW) & PEERS

EXAMPLE (1)





Modules from 1991 (Siemens M55)

<u>BOM very «modern»:</u>

glass-backsheet, EVA, mono-cSi Al-BSF textured cells

Quest et al., EUPVSEC 2025 4BO.6.1

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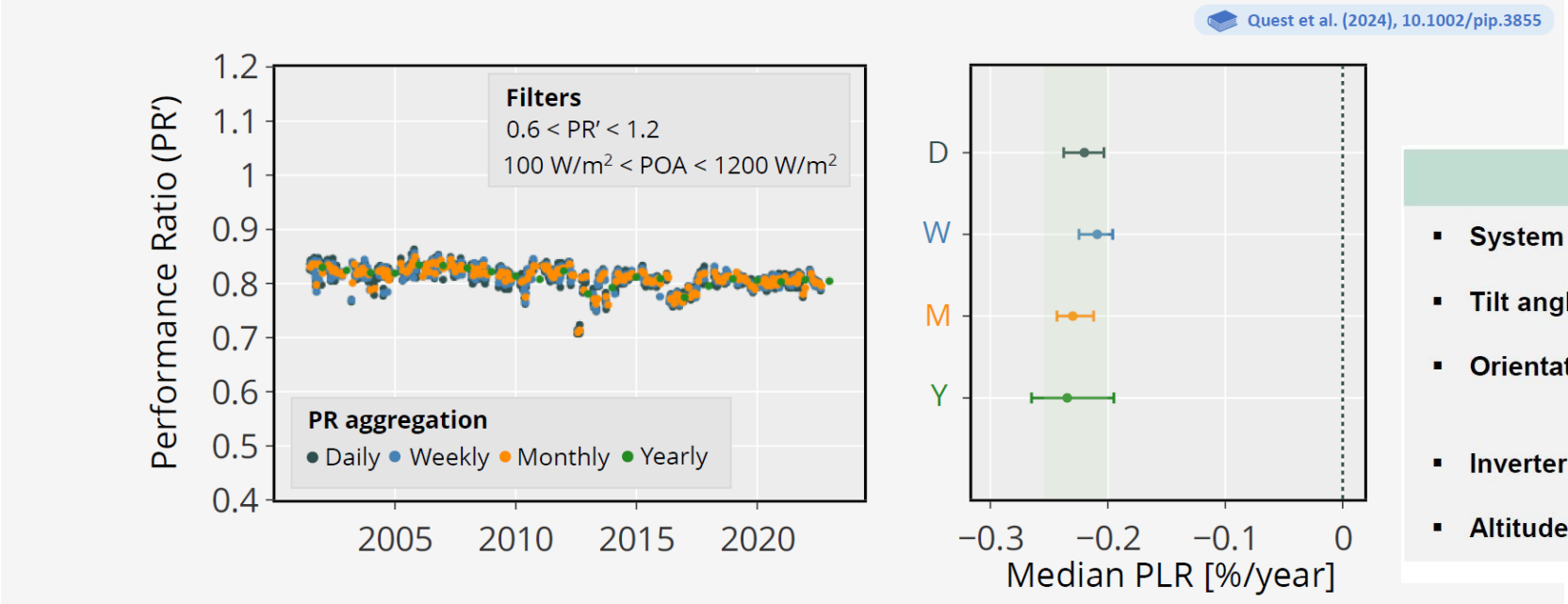
MT-SOLEIL: PERFORMANCE LOSS RATES (PLR)

Main takeaways:

1. PLR: -0.22%/y (very stable)
2. Power > 90% after 30+ yrs
3. BOM + design very «modern»: glass-backsheet, EVA, mono-cSi
4. Correlation of PLR (+ acetic-acid generation) w. avg ambient temperature



Connected to grid in 1992.
Monitored since 2002.

System metadata		
System capacity	554.592 kWp	Feb. 1992
Tilt angle	52°	
Orientation	1st main field 20° East 2nd main field 35° East	
Inverter	ABB central inverter	
Altitude	1270 m.a.s.l.	

PLR = -0.22 %/year, CI = [-0.24, -0.20]

Stable performance in the analysed period (2001 – 2022).

Compliant with warranty of **>90% nameplate power after 30+ years**.

MONT-SOLEIL PV SYSTEM (500 KW) & PEERS

EES Solar

ROYAL SOCIETY OF CHEMISTRY

PAPER

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View Journal

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Cite this: DOI: 10.1039/d4el00040d

Three decades, three climates: environmental and material impacts on the long-term reliability of photovoltaic modules†

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Ozkalay et al. EES Solar 2025
Ozkalay et al. ieee-PVSC 2025
Quest et al. EUPVSEC 2025

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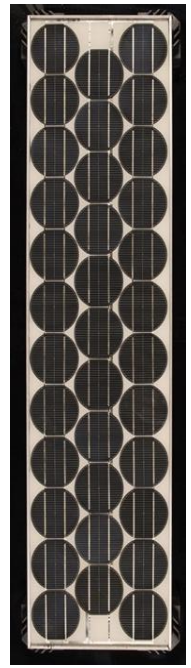
35-YEARS OF PV: THE TISO-10 KW PLANT

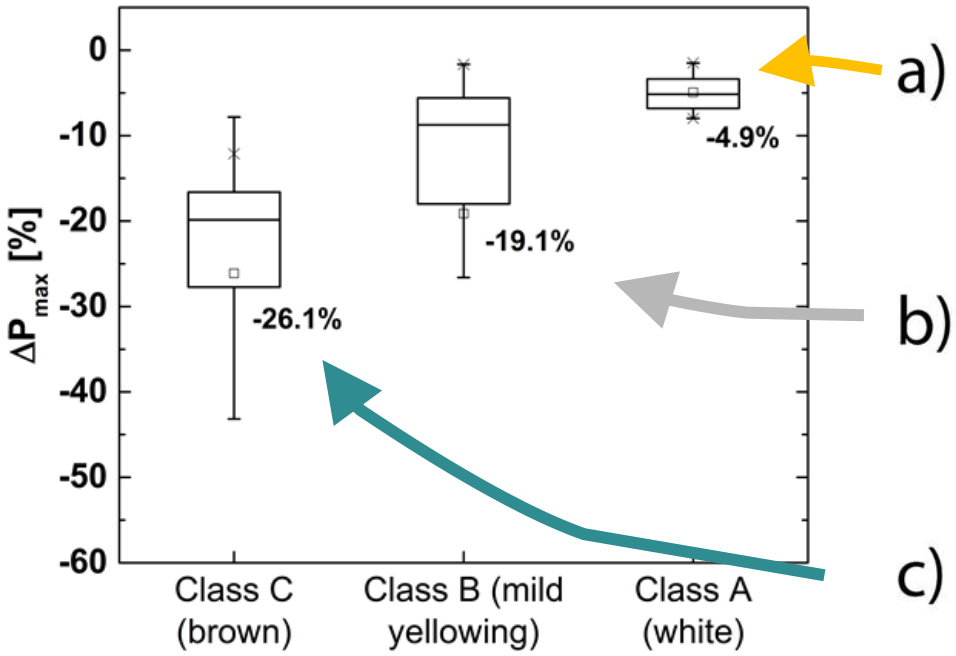
SUPSI :: csem

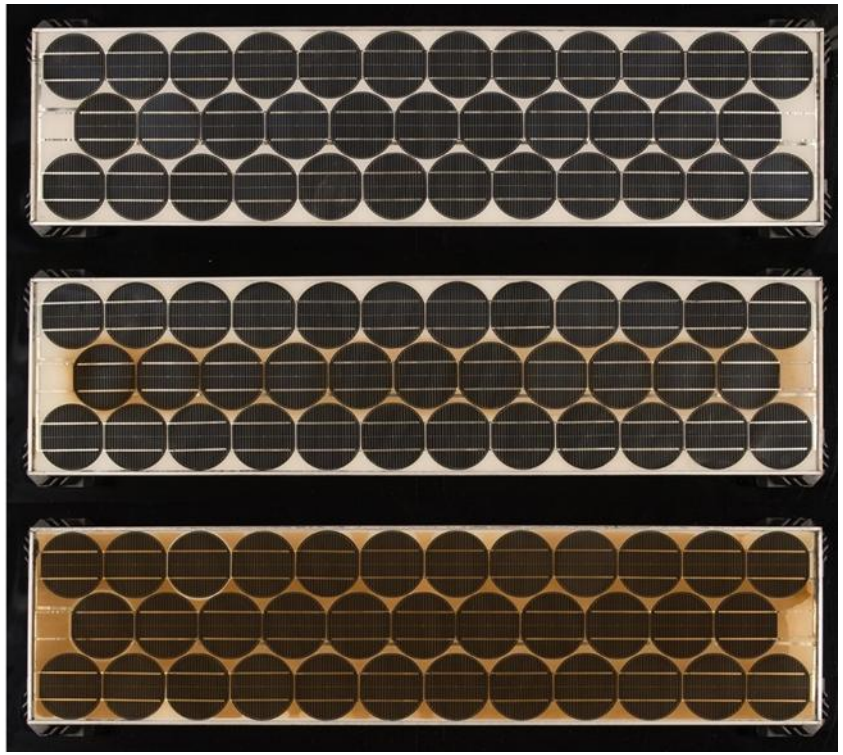
EXAMPLE (2)

- **First grid-connected PV-plant in Europe** (Lugano/CH, temperate climate)
- PV plant's history very well documented
- A history of change: all has changed (site, inverter, monitoring system, …) with the exception of the 288 original PV modules
- Modules: ARCO Solar (36 W, c-Si 4» 330 um, PVB, backsheet: tedlar/steel/tedlar)



TISO-10 PV PLANT: MODULE DEGRADATION AFTER 35 YEARS





1. Module power variation (2017 vs 1982): 3 classes
2. 3 different classes of modules based on encapsulant aging
3. "*Identical*" encapsulant (PVB): 3 suppliers (1981), 3 different chemistries

Virtuani et al.: PiP 2019
Annigoni et al. PiP 2019

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TISO-10 / 35 YEARS OF OPERATION (IN A TEMPERATE CLIMATE)

Main takeaways:

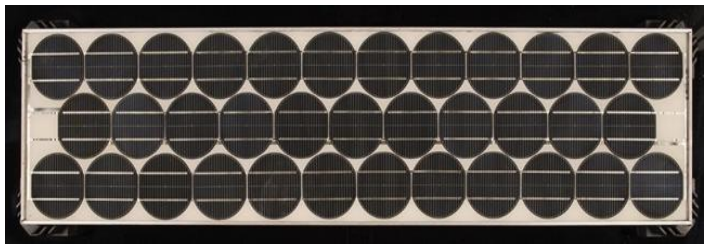
1. 70+% of modules would statisfy a 35-yrs-long warranty set at 80% of the nominal power
2. The long-term performance was strongly correlated to the encapsulant used
3. Changing one single component (e.g. encapsulant) may have a huge impact
4. **The BOM (bill-of-material) matters. A lot!**

RESEARCH ARTICLE

WILEY PROGRESS IN PHOTOVOLTAICS

35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—Part 1

Alessandro Virtuani[1] | Mauro Caccivio[2] | Eleonora Annigoni[1] | Gabi Friesen[2] | Domenico Chianese[2] | Christophe Ballif[1] | Tony Sample[3]



Part 1: PiP 2019
Part 2: PiP 2019

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PV MODULES: RELIABILITY & SERVICE LIFETIME

Can we make solar PV modules that last 30+ years?

YES

(at least in a temperate climate)

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Gonghe (CN) 2,200 MW_{AC} (-)

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PV MODULE: 3X MACRO TRENDS

Post-covid

1. PV market: exponential growth (CAGR-23/22: +88 %/y)
2. Very sharp decline of PV module prices (-40 to -50% in 2023, continued in 2024)
3. **PV module technology: Evolution vs REvolution**
   - 1980 to 1990 (10 years): many changes
   - 1990 to ~2019 (30 years) Evolution.
   - last 5 years: REvolution

Consequences for PV module reliability:

a) Market introduction of new concepts/materials is too fast

b) Increased reliability risk

c) High risk of loosing understanding of aging behaviors

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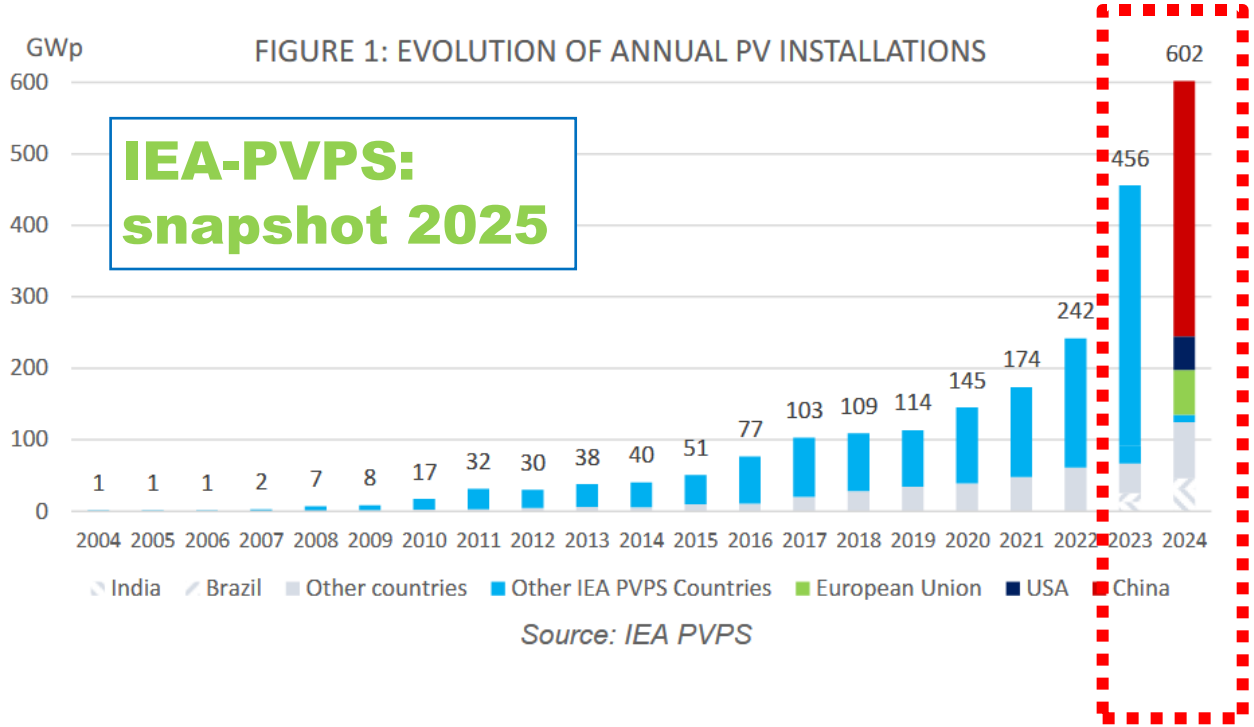
GLOBAL PV MARKET



50% of global capacity installed in last 2 yrs !!!

2025: newly added
PV installation: + ~605 GWp

CAGR-23/22: +88 %/y
CAGR-24/23: +32 %/y
CAGR historical: 30-40 %/y

Cumulative installations: ~2.2 TW

Dominant PV technology:
c-Si wafer-based
95+ % of new additions
95++ % of cumulative capacity

China share in manufacturing: ~85% modules, >92% cells, ~95% wafers

PV MODULE PRICES

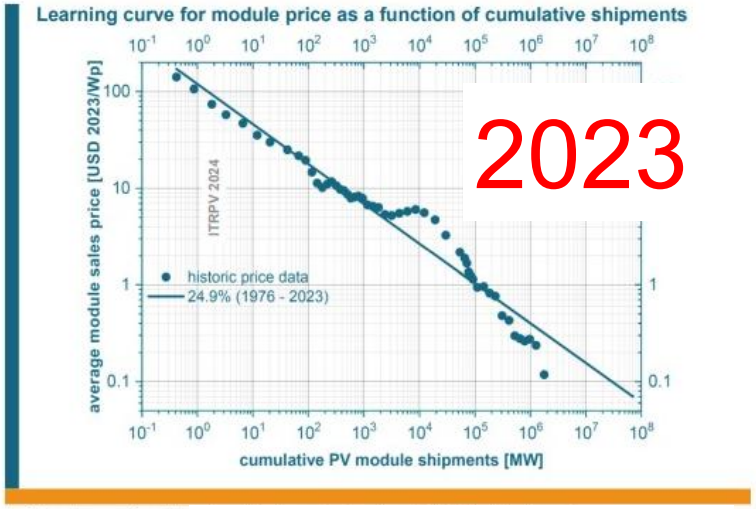
Very sharp decline of PV module prices:
-50% in 2023, -30 to 40% in 2024, **-5 to 10% in 2025**
Supply vs demand unbalanced

ITRPV says solar module prices fell 50% in 2023

The new edition of the International Technology Roadmap for Photovoltaic (ITRPV), published this week, reveals that the world's installed PV capacity reached 1.6 TW at the end of last year. The learning curve, which reflects average module prices relative to cumulative shipments, is 24.9% for the period from 1976 to 2023.

JUNE 5, 2024 SANDRA ENKHARDT

MARKETS | MODULES & UPSTREAM MANUFACTURING | TECHNOLOGY AND R&D | WORLD

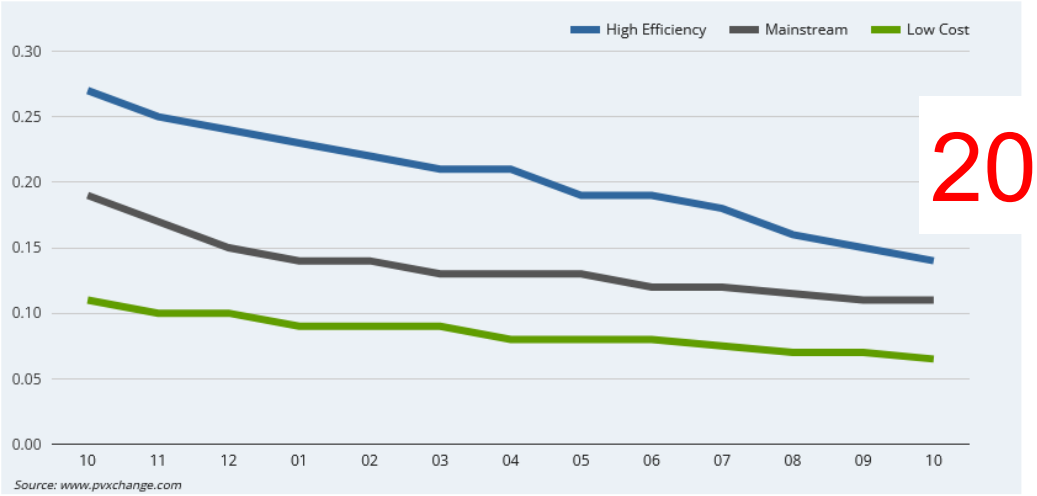


2023

Fig. 1: Learning curve for module

PV-magazine: 06.2024

Price trend for solar modules by month from **October 2023 to October 2024** per category (the prices shown reflect the average offer prices for duty paid goods on the European spot market):



2024

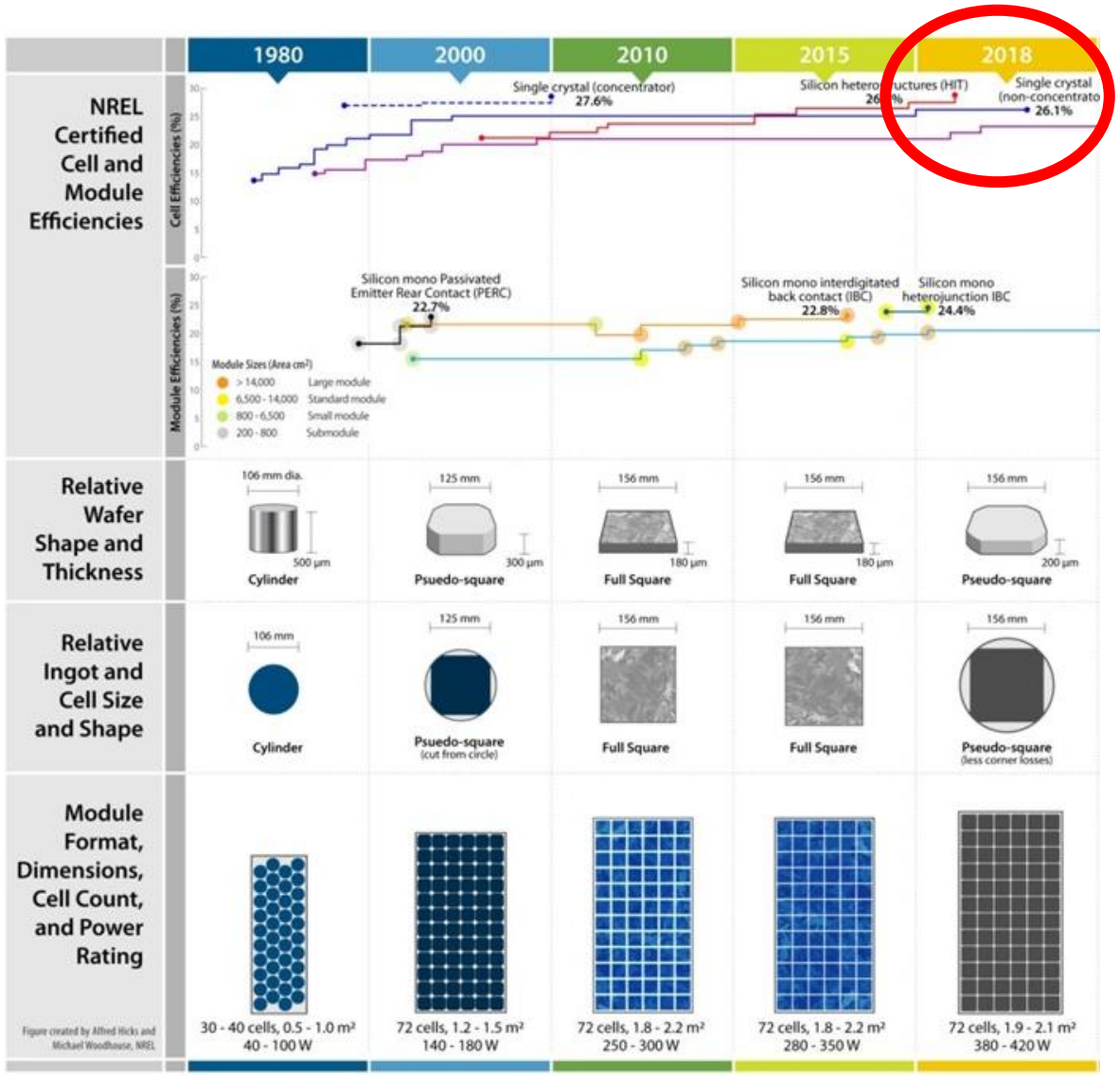
Overview by technology of different price points in **October 2024**, including the changes over the previous month:

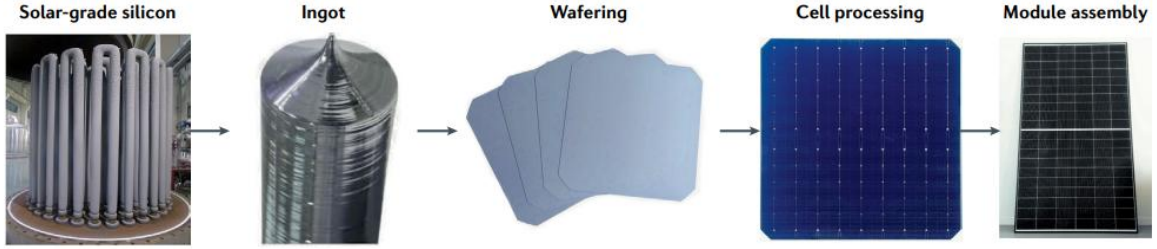
Module class	€/Wp	Trend since September 2024	Trend since January 2024	Description
Crystalline modules				
High Efficiency	0.14	- 6.7 % ↘	- 39.1 % ↘	Crystalline modules with mono- or bifacial HJT, N-type/ TOPCon or IBC (Back Contact) cells and combinations thereof, which have efficiencies higher than 22 percent.
Mainstream	0.11	0.0 % ➡	- 21.4 % ↘	Standard modules, typically with monocrystalline cells (also TOPCon), which are mainly used in commercial PV systems and which have an efficiency of up to 22 percent.
Low Cost	0.065	- 7.1 % ↘	- 27.8 % ↘	Stock lasts, factory seconds, insolvency goods, used or low-output modules (crystalline), products with limited or no warranty, wich usually also have no bankability.

Source: www.pvxchange.com

www.pvxchange.com: 12.2024

PAST: TECHNOLOGY EVOLUTION





~1990 to ~2020

Crystalline-silicon (c-Si):

1. Cell: Al-BSF
2. Interconnects: 3-4 bus-bars (BBs) + soldered ribbons
3. Encapsulant: EVA
4. Module structure: glass/foil

Alfred Hicks & Michael Woodhouse (NREL):
ITRPV 2021: web seminar

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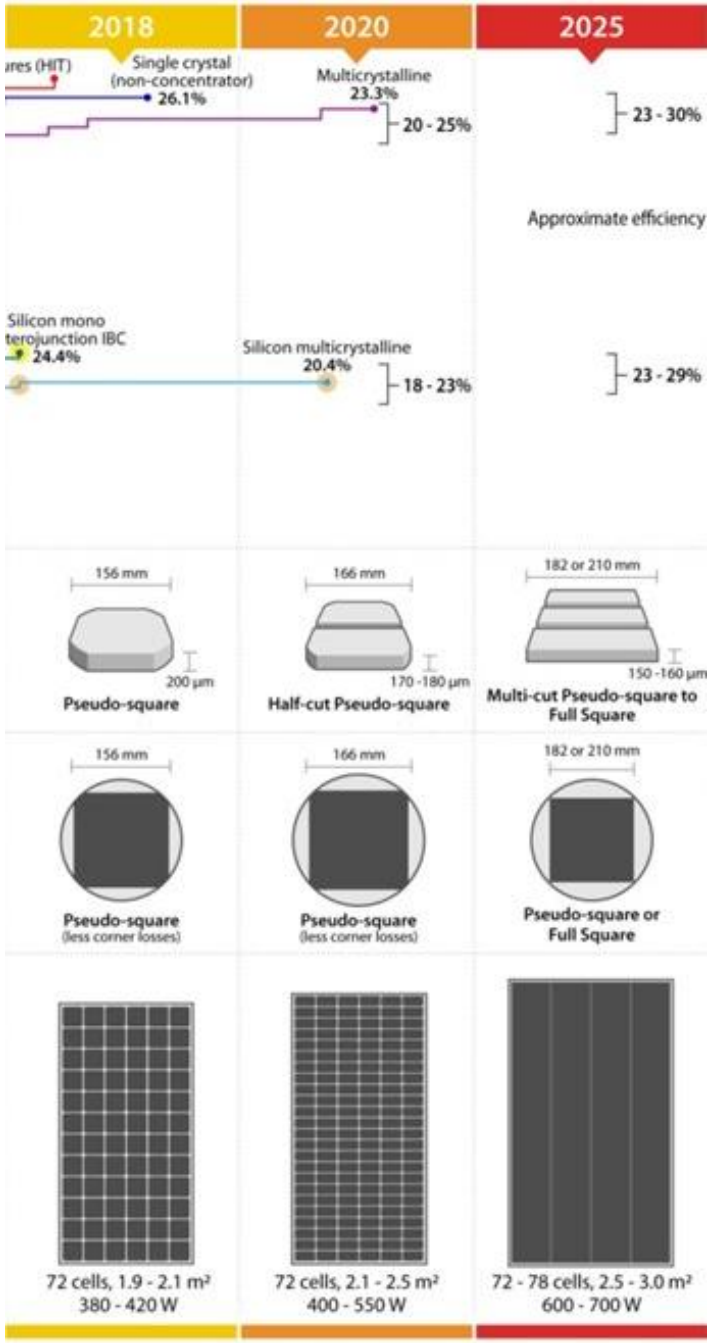

PRESENT: Technology R-EVOLUTION

Why?

Main drivers:

Innovation, cost-reduction, higher efficiency, scale-up favored over **long-term qualification of materials/products**

What is changing?

1. New cells: PERC, SHJ, TopCon, half-cells, 1/3-cells, bifacial cells…
2. Doping: Ga-doping, n-type cells, ..
3. Larger cells/modules >> higher powers
4. Interconnects: multi bus-bars, wires, shingled, overlap, …
5. Non-soldering interconnection techniques & low T processes
6. Glass/glass modules: thinner glass, untempered glass
7. New encapsulants: polyolefins (POE, TPOs, …), backsheet foils..
8. Module structure: glass/foil vs glass/glass
9. Higher-system voltages (1500 V vs 1000 V): a comeback for PID?
10. Module-integrated electronics
11. ……

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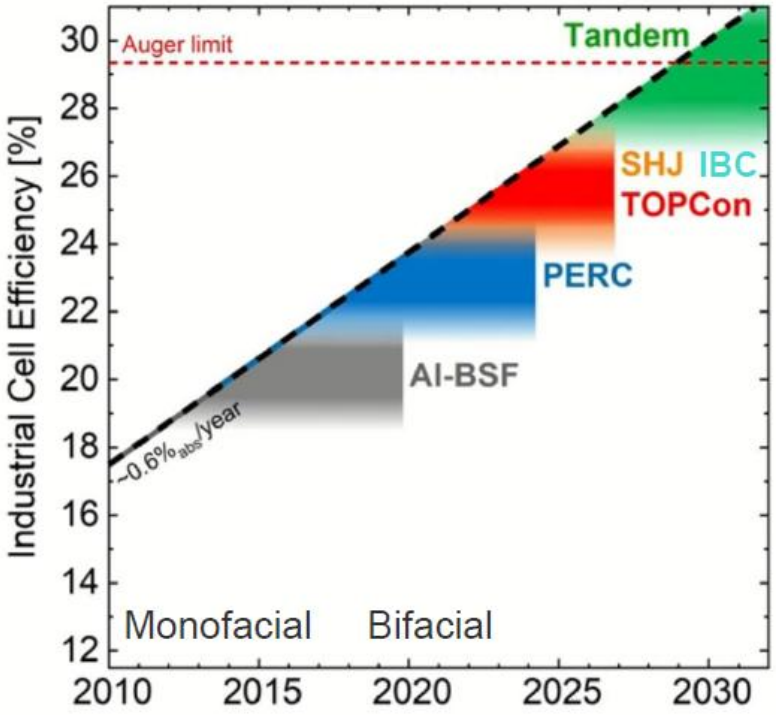
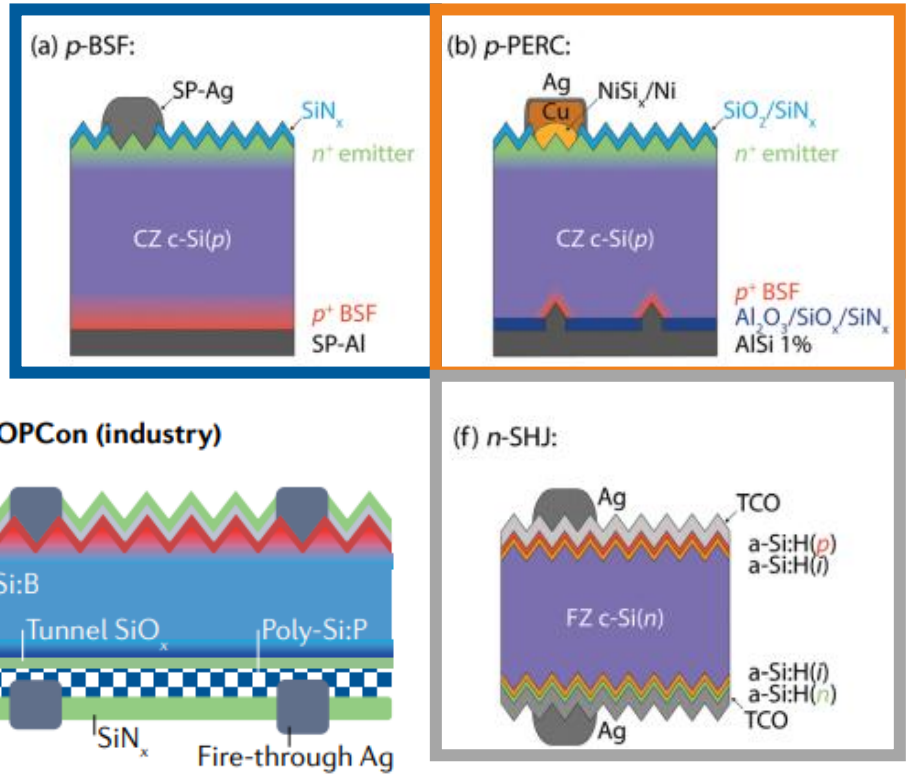
Example (1): solar cells

1. Crystalline silicon (c-Si) dominant technology. Presently bifacial.
2. c-Si: until 2018 BSF (Back-Surface-Field), from 2016 onwards rapid transition to PERC (Passivated-Emitter-Rear-Contact)
3. Rapid transition from poli (~BSF) to mono (~PERC) + Ga-doping in place of B-doping (for p-type)
4. **NOW:** Si n-doped wafers, TOPCON (Tunnel Oxide Passivated Contacts), SHJ (Si-Hetero-Junction), BC (back-contact)

STABILITY: novel architectures boost efficiency, likely at the price of stability.
«New» degradation mechanisms are observed.



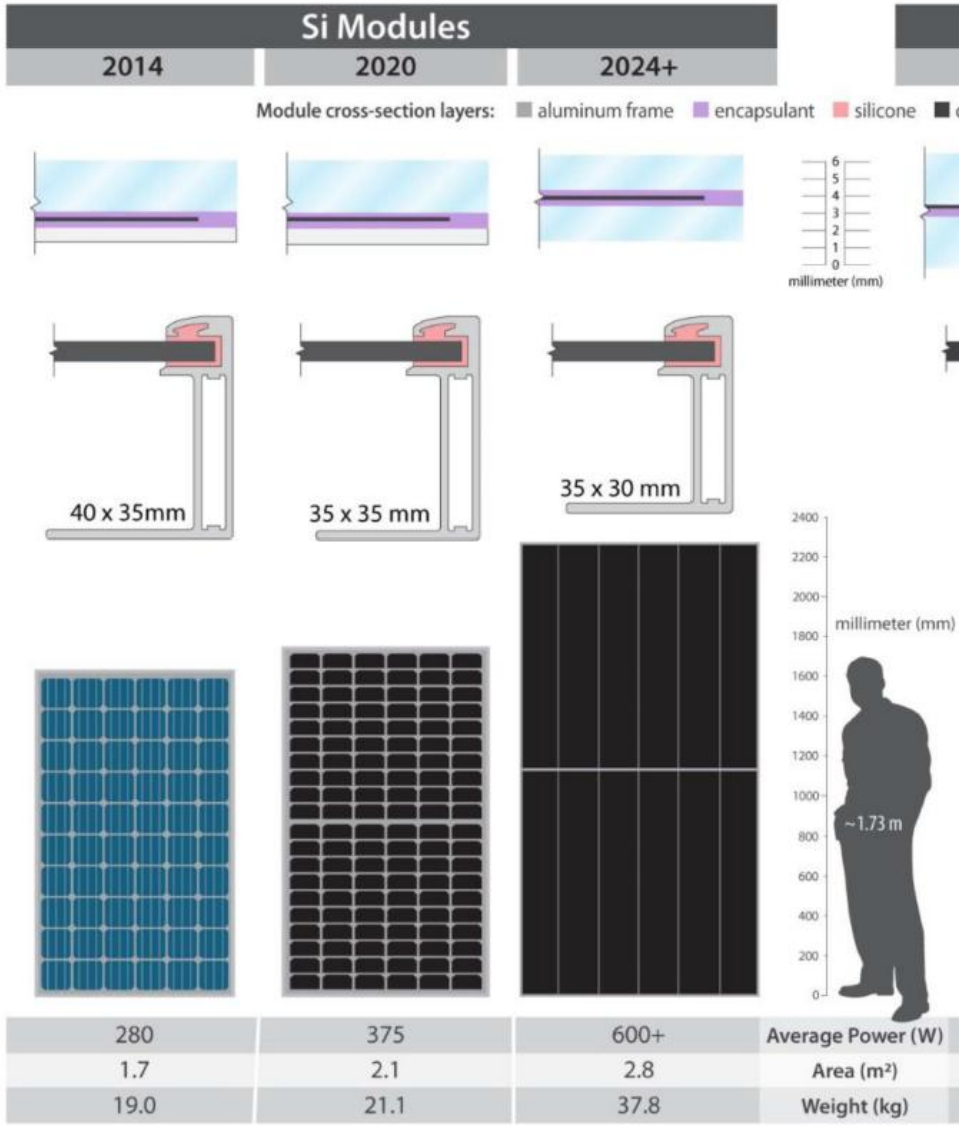
Hermle et al., App. Phys. Rev. 2023



Hascke et al. En. Env. Sci. 2017
Ballif et al. Nature Mat. 2022

Example (2): module design

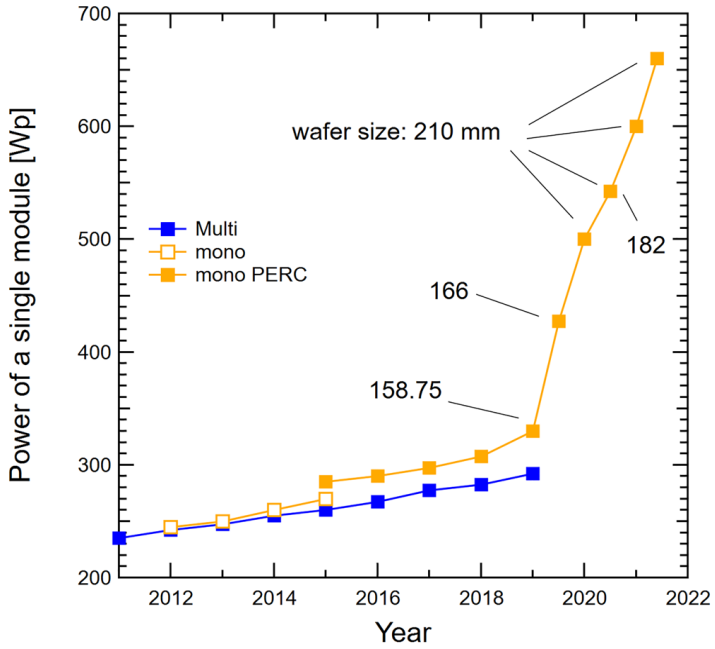
"Big floppy modules" (© NREL)



Palmiotti et al. ieee JPV 2025

TRENDS:

- Larger cells/modules, higher power…
- Glass/glass with thinner glass (bifacial)
- Heat-strenghtened vs tempered glass
- Thinner encapsulants
- Lighter frames & different fixation systems
- Multi-wire
- ….



Chen et al., PiP 2023

Example (3): encapsulants

Fast transition from EVA to PO (polyolefins)….

- ❑ EVA has standardized formulation (+/-), long-track record.
- ❑ POs is broad class of materials, lack of standardization, lack of track-record.

POs pro:

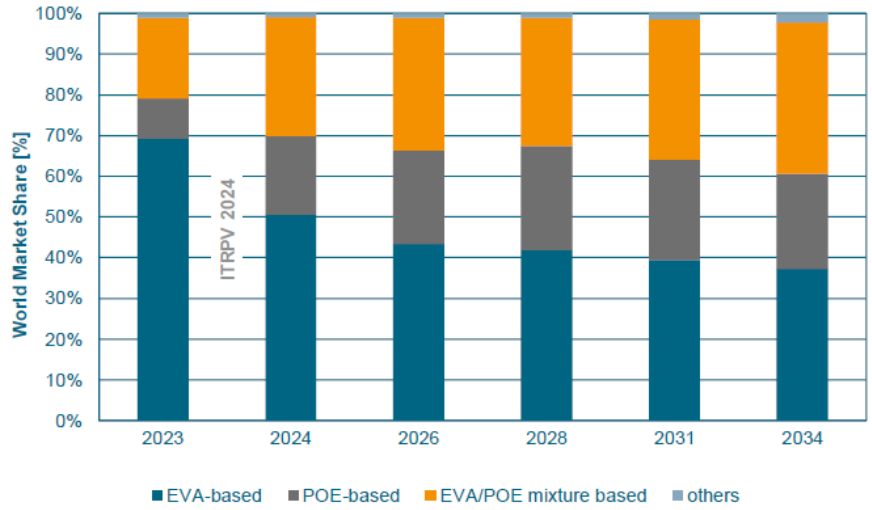
- Low water uptake, barrier against ion diffusion
- does not generate acetic-acid…..

POs cons:

- More complicate processes
- More sensitive to storage conditions, shorter shell-life….
- Poorer adhesion
- Field delamination (?)

Different encapsulation material

ITRPV 2024



Oreski et al. 2025, PIP
REVIEW paper (accepted)

What is a polyolefin? A critical overview of ethylene copolymers used as solar photovoltaic module encapsulants¶

¶

Gernot Oreski[1,2*], Chiara Barretta[1], Petra Christöfl[1], Paul Gebhardt[3], Karl-Anders Weiß[3], David C. Miller[4], Soňa Uličná[4], Michael Kempe[4], Laura S. Bruckman[5], Alessandro Virtuani[6], Hengyu Li[6], Brian Habersberger[7], Jeff Munro[7], Kristof Proost[8], Marcel Kühne[9]¶

¶

PV MODULES: RELIABILITY & SERVICE LIFETIME

Can we make solar PV modules that last for 30+ years?

YES

Is the industry doing it ?!?

Mhhh

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CONCLUSIONS (1)

Solar PV has earned a **well-deserved good reputation** (over 40 years).

This reputation may now be at stake:

- ❑ PV market strongly unbalanced (supply/demand)
- ❑ Innovation cycles are too fast
- ❑ **Innovation, cost-reduction, higher efficiency, fast upscaling are favoured over long-term qualification of materials & products**

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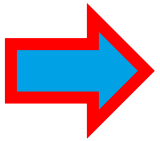
CONCLUSIONS (2)

……

- If we change more than 1 parameter at the time, we stop understanding aging behaviors.
- We massively install new PV technology without any trackrecord.
- If we do this in a exponentially-growing («unbalanced») market and companies need to cut cost to remain competitive the situation may even be worse.



ACKNOWLEDGEMENTS

Muchas gracias!

All PV-lab & CSEM & oSole staff members

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OUTLOOK

www.eupvsec.org/index.php/pd-programme-tue-bo13

TUESDAY, 23 SEPTEMBER 2025, 13:30–15:00

Panel Discussion

Session BO.13:
Reliability and Bankability in PV

Reliability matters !

What to do to preserve reputation of solar PV?

(+ profitability, low LCOE, low C-footrprint, etc.)

- ❑ **TRANSPARENCY**: which BOMs are used by manufacturers?
- ❑ **CONSISTENCY IN MANUFACTURING:** factory/batch inspections/audits.
- ❑ **TESTING**: beyond IEC (extended/sequential/combined testing) + climate/application/tech-specific testing.
- ❑ **MODELLING**: side-by-side with TESTING (we cannot wait 30+ years to receive field feedback)
- ❑ **DELIVERY + ACCEPTANCE TESTING**: container + lot-acceptance testing
- ❑ **COMMUNICATION**: data sharing from manufacturers, EPC, system owners, asset managers, …

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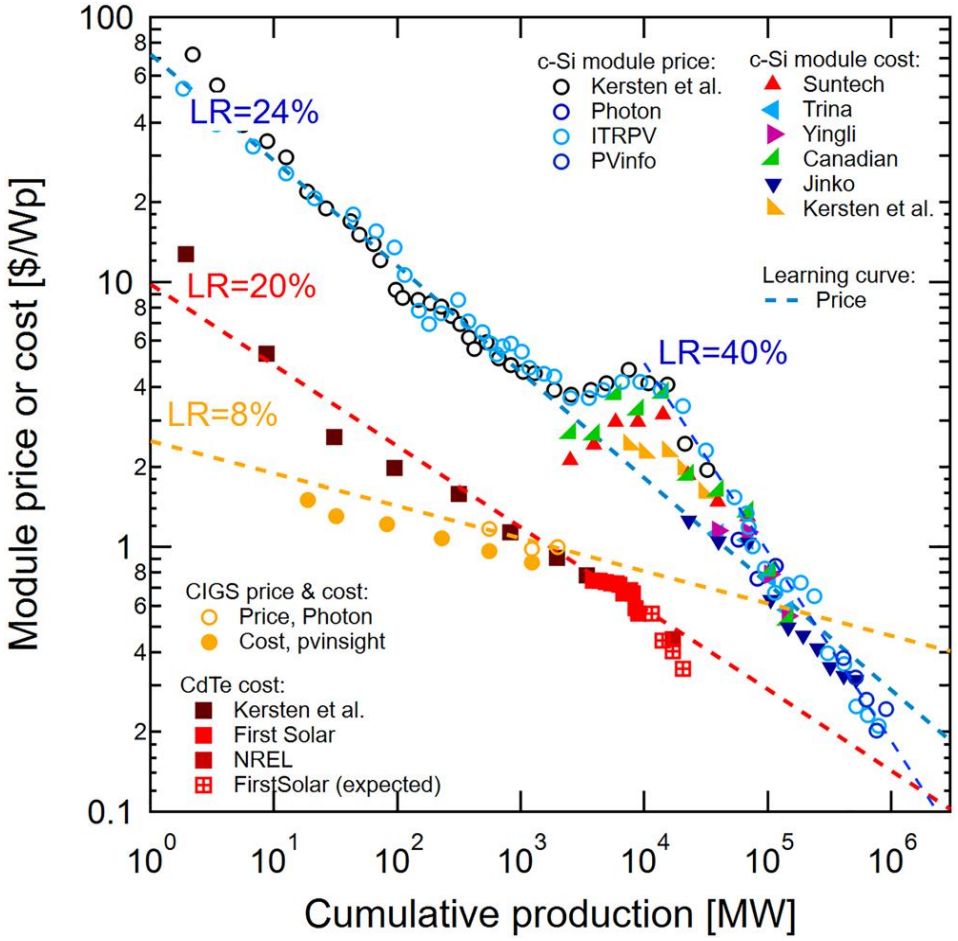
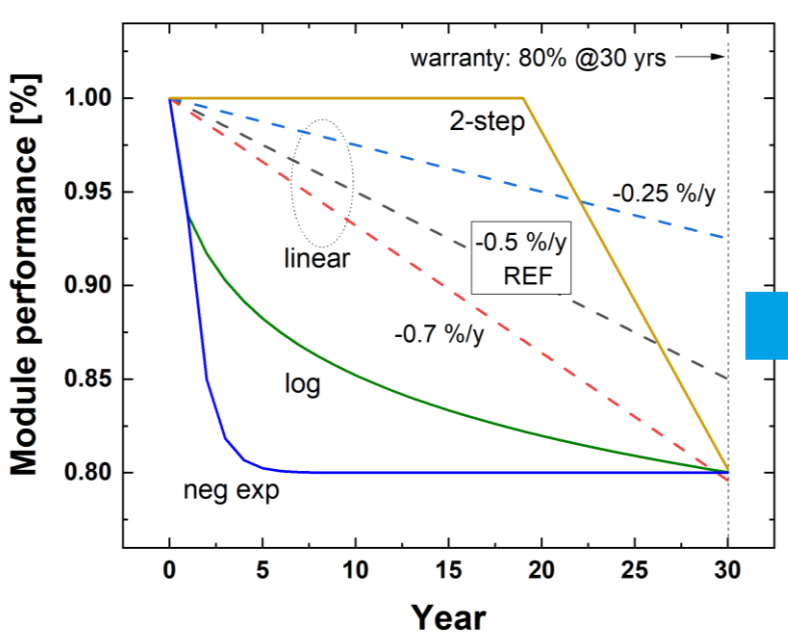
PV module price & cost [$/Wp]

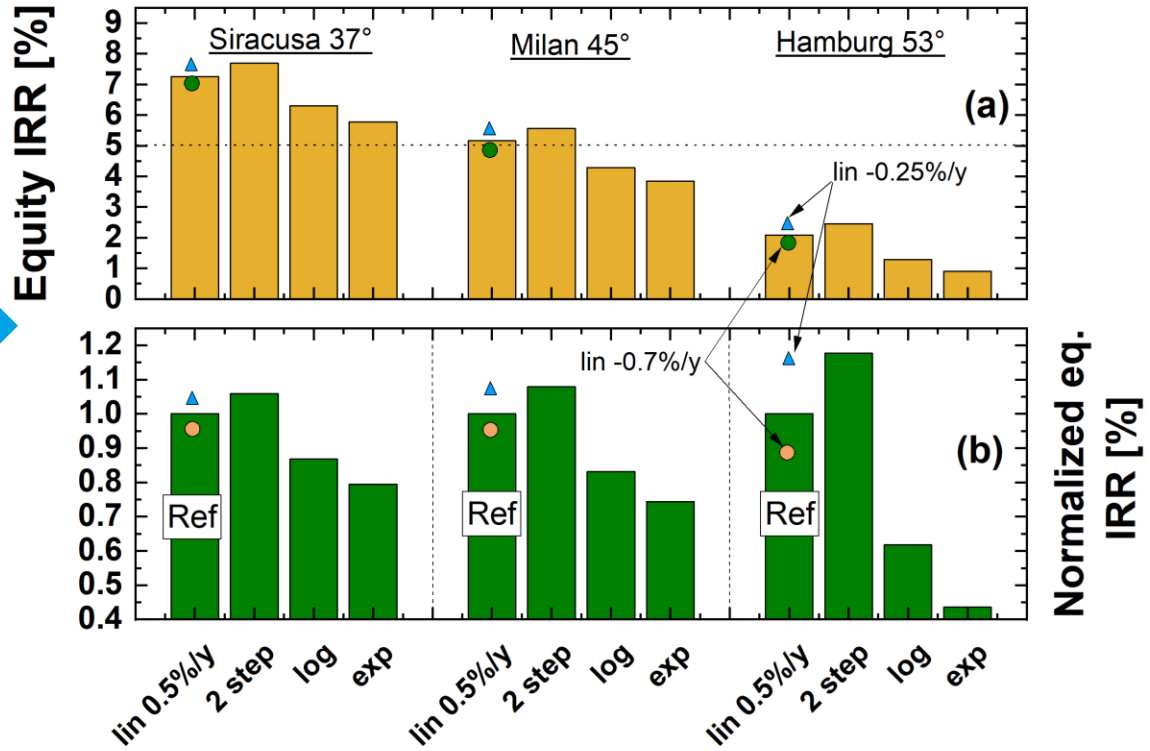


Chen et al., PiP 2023

IMPACT OF DEGRADATION RATES AND CURVES ON THE PROFITABILITY OF SOLAR PROJECTS IN EUROPE

Virtuani et al., PiP 2019
Annigoni et al. PiP 2019
Jordan et al. PiP 2016





- Unleveraged-IRR (Interest Return Rate) for 3 sites in Europe
- Non-linear degradation rates (or higher PLR) have a higher impact for sites in which the availability of solar resources is lower.

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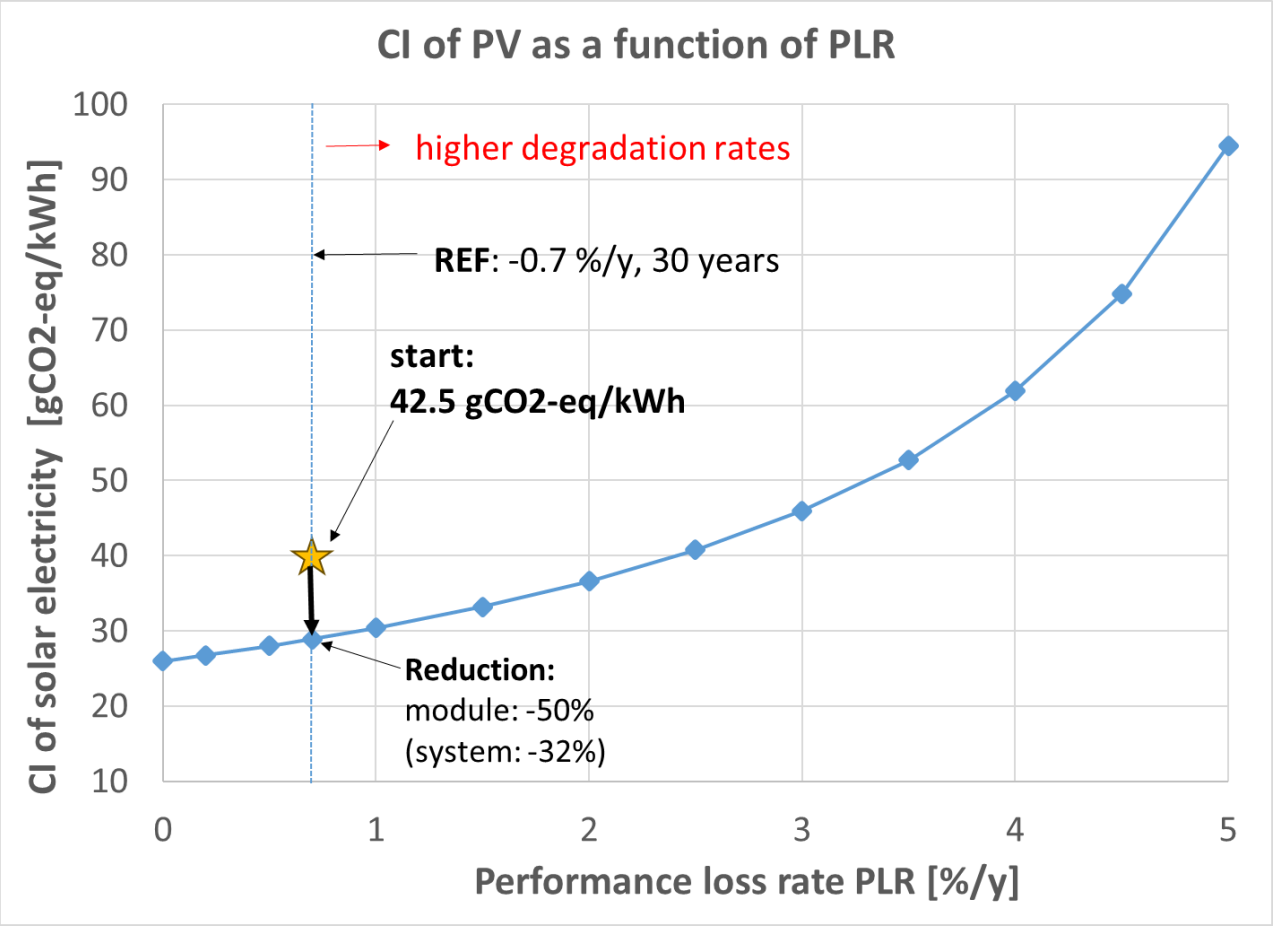
CARBON INTENSITY (CI) OF SOLAR ELECTRICITY VS PLR

CI *PV-2022*:
42.5 gCO2eq/kWh
(rooftop PV
in Central Europe)

Source:
IEA-PVPS Factsheet (2021)

Virtuani et al.
EUPVSEC 2024



REF: 30 years lifetime, PLR 0.7 %/y
Model: 50% reduction of GHG in module manufacturing (>> -32% of system GHG).
>> CI of solar electricity vs PLR

We should not reduce the CI of modules (other components or full systems) at the expense of reliability and long-term performance.

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