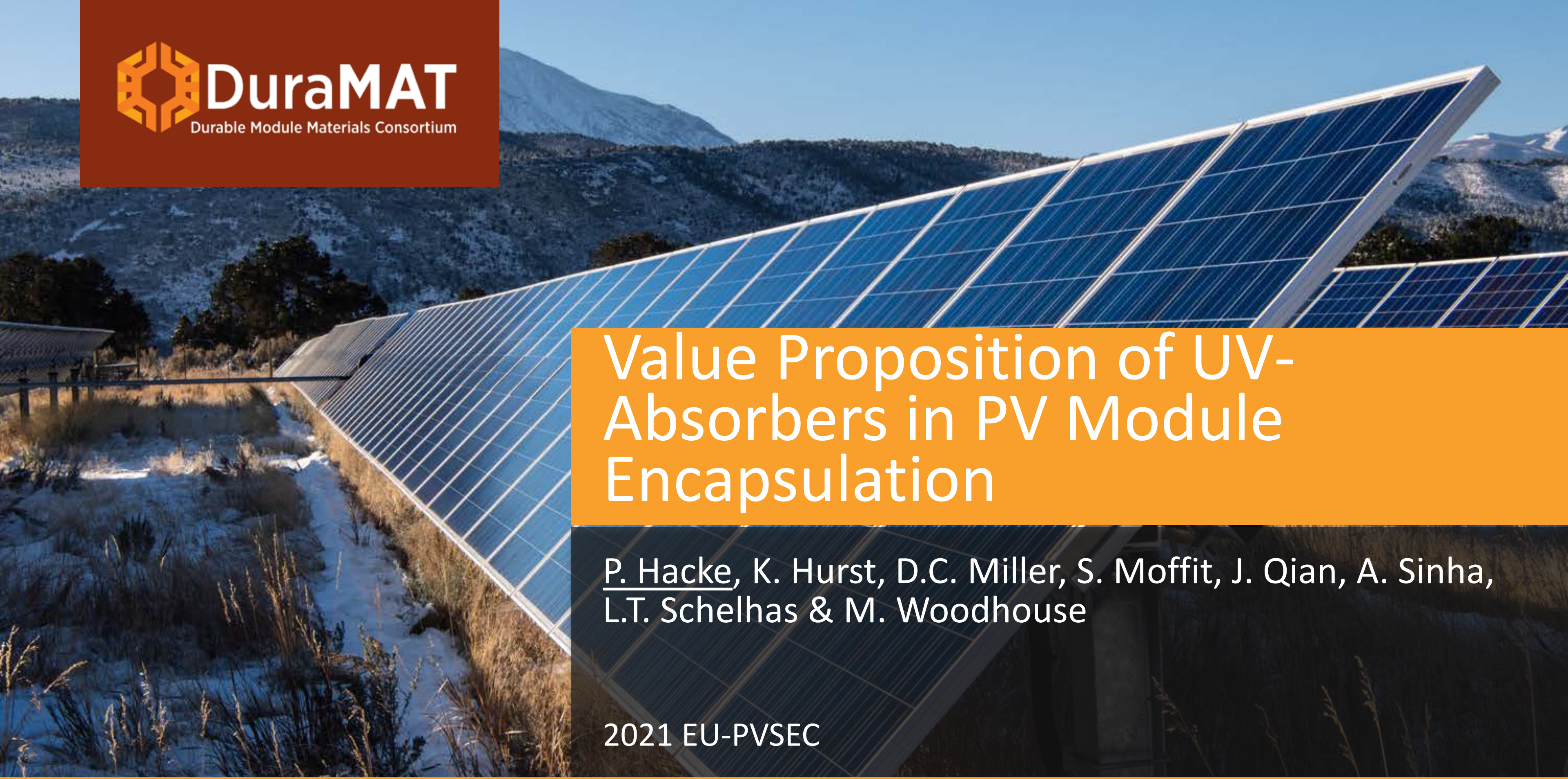


DuraMAT
Durable Module Materials Consortium

Value Proposition of UV-Absorbers in PV Module Encapsulation

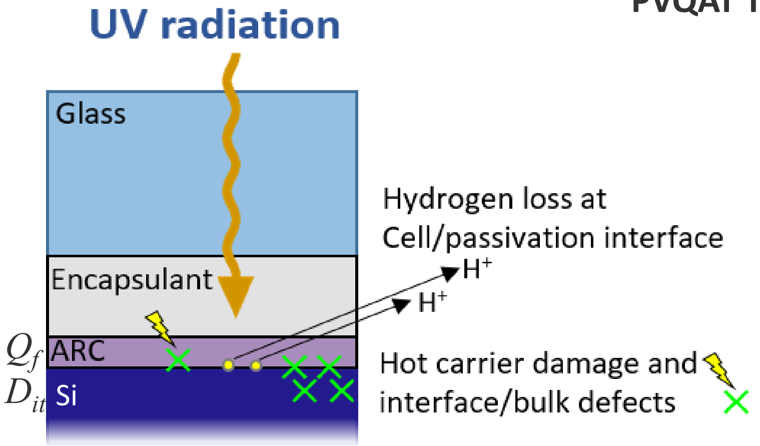
P. Hacke, K. Hurst, D.C. Miller, S. Moffit, J. Qian, A. Sinha, L.T. Schelhas & M. Woodhouse

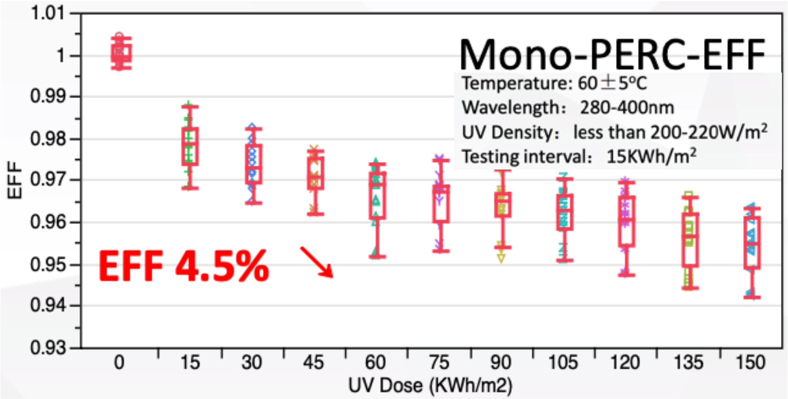
2021 EU-PVSEC

Background: UV-induced degradation

Gruenbaum & coworkers 1990, 1998	Recombination centers at SiO_2/Si interface: Hot carriers
Lauinger & coworkers 1996	Increase S_{eff} at CVD–SiN:H/Si interface: H passivation loss
Kamioka & coworkers 2015	Plasma deposition of SiN:H causes UV damage, passivated by H
Witteck & coworkers 2017	UV-transparent encapsulation permits UV degradation; H-model
Jin & Coworkers 2018	UV-induced degradation present in modern PV cells

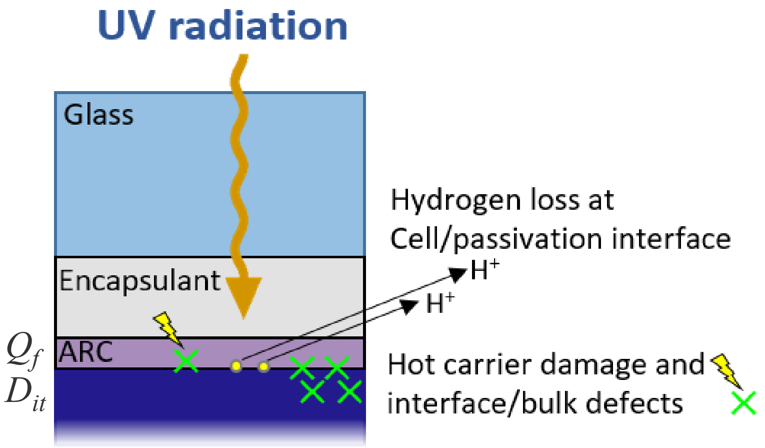
PVQAT TG 13 , Hao Jin, Ning Li, Xinyu Zhang, and Qi Wang, 2018 NREL PVMRW

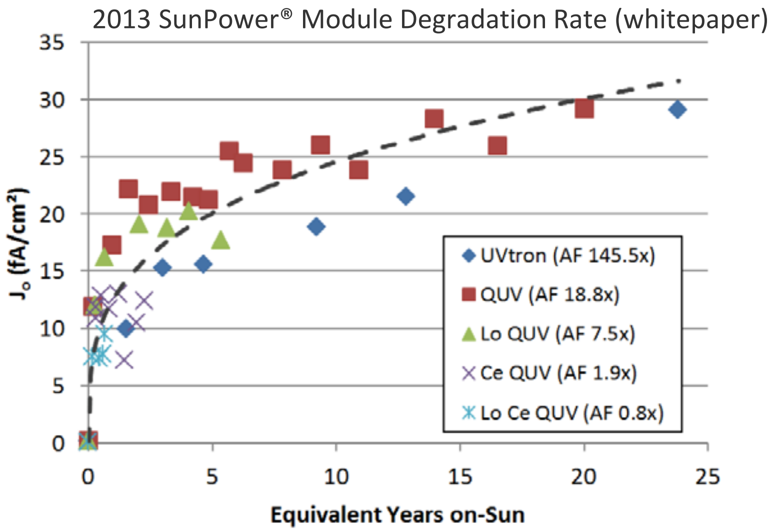




※ *Distinctly separate from B-O LID and LeTID*

Degradation of cell properties under UV irradiation





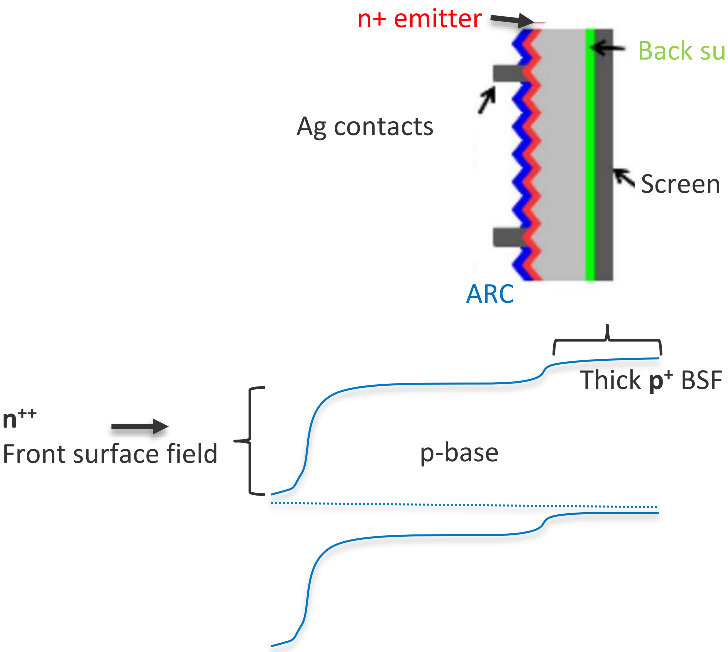
$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{S_{front}(\Delta n) + S_{back}(\Delta n)}{W}$$

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{J_{oe\,front} + J_{oe\,back}}{q n_i^2 W}[N_A + \Delta n]$$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_{sc}}{J_0} + 1\right)$$

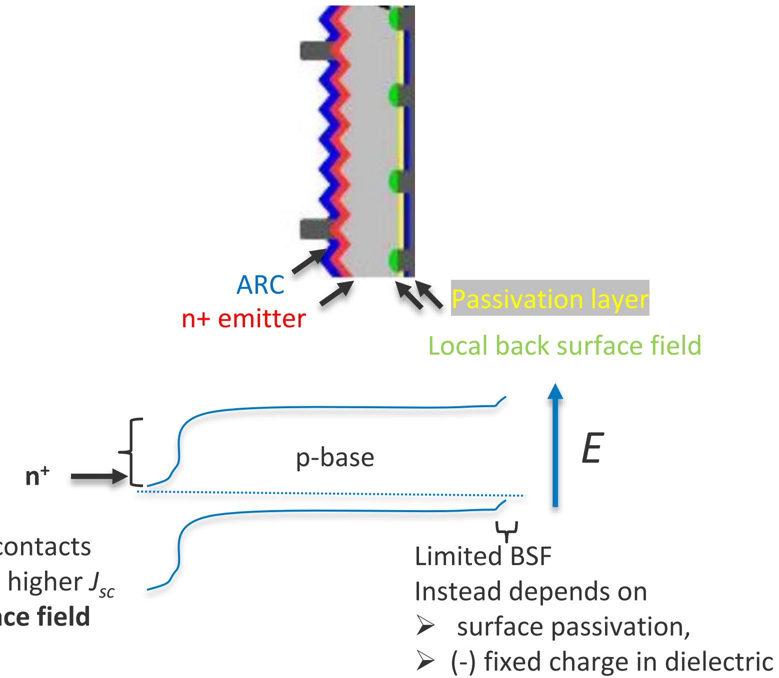
Why now? Modern cells may have more sensitivity to increasing surface recombination velocity from UV damage

1990s BSF cell



- Selective emitter
- High sheet resistance Ag contacts
- Dead-layer reduction for higher J_{sc}
- **More limited front surface field**

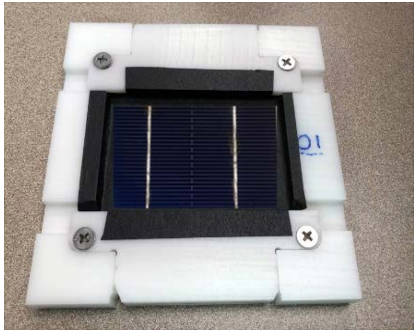
PERC cell



Experiment

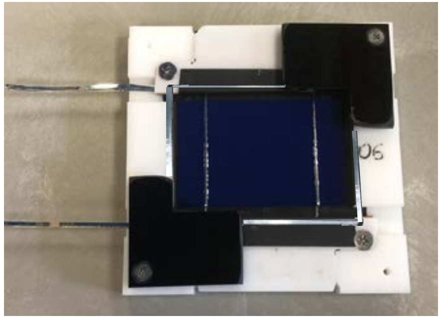
- Cells cut to 1/6 size
- Samples light soaked to 15 kWh/m^2 to precipitate any B-O degradation beforehand (no UV below 404 nm)
- UV exposure under Q-lab UVA 340 fluorescent bulbs, 1.24 $W/m^2/nm$ at 340 nm
- 45 °C, low T to prevent LeTID and H redistribution from affecting results

Screening test

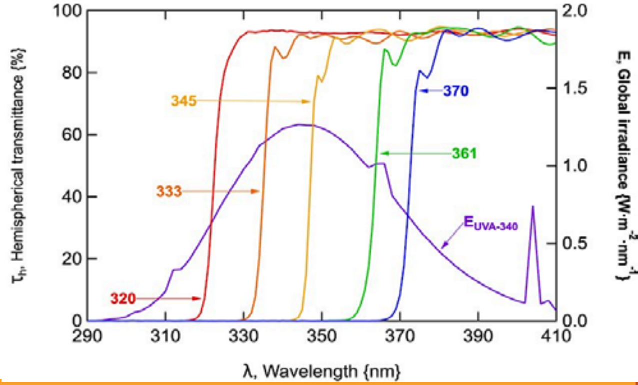


Index	Cell technology	Cell construction (mono-/multi-)	Bifacial?	Front structure	Rear structure
A	SHJ	mono	y	ITO/(p+)a-Si/(i)a-Si	n Si/(i)a-Si/(n+)a-Si/ITO
B	IBC	mono	y	SiN_x/SiO_2/n+Si	-
C	n-PERT	mono	y	SiN_x/SiO_2/p+Si/n Si	n Si/n+Si/SiN_x
D		mono	n	SiN_x/SiO_2/p+Si/n Si	-
E		mono	y	SiN_x/SiO_2/p+Si/n Si	n Si/n+Si/SiN_x
F		mono	n	SiN_x/SiO_2/p+Si/n Si	-
G	p-PERC	mono	y	SiN_x/SiO_x/n+Si/p Si	p-Si/AlO_x/SiN_x
H		mono	n	SiN_x/n+Si/p Si	-
I		mono	n	SiN_x/n+Si/p Si	-
J		mono	y	SiN_x/SiO_x/n+/p Si	p-Si/AlO_x/SiN_x
K		multi	y	SiN_x/SiO_x/n+/p Si	p-Si/AlO_x/SiN_x
L	Al-BSF	multi	n	SiN_x/n+Si/p Si	-

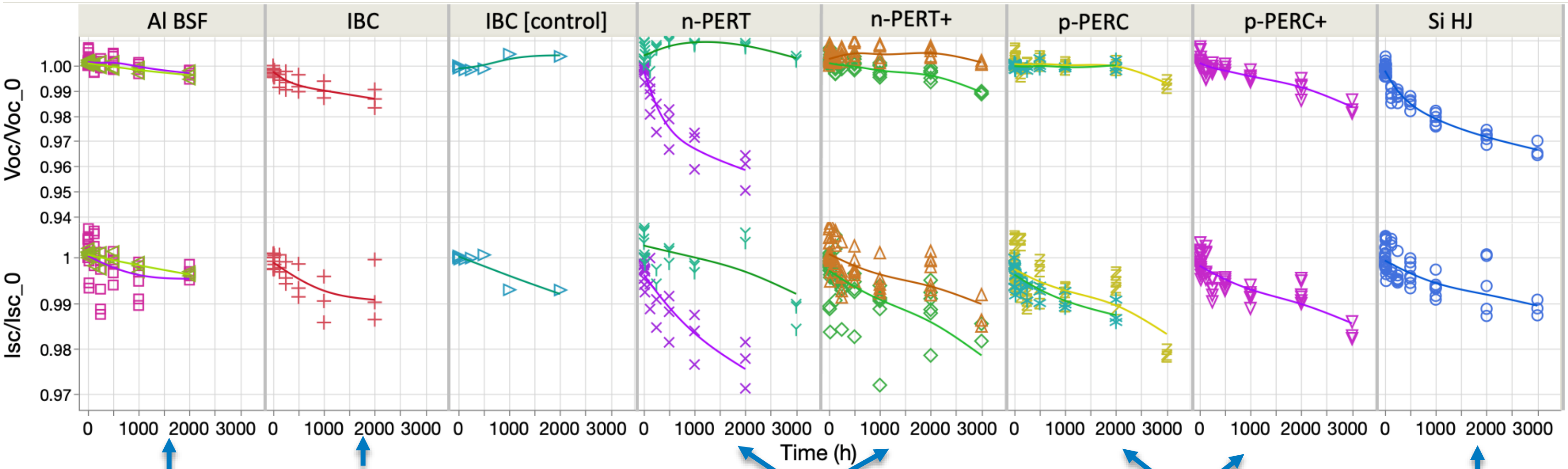
Long pass filter test



PERT, IBC, Si-HJ cells tested, 320 nm – 370 nm long-pass filters.



Results – screening test (bare cell fronts)



1990's technology relatively robust

Optimized for concentration

p⁺/n front's
B emitter solubility & diffusivity low
Front surface field difficult?

n⁺/p front
More degradation than 1990's BSF technology in most cases

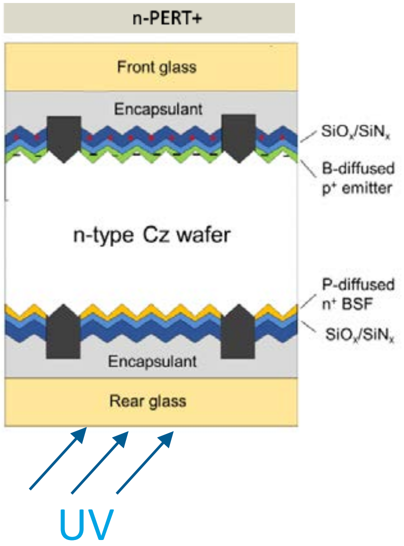
a-Si:H front has sensitivity to UV

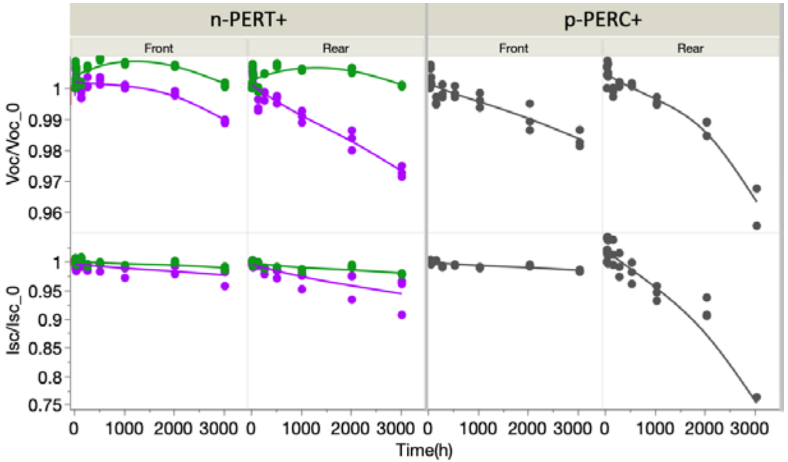
Color = cell model (maker/ brand)

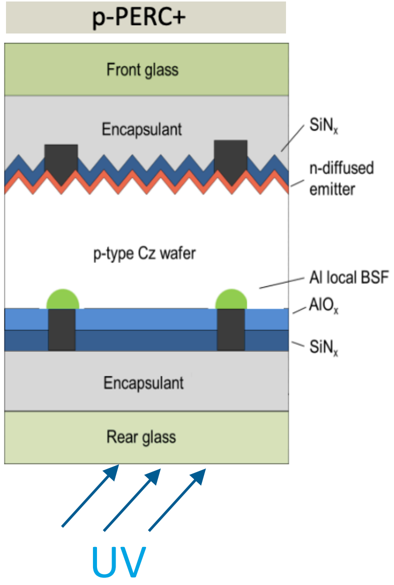
UVA 340 fluorescent bulbs, 1.24 W/m^2/nm at 340 nm, 45 °C

Fill factor not considered because of noise from physical damage to cells and not a primary key to most UV-ID

Results – screening test (bare cell back)

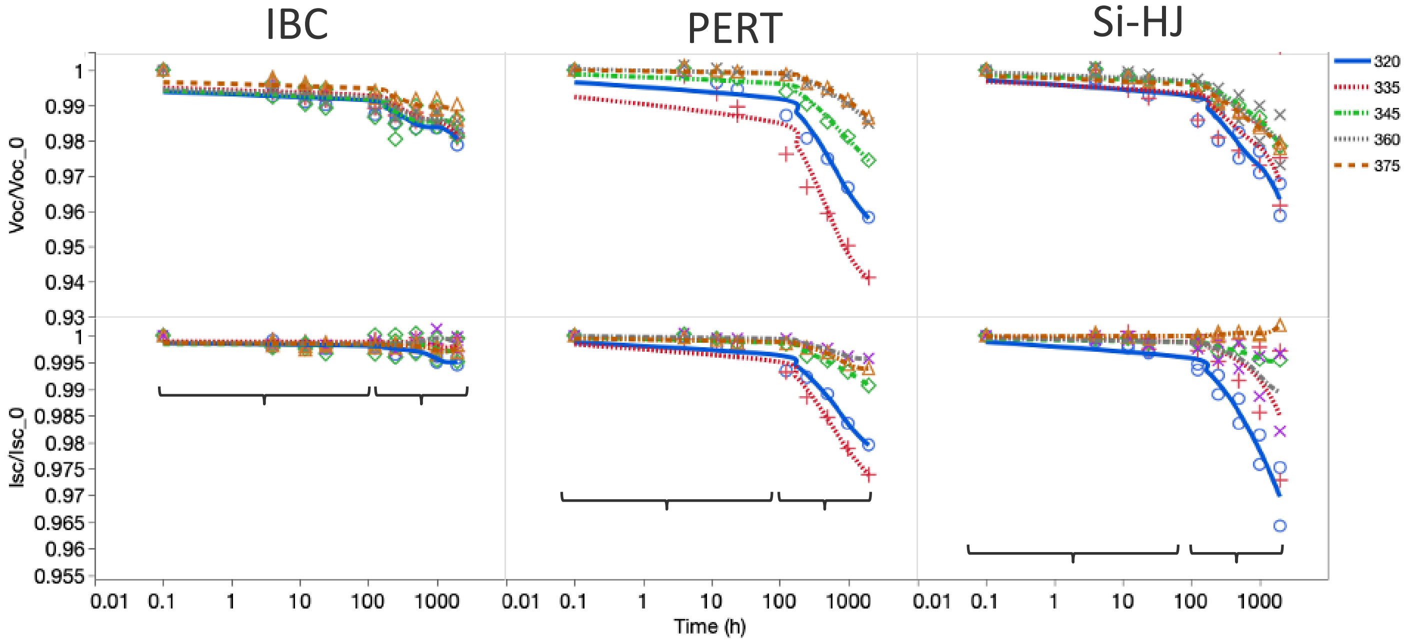






limited BSF of bifacial PERC leads to susceptibility in UV-ID
(of course UV incident on the rear is limited)

Normalized I_{sc} and V_{oc} of three cell types (IBC, n-PERT and Si HJ) fronts under UV-cut long pass filters

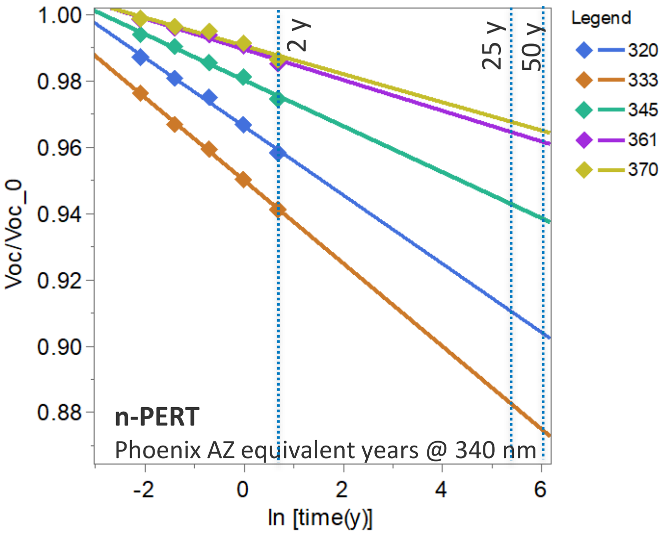


ln(t) plot: two regimes

1 h- 100 h (5% of the test duration)

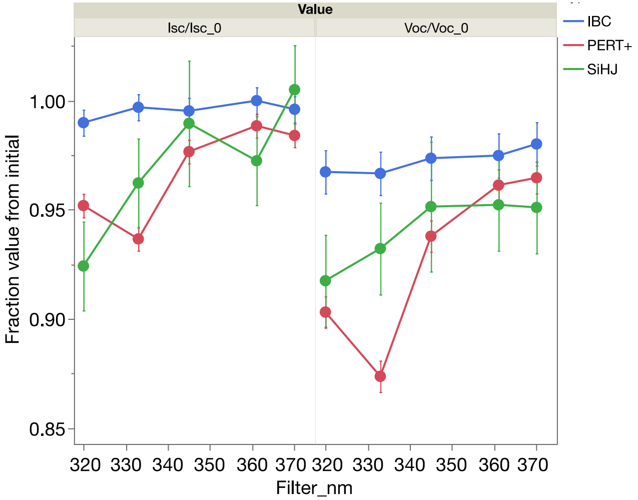
100 h -2000 h (95% of the test duration)

Projecting degradation to 25 y and 50 y (cell fronts) – time basis



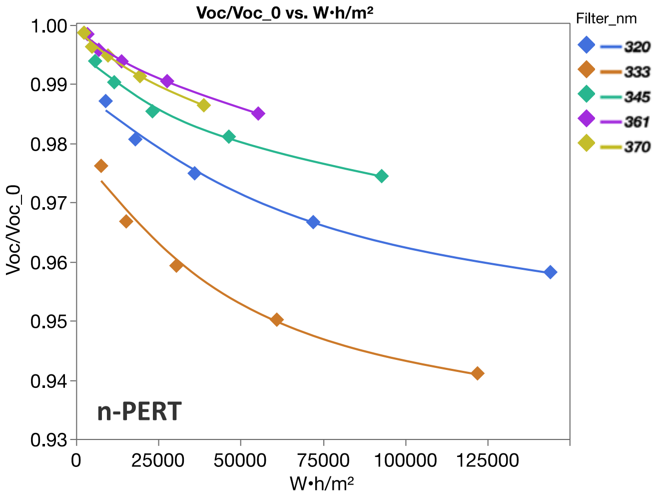
Linearizing the data with a ln[time(y)] transform
(1000 h chamber = 1 y Phoenix AZ @340 nm)

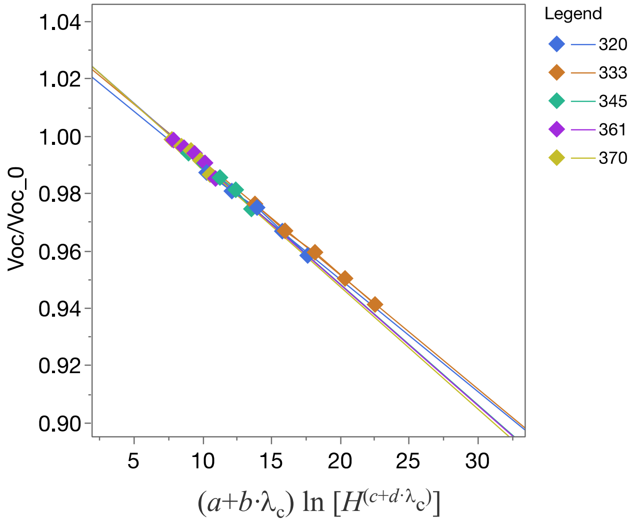
Projected fraction drop in I_{sc} and V_{oc} at 50 y



Projecting degradation to 25 y and 50 y (cell fronts) – irradiance basis

Transmitted irradiance considering long pass filters and UVA 340 bulbs





H: {$\mathrm{W \cdot h/m^2}$} UV irradiance reaching cell

λ_c : filter cutoff at 10% transmission

- Empirical transformation for linearization of data for modeling purposes
- Suggests actual energy threshold for damage can be neglected for modeling purposes
- Single equation may suggest single dominant mechanism

Modelling of UV-induced degradation to 50 y – PERT case (front face)

Independent axis transform for normalized V_{oc} and I_{sc}

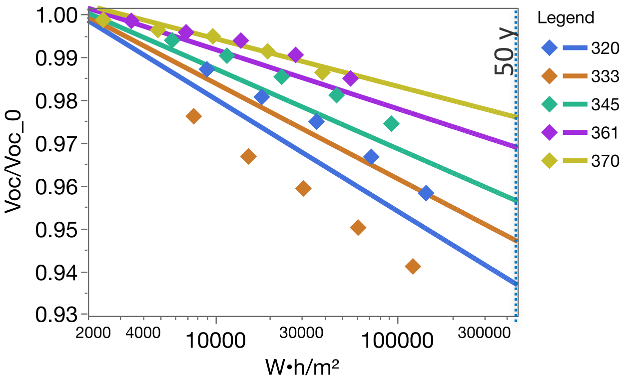
$(a+b\cdot\lambda_c)\ \ln\,[H^{(c+d\cdot\lambda_c)}]$

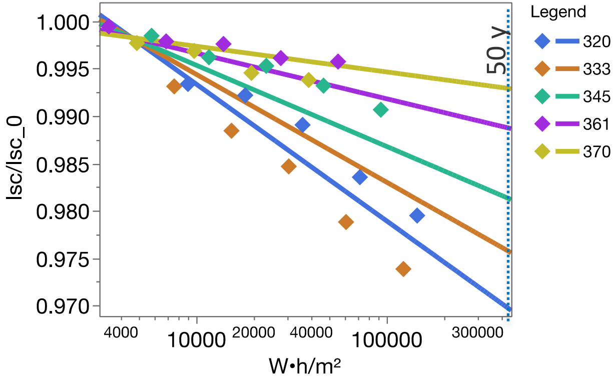
Fill factor losses associated with V_{oc} (minority carrier lifetime losses) calculated as:

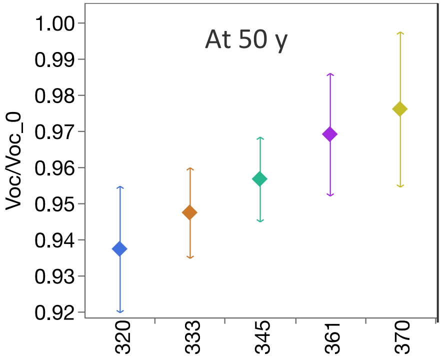
$$\frac{v_{oc}-\ln(v_{oc}+0.72)}{v_{oc}+1}$$

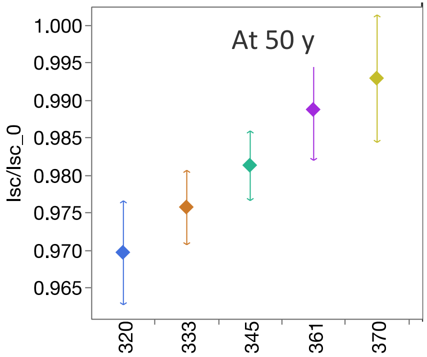
where

$$v_{oc}=\frac{q}{nkT}V_{oc}$$



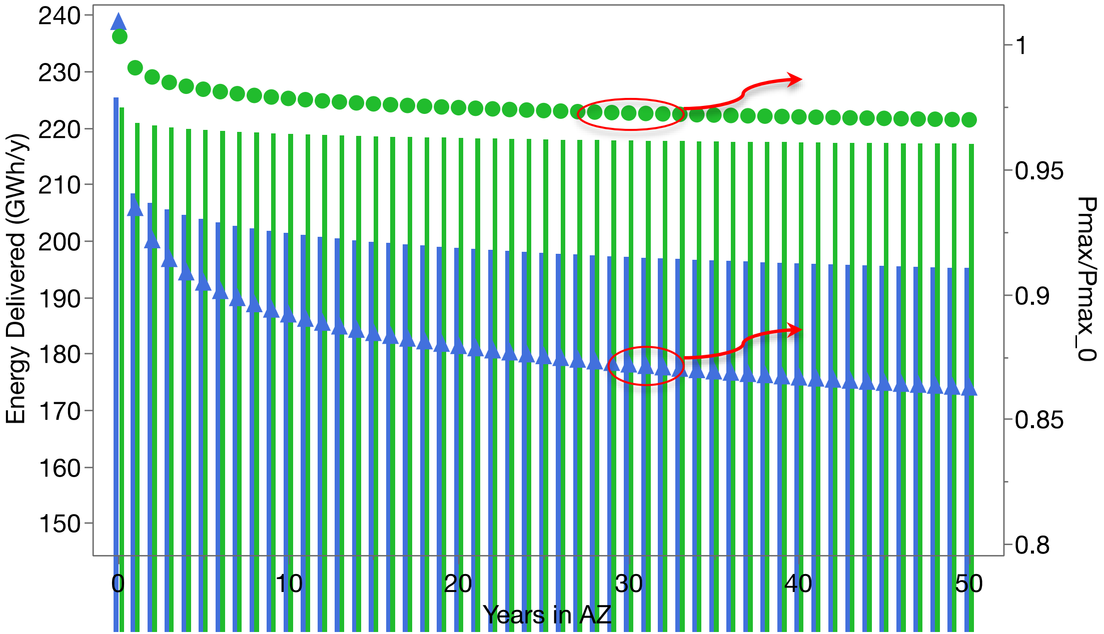






Plant power loss and SAM calculation of LCOE – PERT modules

➢ 100 MW DC power plant



UV filter cutoff λ (nm, 10% transmission)

Metric	Value (320)	Value (375)
Annual energy (year 1)	225,156,720 kWh	223,423,680 kWh
Capacity factor (year 1)	25.7%	25.5%
Energy yield (year 1)	2,251 kWh/kW	2,234 kWh/kW
Performance ratio (year 1)	0.77	0.76
PPA price (year 1)	3.30 ¢/kWh	3.06 ¢/kWh
PPA price escalation	0.00 %/year	0.00 %/year
Levelized PPA price (nominal)	3.30 ¢/kWh	3.06 ¢/kWh
Levelized PPA price (real)	2.23 ¢/kWh	2.06 ¢/kWh
Levelized COE (nominal)	3.18 ¢/kWh	2.94 ¢/kWh
Levelized COE (real)	2.15 ¢/kWh	1.98 ¢/kWh
Net present value	$4,039,644	$4,317,500
Internal rate of return (IRR)	6.00 %	6.00 %

Improved UV filtering 320 nm → 375 nm:

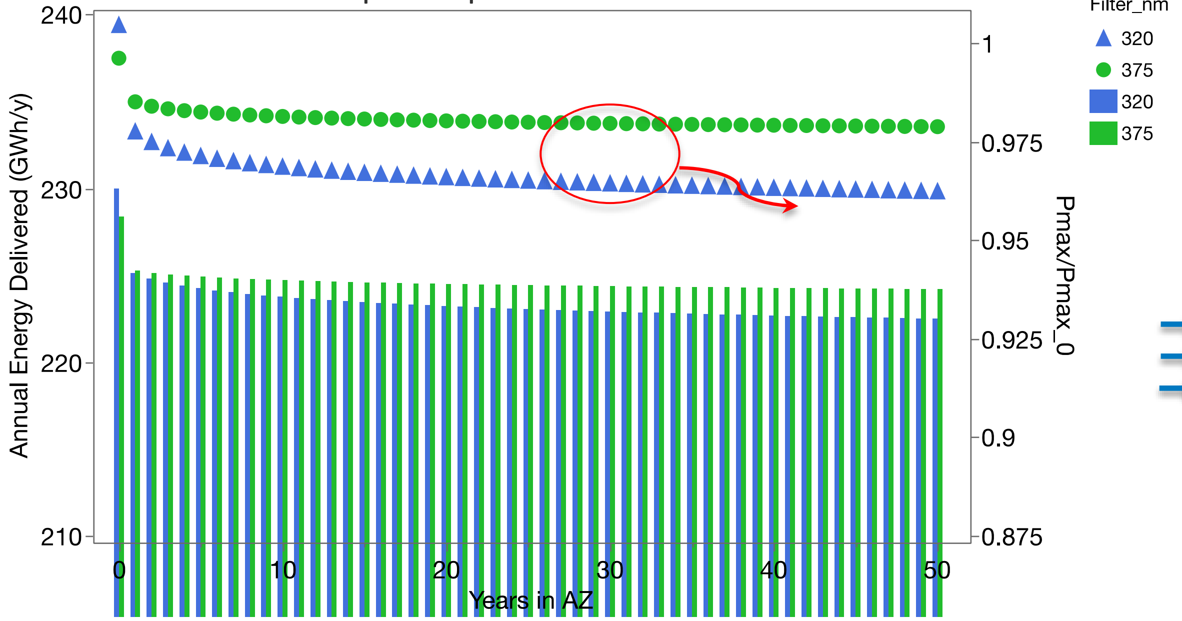
Improvement in nominal LCOE: **0.24 ¢/kWh**

Improvement in real LCOE: **0.17 ¢/kWh**

Improvement in net present value: **6.9%**

Plant power loss and SAM calculation of LCOE – IBC modules

- 100 MW DC power plant



UV filter cutoff λ (nm, 10% transmission)

Metric	Value (320)	Value (375)
Annual energy (year 1)	229,870,688 kWh	228,266,512 kWh
Capacity factor (year 1)	26.2%	26.1%
Energy yield (year 1)	2,299 kWh/kW	2,283 kWh/kW
Performance ratio (year 1)	0.79	0.78
PPA price (year 1)	3.00 ¢/kWh	2.99 ¢/kWh
PPA price escalation	0.00 %/year	0.00 %/year
Levelized PPA price (nominal)	3.00 ¢/kWh	2.99 ¢/kWh
Levelized PPA price (real)	2.01 ¢/kWh	2.01 ¢/kWh
Levelized COE (nominal)	2.87 ¢/kWh	2.86 ¢/kWh
Levelized COE (real)	1.93 ¢/kWh	1.92 ¢/kWh
Net present value	$4,334,852	$4,373,623
Internal rate of return (IRR)	6.00 %	6.00 %
Year IRR is achieved	30	30
IRR at end of project	6.57 %	6.57 %

Improved UV filtering 320 nm → 375 nm:

Improvement in nominal LCOE: **0.01 ¢/kWh**

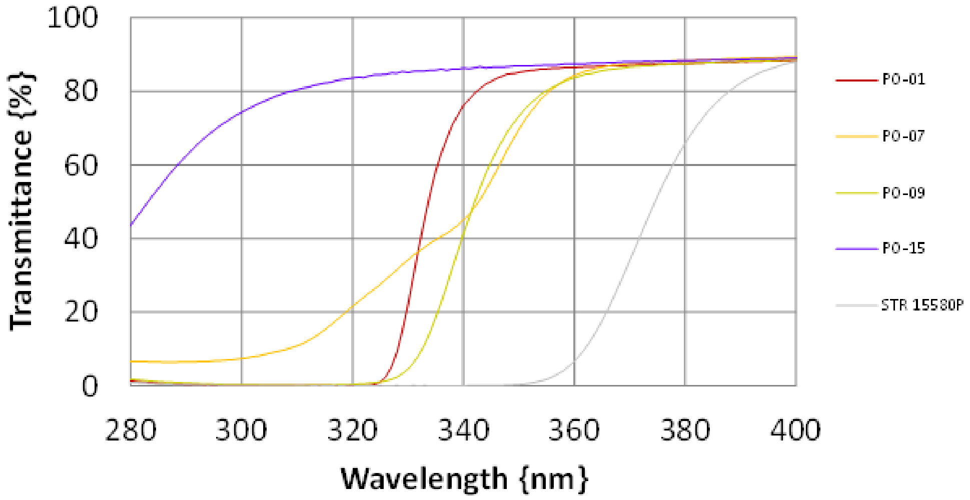
Improvement in real LCOE: **0.01 ¢/kWh**

Improvement in net present value: **0.1%**

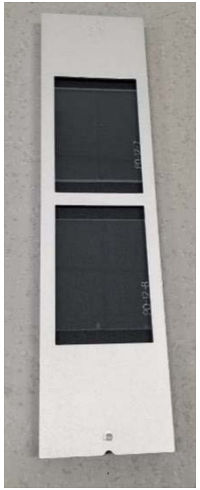
UV-ID – resistant cells yield long term LCOE improvement such that UV filtering in encapsulation may be omitted

Future stage: Use of UV absorbers in encapsulant to mitigate UV

Time zero transmittance of candidate encapsulants



Samples (mini modules)



Forthcoming…

Summary and Conclusions

- Modern cell designs are sensitive to UV-ID
  - Reduced or eliminated front and back surface field
  - Increased dependence on high quality surface passivation
- Single transformation of the independent variable (t, $kW \cdot h/m^2$) could be used to achieve linear model of the data to extrapolate to 50 y
- Solar Advisor Model (SAM) shows appropriate filtering of UV-irradiation can improve LCOE and net present value of plant
- Some advanced cell types are seen to be UV-resistant (cell level solutions also exist)
- Solutions exist on the cell, glass, and encapsulant level
  - Changes over time in each of these would also need to be considered (solarization, encapsulant browning…)

Thank you !

The authors are grateful to André F. R. Augusto, Stanislau Herasimenka, Som Dahal, Pradeep Balaji, and Stuart Bowden of Arizona State University (ASU);
Afshin Andreas and Paul Ndione of NREL;
Wei Luo of Solar Energy Research Institute of Singapore (SERIS); Katherine Han of SunPower Corp.;
Lizhong Mao and Jean-Nicolas Jaubert of Canadian Solar;
Qi Wang and Lin Zhang of Jinko Solar;

Brian Habersberger of Dow Chemical; and Sari-Beth Samuels of Solvay

NREL/PR-5K00-80994

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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