Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Application of the Intrinsic-Adjusted Single Diode Model to Production Data

PVPMC, Albuquerque, USA 12-14 May 2026

P. Hamer[1], H. Tong[2], X. Xu[2], S. Chen[2], W. Yao[2], J. Kang[2], R. Cavieres[1,3], B. Hoex[1]

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[3] Atamostec, Center for Solar Energy Technologies, Antofagasta, Chile

A Dark Past

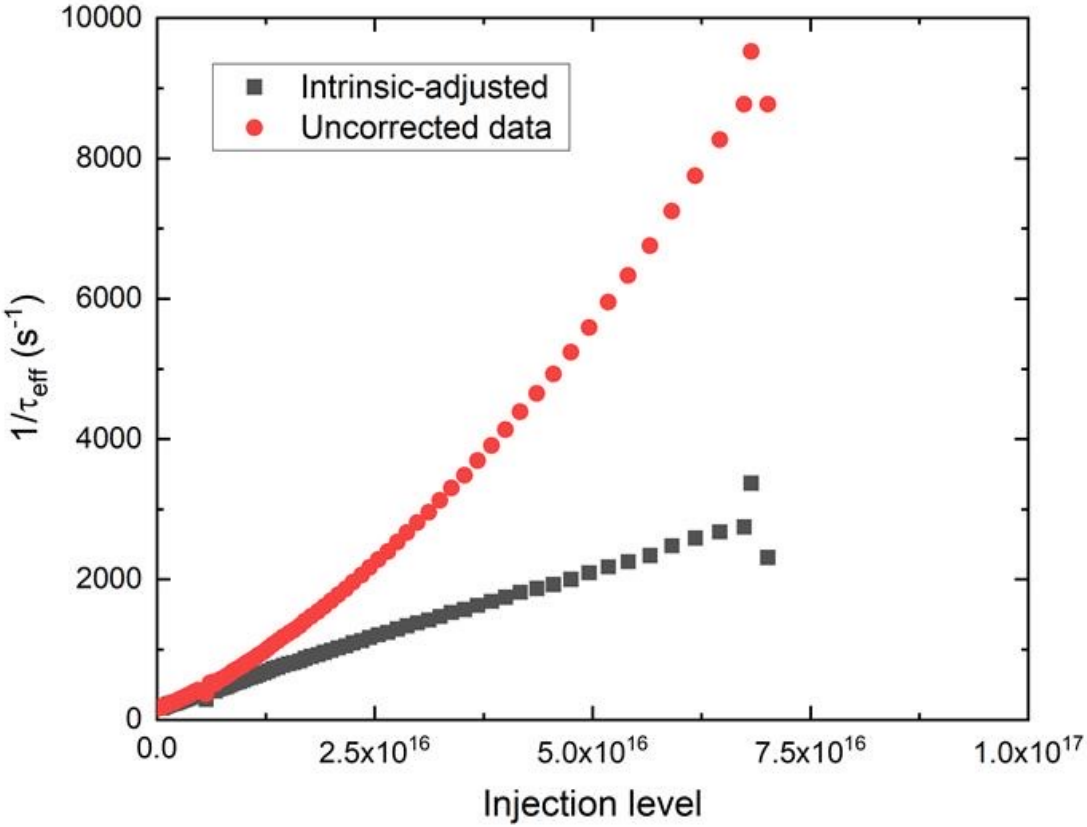
- Sinton PCD Tester: The *most* common tool in any photovoltaic research laboratory
- Used to measure carrier recombination lifetimes
- Less recombination → Higher device efficiencies

R.A. Sinton, A. Cuevas, *Appl. Phys. Lett.* **69**, 2510 (1996).

https://www.sintoninstruments.com/products/

A Dark Past

B. Hoex, *et al*. *Applied Physics Letters* 91 (2007).



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A Dark Past

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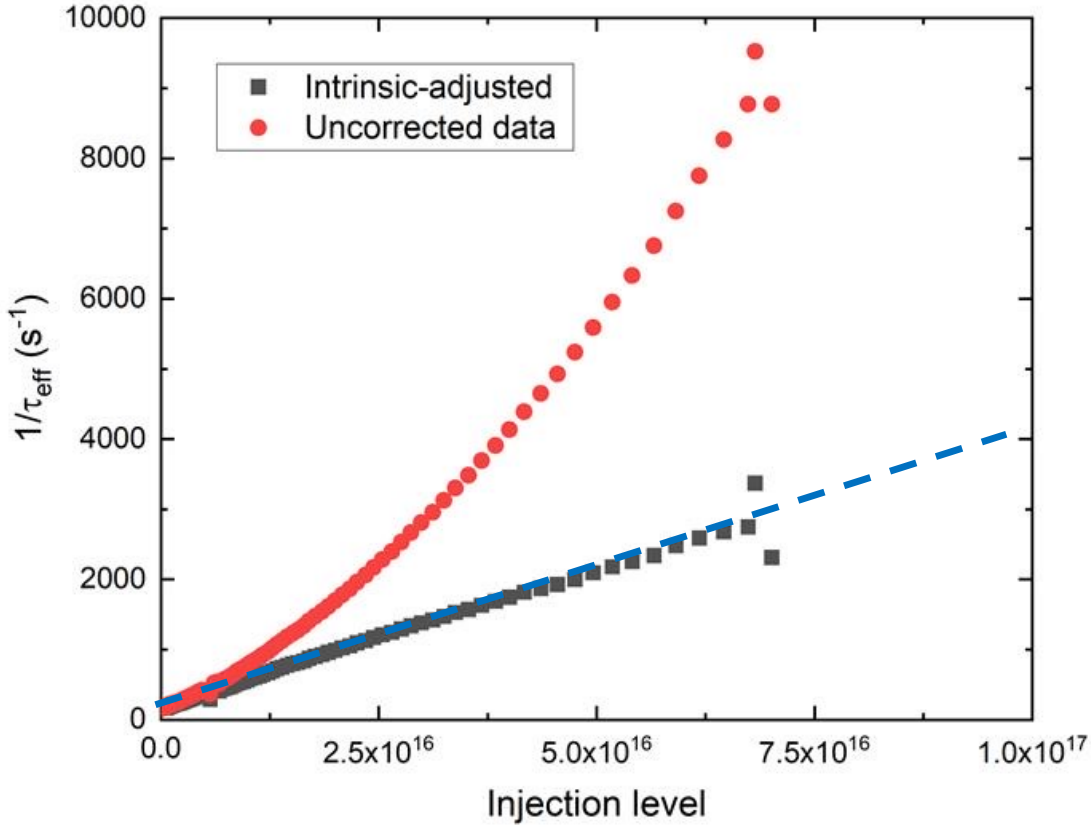

$$I_{cell} = I_{ph} - I_0 \left[e^{\frac{V_{cell}+I_{cell}R_{S.cell}}{nV_{th}}} - 1 \right] - \frac{V_{cell} + I_{cell}R_{S.cell}}{R_{SH.cell}}$$

R.A. Sinton, A. Cuevas, *Appl. Phys. Lett.* **69**, 2510 (1996).

https://www.sintoninstruments.com/products/

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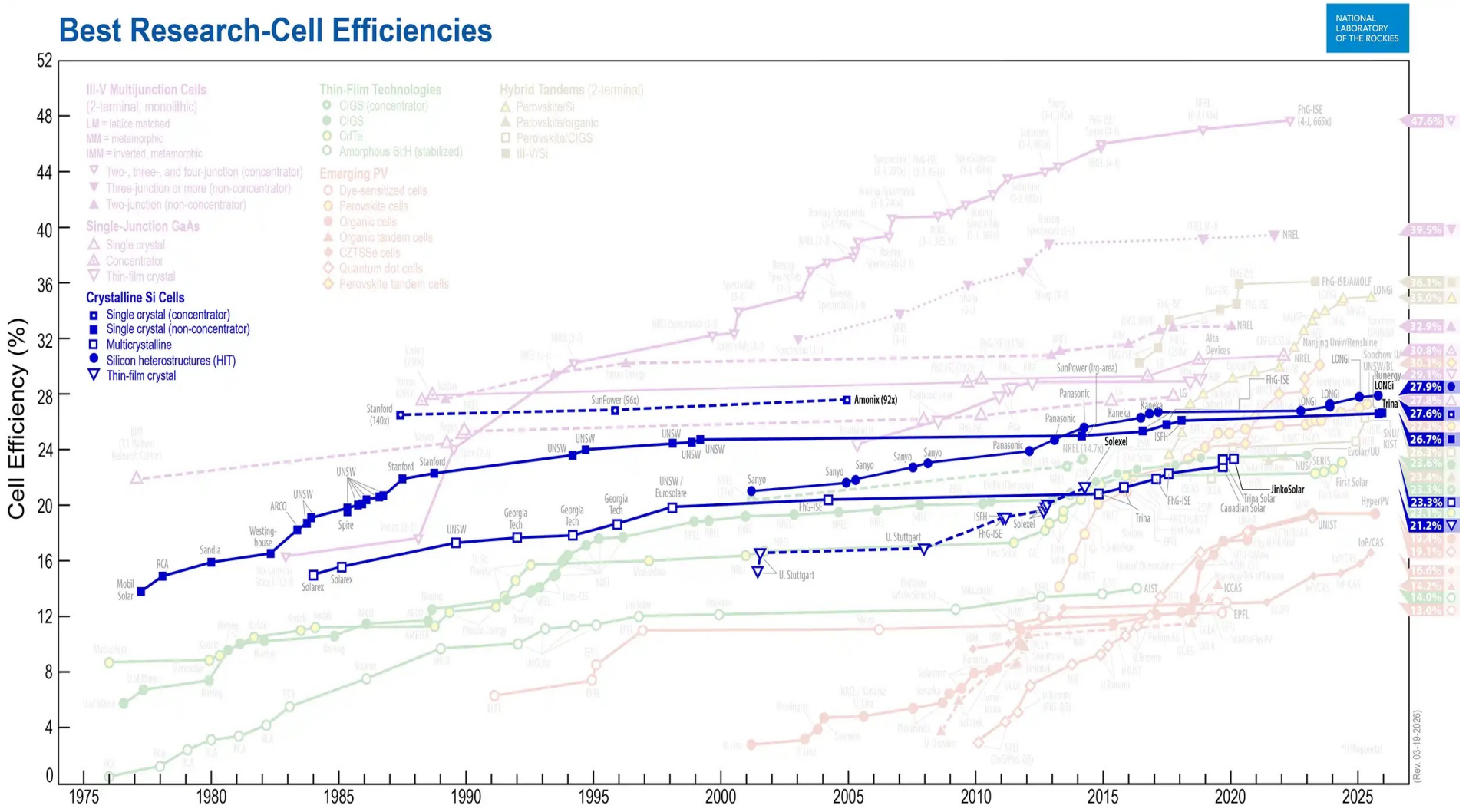
A Bright Future



Source: https://www.nlr.gov/pv/cell-efficiency

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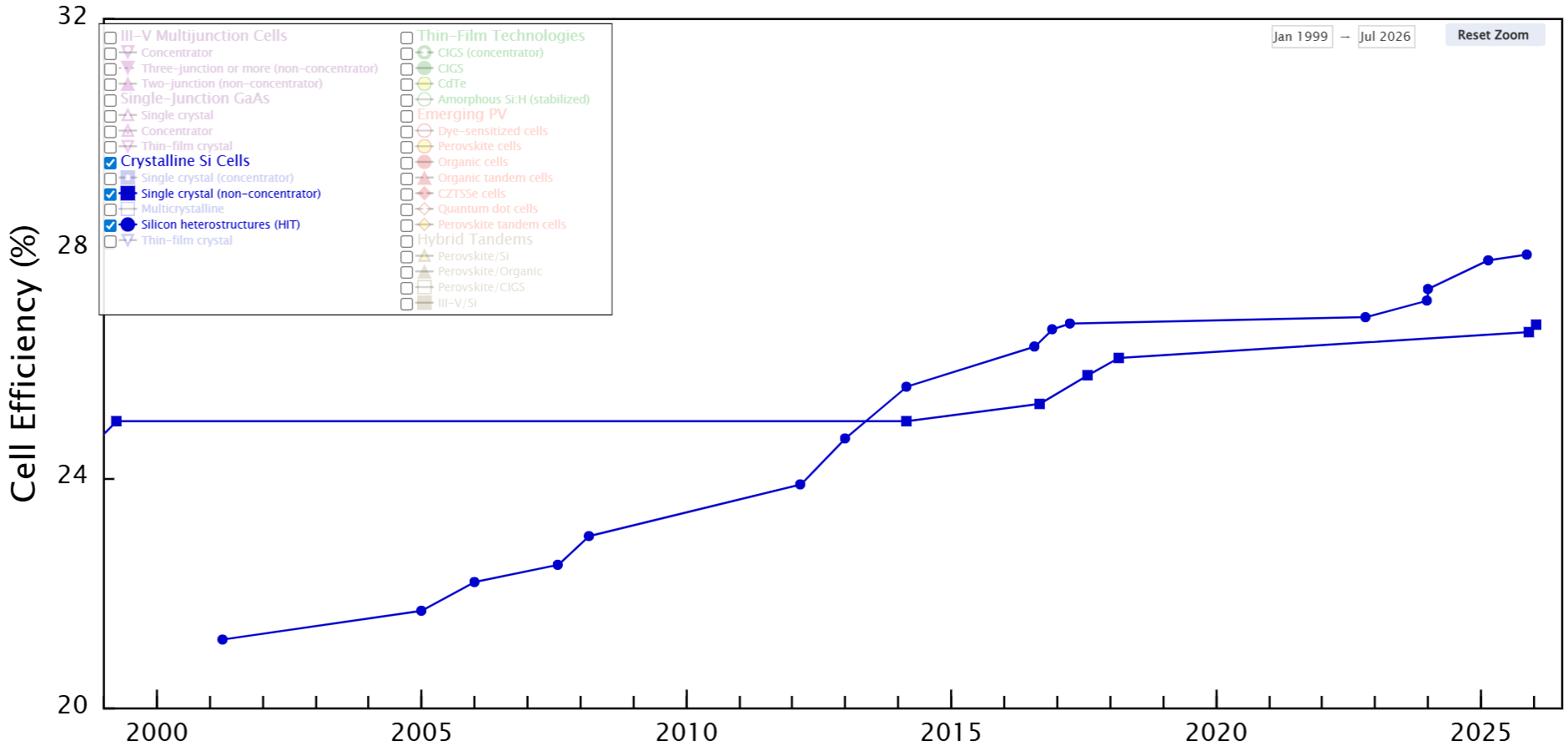

Source: https://www.nlr.gov/pv/cell-efficiency

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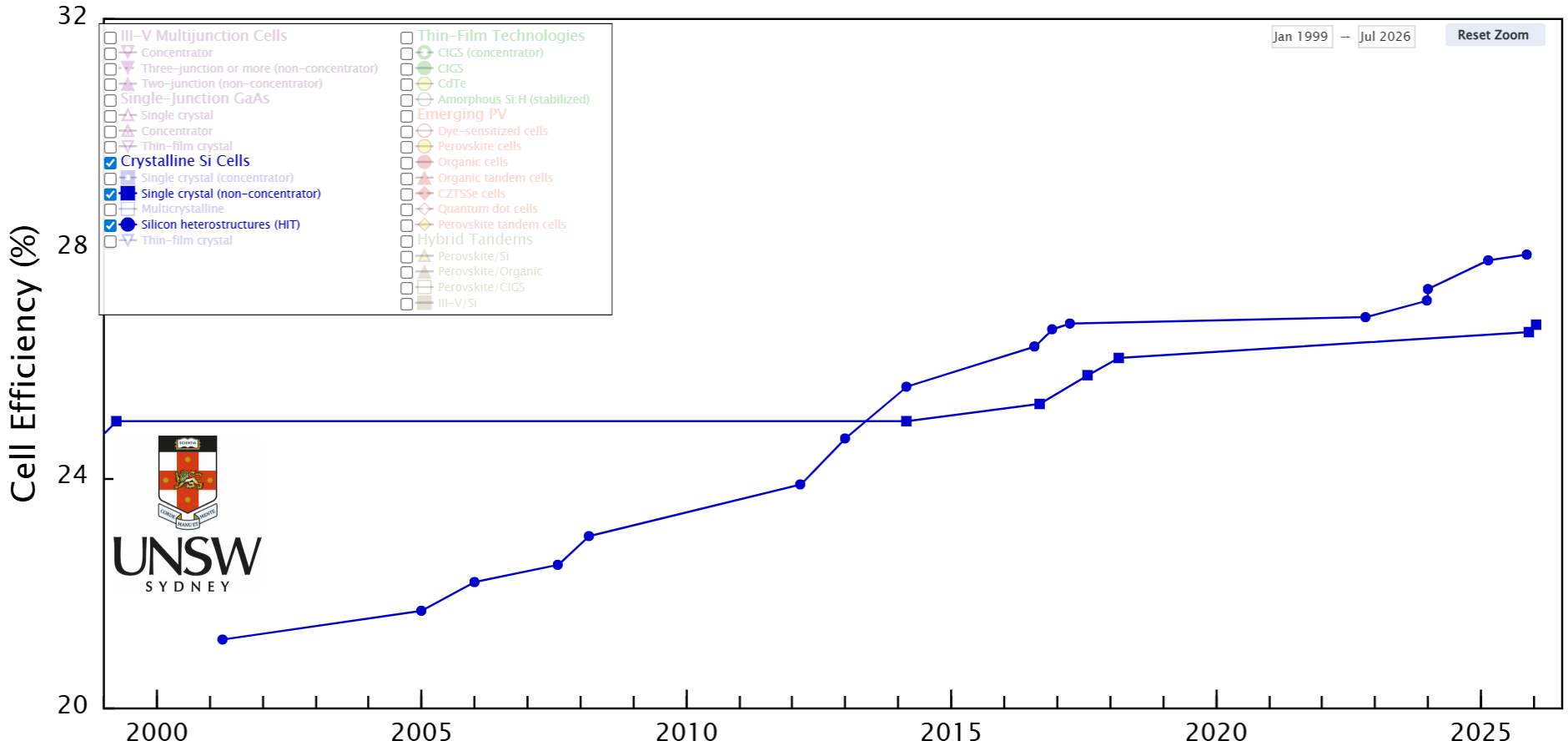

Source: https://www.nlr.gov/pv/cell-efficiency

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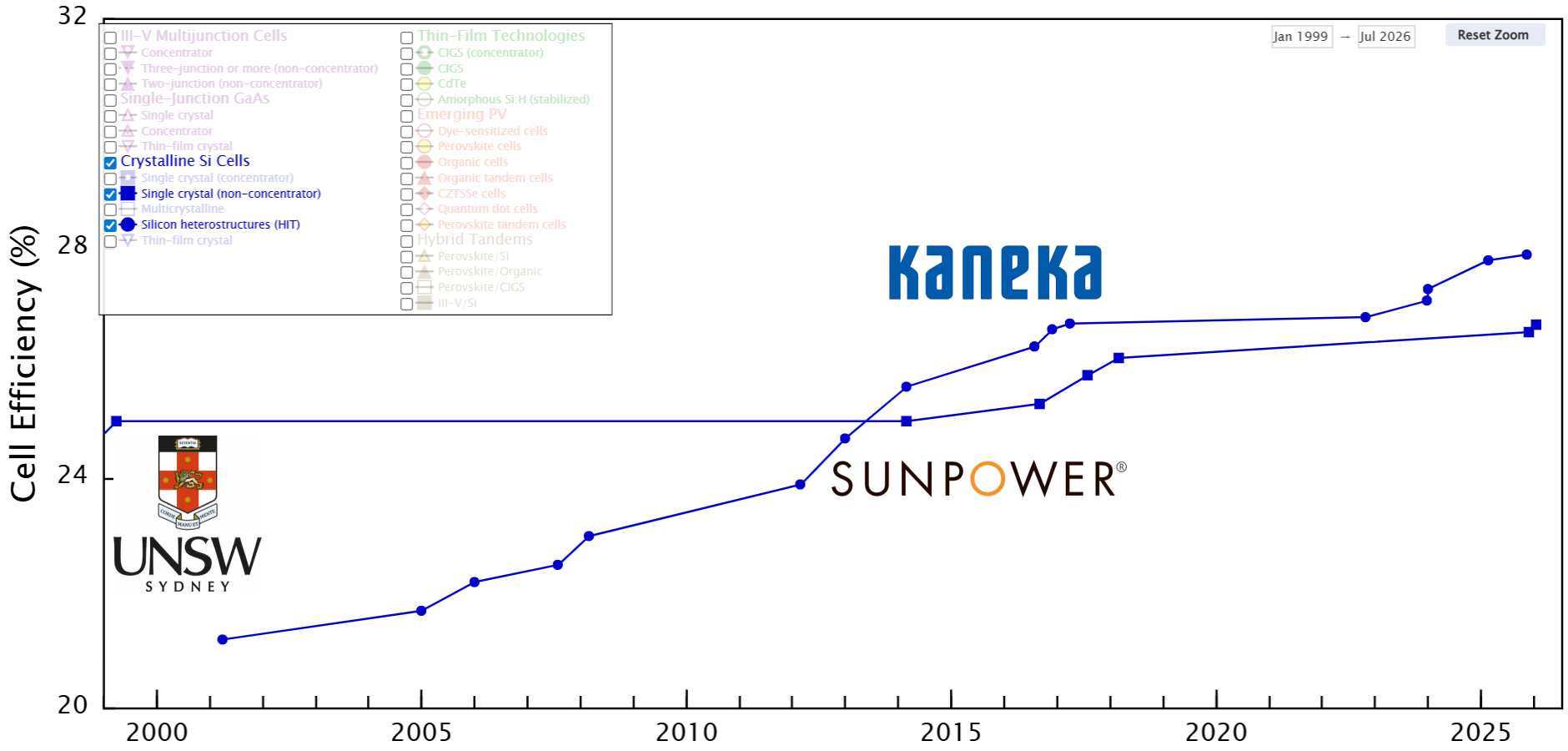

Source: https://www.nlr.gov/pv/cell-efficiency

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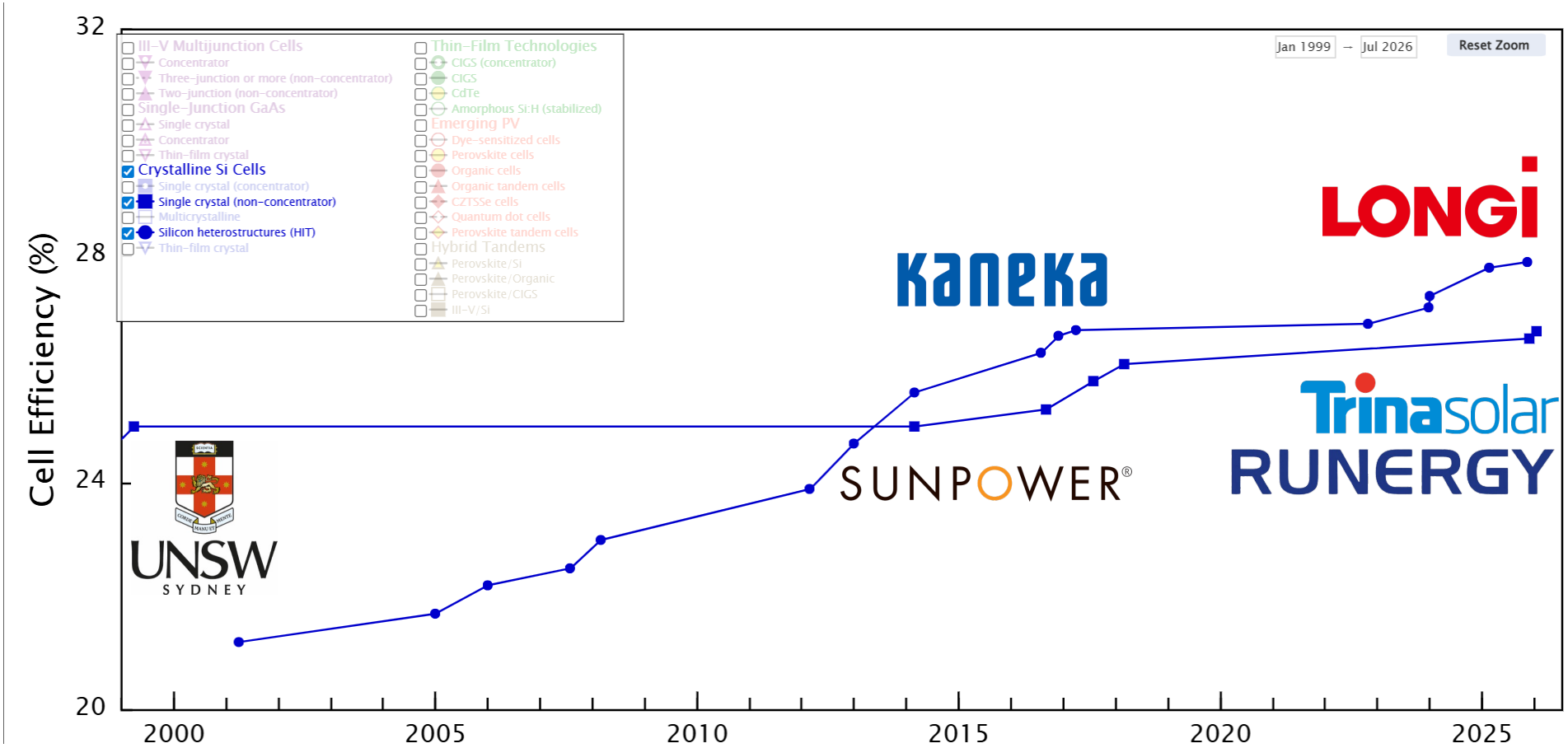

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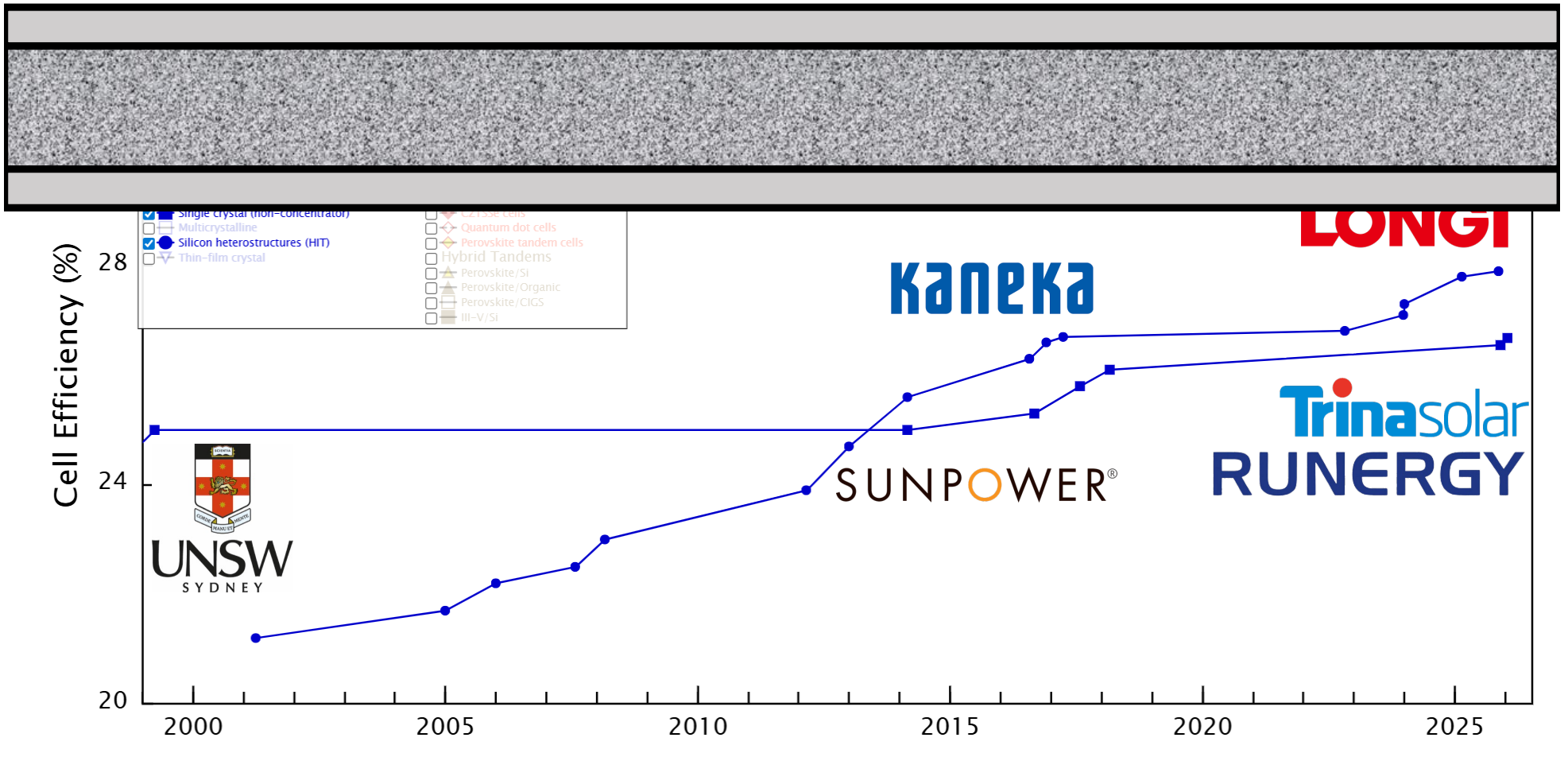
A Bright Future



Source: https://www.nlr.gov/pv/cell-efficiency

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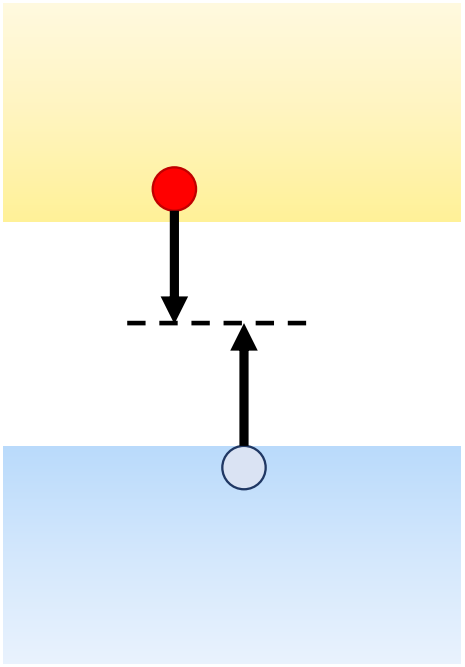
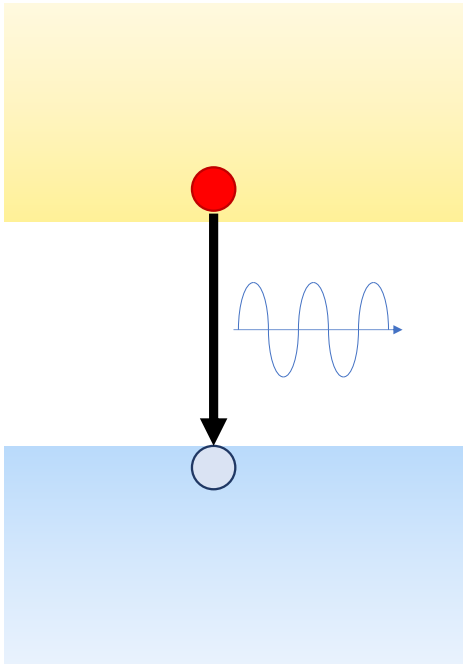
Recombination in Silicon

Shockley-Read Hall



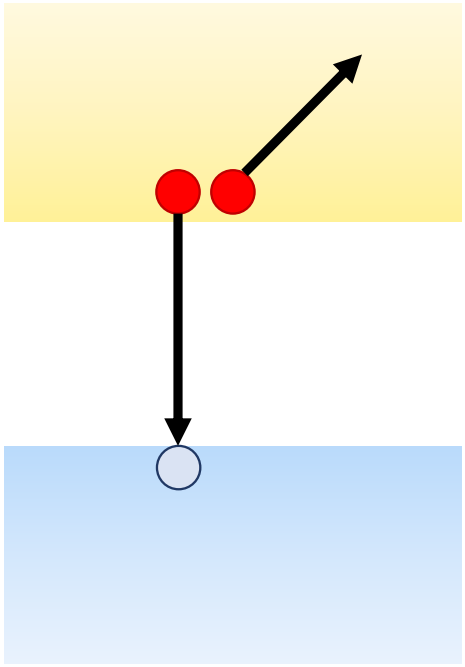
$\propto np$

Radiative



$\propto np$

Auger

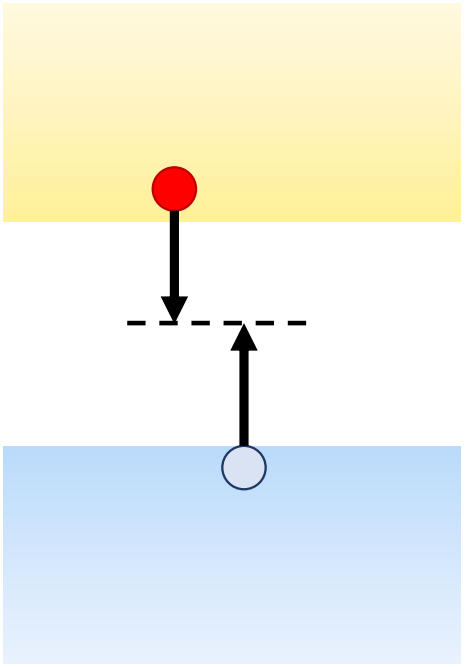


$\propto n^2p + np^2$

Recombination in Silicon

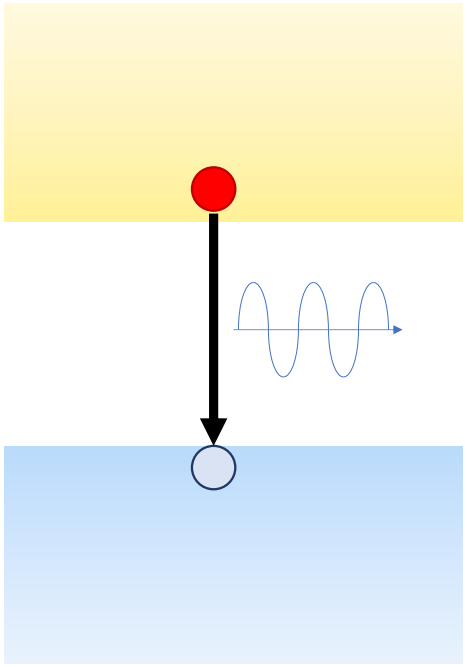
Intrinsic Recombination

Shockley-Read Hall



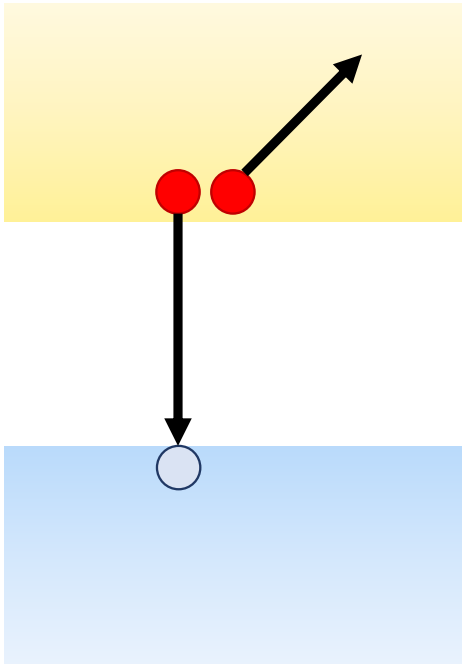
$\propto np$

Radiative



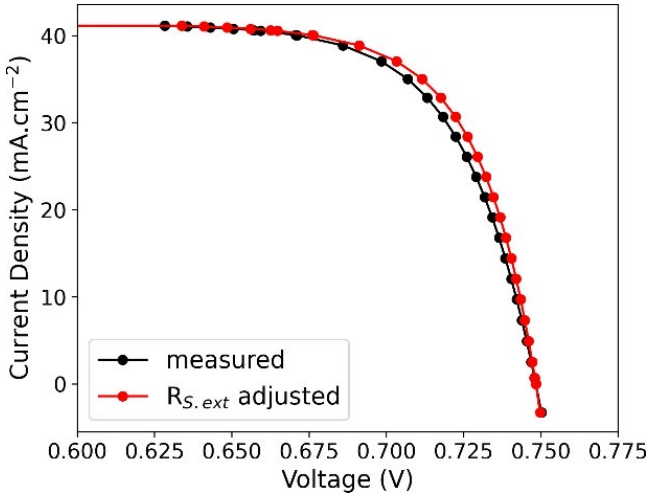
$\propto np$

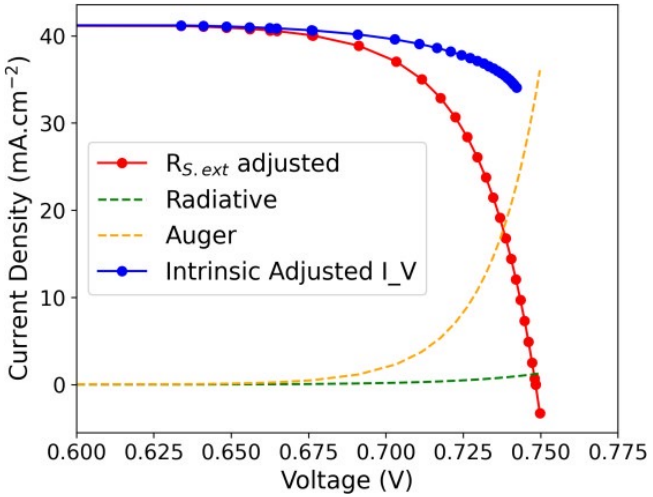
Auger



$\propto n^2p + np^2$

Adjusting the Single-Diode Model





Hamer, P, *et al*. "The intrinsic adjusted single-diode model: Solid State Physics meets accurate yield simulation." *Solar Energy Materials and Solar Cells* 300 (2026): 114218.

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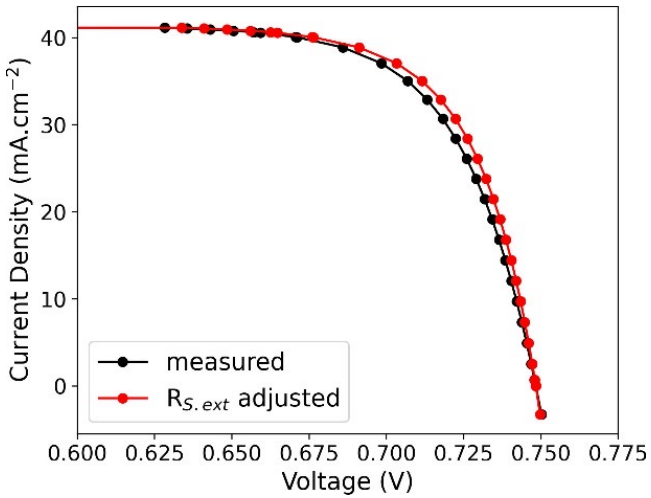
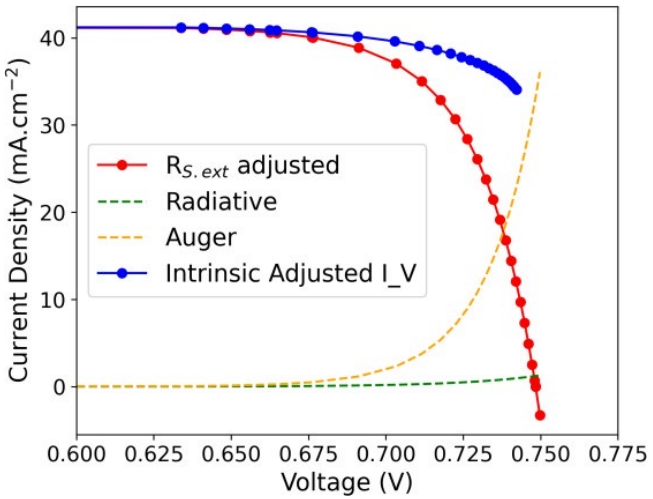
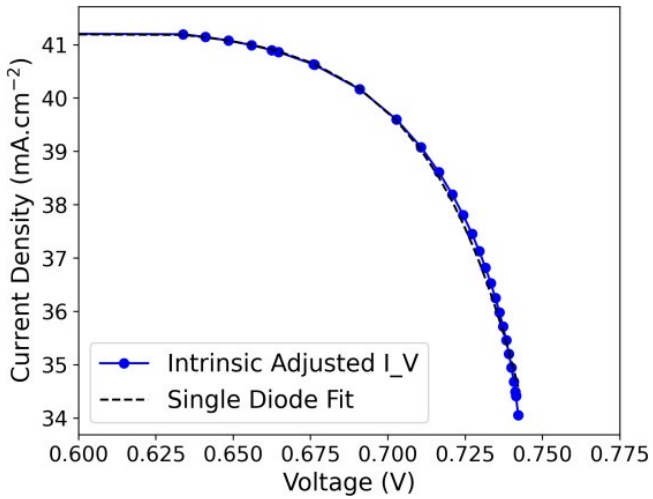
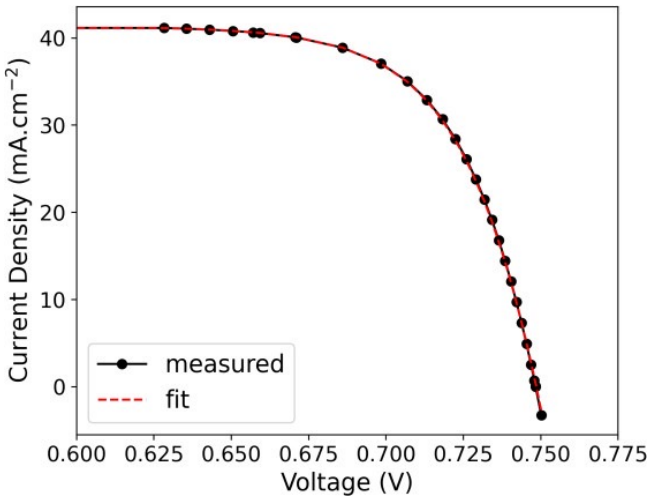
Adjusting the Single-Diode Model









Hamer, P, *et al*. "The intrinsic adjusted single-diode model: Solid State Physics meets accurate yield simulation." *Solar Energy Materials and Solar Cells* 300 (2026): 114218.

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Calculating Intrinsic Recombination

$$I = I_{ph} - \boldsymbol{I_{rad}(V_{adj}, w, N_D)} - \boldsymbol{I_{Auger}(V_{adj}, w, N_D)} - I_0\left[\frac{V_{adj}}{e^{nV_{th}} - 1}\right] - \frac{V_{adj}}{R_{SH}}$$

$V_{adj} = V + IR_S$

$Cell\ Volume\ (width)$

$Bulk\ Doping$

Hamer, P, *et al*. "The intrinsic adjusted single-diode model: Solid State Physics meets accurate yield simulation." *Solar Energy Materials and Solar Cells* 300 (2026): 114218.

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Calculating Intrinsic Recombination

$$I = I_{ph} - \boldsymbol{I_{rad}(V_{adj}, w, N_D)} - \boldsymbol{I_{Auger}(V_{adj}, w, N_D)} - I_0\left[e^{\frac{V_{adj}}{nV_{th}}} - 1\right] - \frac{V_{adj}}{R_{SH}}$$

$$np = n_{i.eff}^2 e^{\frac{(\Delta\phi)}{V_{th}}}$$

Kerr, M., and Cuevas, A. *Journal of Applied Physics* 91.4 (2002): 2473-2480.

$$n_i = 1.541\times10^{15} T^{1.712} e^{\frac{qE_g}{2kT}}$$

$$R_{rad} = B_{low} n_{i,0}^2 e^{\frac{\Delta\phi}{kT}}(1 - f_{PR})$$

Richter, A, *et al. Phys Rev. B*—86.16 (2012): 165202.

$$g_{exh} = 1 + (g_{exh.max} - 1)\frac{1}{1 + (n+p)^{\alpha_{Auger}}}$$

$$\Delta\phi = V + JR_{S.ext}$$

Niewelt, T., *et al. SOLMAT* 235 (2022): 111467.

Black, L., and Macdonald, D., *SOLMAT* 234 (2022): 111428.

$$\Delta_{\chi ce} = \Delta_{\chi ce.1} \times \Delta_{\chi ce.2} \times$$

Black, L., *et al. SOLMAT* 295 (2026): 113985.

$$9.71\times10^{-32}\left(1 + 2e^{\frac{qhw_{eeh}}{kT}}\right)^{-1}$$

Hamer, P, *et al*. "The intrinsic adjusted single-diode model: Solid State Physics meets accurate yield simulation." *Solar Energy Materials and Solar Cells* 300 (2026): 114218.

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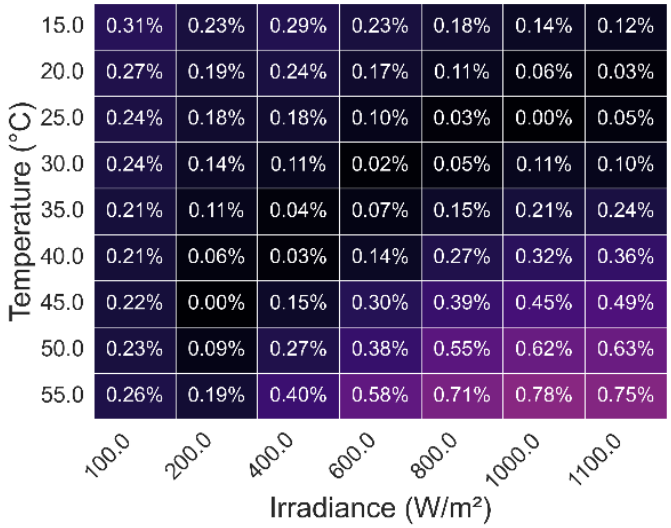
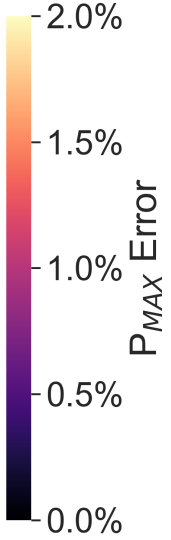
Cell Fitting – Quokka (P_{MAX})

Datasheet Fit





https://www.quokka3.com/

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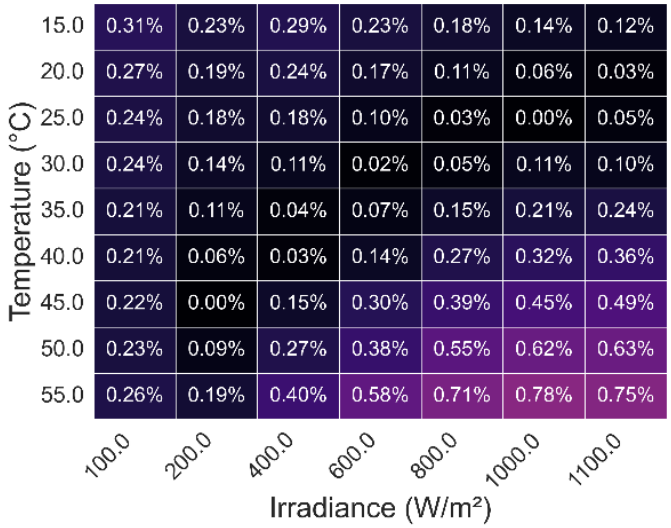
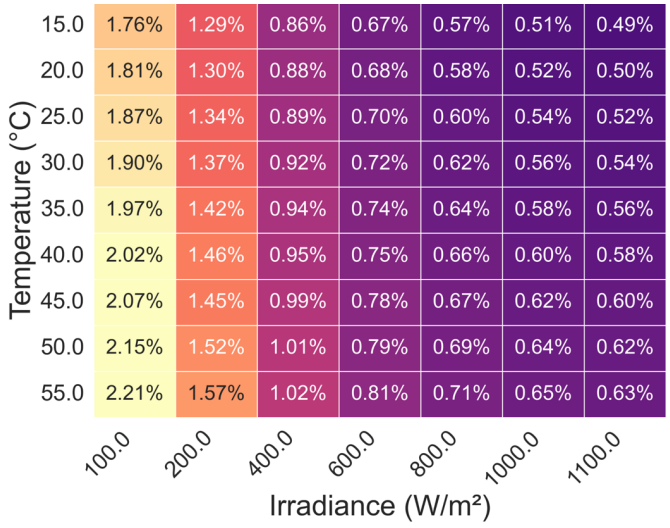
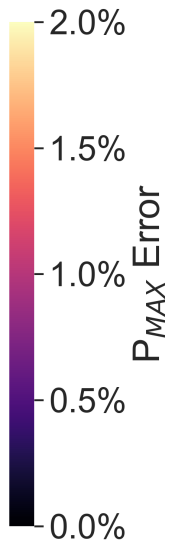
Cell Fitting – Quokka (P_{MAX})

Datasheet Fit





Single-Diode Fit



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Cell Fitting – Quokka (P_{MAX})

Datasheet Fit

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	0.31%	0.23%	0.29%	0.23%	0.18%	0.14%	0.12%
20.0	0.27%	0.19%	0.24%	0.17%	0.11%	0.06%	0.03%
25.0	0.24%	0.18%	0.18%	0.10%	0.03%	0.00%	0.05%
30.0	0.24%	0.14%	0.11%	0.02%	0.05%	0.11%	0.10%
35.0	0.21%	0.11%	0.04%	0.07%	0.15%	0.21%	0.24%
40.0	0.21%	0.06%	0.03%	0.14%	0.27%	0.32%	0.36%
45.0	0.22%	0.00%	0.15%	0.30%	0.39%	0.45%	0.49%
50.0	0.23%	0.09%	0.27%	0.38%	0.55%	0.62%	0.63%
55.0	0.26%	0.19%	0.40%	0.58%	0.71%	0.78%	0.75%

Single-Diode Fit

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	1.76%	1.29%	0.86%	0.67%	0.57%	0.51%	0.49%
20.0	1.81%	1.30%	0.88%	0.68%	0.58%	0.52%	0.50%
25.0	1.87%	1.34%	0.89%	0.70%	0.60%	0.54%	0.52%
30.0	1.90%	1.37%	0.92%	0.72%	0.62%	0.56%	0.54%
35.0	1.97%	1.42%	0.94%	0.74%	0.64%	0.58%	0.56%
40.0	2.02%	1.46%	0.95%	0.75%	0.66%	0.60%	0.58%
45.0	2.07%	1.45%	0.99%	0.78%	0.67%	0.62%	0.60%
50.0	2.15%	1.52%	1.01%	0.79%	0.69%	0.64%	0.62%
55.0	2.21%	1.57%	1.02%	0.81%	0.71%	0.65%	0.63%

P_{MAX} Error: 2.0%, 1.5%, 1.0%, 0.5%, 0.0%

Adjusted Model

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	0.12%	0.12%	0.08%	0.06%	0.05%	0.03%	0.03%
20.0	0.13%	0.11%	0.08%	0.06%	0.05%	0.03%	0.03%
25.0	0.15%	0.12%	0.08%	0.06%	0.05%	0.04%	0.04%
30.0	0.16%	0.13%	0.09%	0.07%	0.06%	0.05%	0.05%
35.0	0.19%	0.15%	0.10%	0.08%	0.07%	0.07%	0.07%
40.0	0.21%	0.17%	0.11%	0.09%	0.09%	0.09%	0.09%
45.0	0.24%	0.17%	0.13%	0.11%	0.11%	0.11%	0.11%
50.0	0.27%	0.20%	0.14%	0.12%	0.13%	0.13%	0.13%
55.0	0.30%	0.23%	0.16%	0.14%	0.14%	0.15%	0.15%

https://www.quokka3.com/

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Cell Fitting – Quokka (n-RMSE)

Datasheet Fit

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	1.97%	2.20%	1.69%	1.47%	1.92%	2.50%	2.78%
20.0	3.18%	3.51%	3.03%	2.51%	2.27%	2.28%	2.45%
25.0	3.81%	4.69%	4.55%	4.02%	3.59%	3.68%	3.62%
30.0	5.07%	6.28%	5.96%	5.50%	5.06%	4.88%	5.25%
35.0	6.07%	7.54%	8.29%	6.85%	6.58%	6.47%	6.46%
40.0	7.45%	8.48%	7.15%	8.70%	7.91%	8.23%	7.92%
45.0	5.49%	7.53%	8.24%	7.97%	9.68%	9.58%	9.26%
50.0	6.67%	8.37%	9.60%	10.20%	9.66%	9.38%	10.92%
55.0	6.24%	5.90%	10.97%	11.61%	10.17%	11.06%	10.22%

Single-Diode Fit

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	4.46%	4.66%	3.10%	2.44%	1.84%	1.58%	1.59%
20.0	2.63%	4.40%	2.98%	1.92%	1.43%	1.29%	1.38%
25.0	2.24%	4.12%	2.85%	1.69%	1.15%	1.24%	1.24%
30.0	2.10%	2.88%	2.65%	1.48%	0.99%	1.20%	1.47%
35.0	2.01%	2.11%	2.06%	1.35%	0.90%	1.28%	1.53%
40.0	2.07%	2.04%	1.56%	1.41%	0.82%	1.31%	1.57%
45.0	1.99%	1.94%	1.46%	1.06%	0.82%	1.19%	1.47%
50.0	2.00%	2.52%	1.51%	1.19%	0.81%	0.65%	1.37%
55.0	2.16%	1.74%	1.84%	1.29%	0.88%	0.76%	0.62%

n-RMSE: 5.0% 4.0% 3.0% 2.0% 1.0% 0.0%

Adjusted Model

Temperature (°C) \ Irradiance (W/m²)	100.0	200.0	400.0	600.0	800.0	1000.0	1100.0
15.0	0.93%	0.67%	0.35%	0.31%	0.41%	0.53%	0.58%
20.0	0.51%	0.61%	0.29%	0.24%	0.28%	0.39%	0.44%
25.0	0.35%	0.53%	0.27%	0.20%	0.26%	0.34%	0.35%
30.0	0.30%	0.34%	0.25%	0.16%	0.21%	0.28%	0.33%
35.0	0.30%	0.26%	0.24%	0.17%	0.16%	0.22%	0.25%
40.0	0.35%	0.26%	0.20%	0.23%	0.15%	0.18%	0.20%
45.0	0.27%	0.26%	0.21%	0.19%	0.22%	0.22%	0.22%
50.0	0.40%	0.32%	0.23%	0.23%	0.21%	0.23%	0.35%
55.0	0.48%	0.28%	0.31%	0.26%	0.25%	0.28%	0.25%

https://www.quokka3.com/

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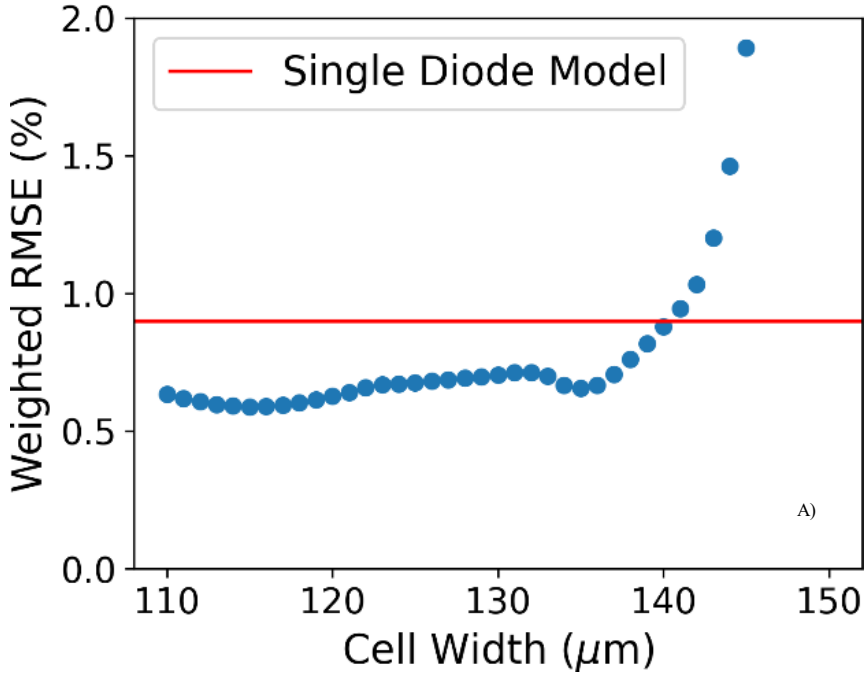
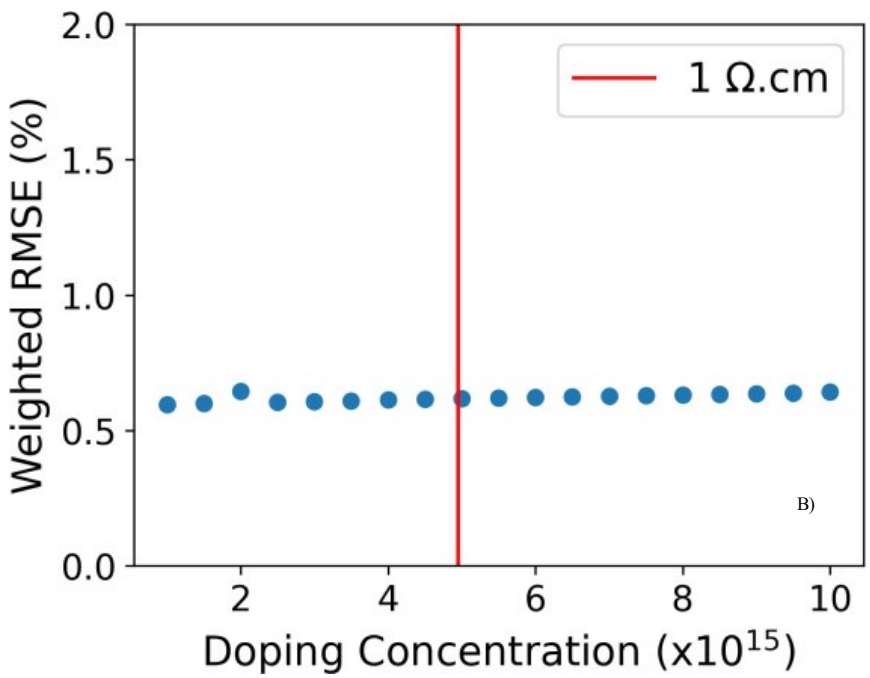
Fitting to Real Cells

- Real Cells – Hard to know actual cell thickness and doping
- We can instead use them as fitting parameters
- Bulk Doping has minimal impact





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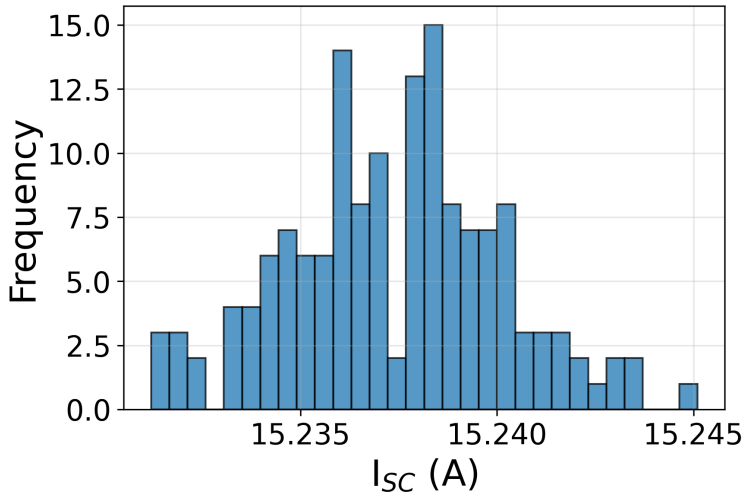
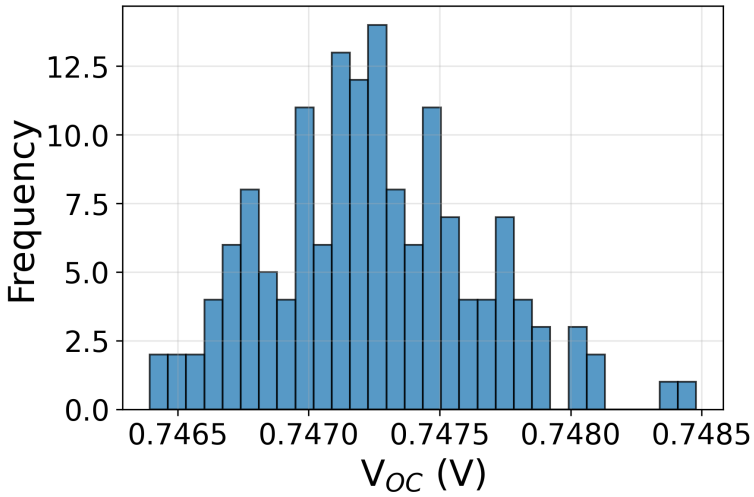
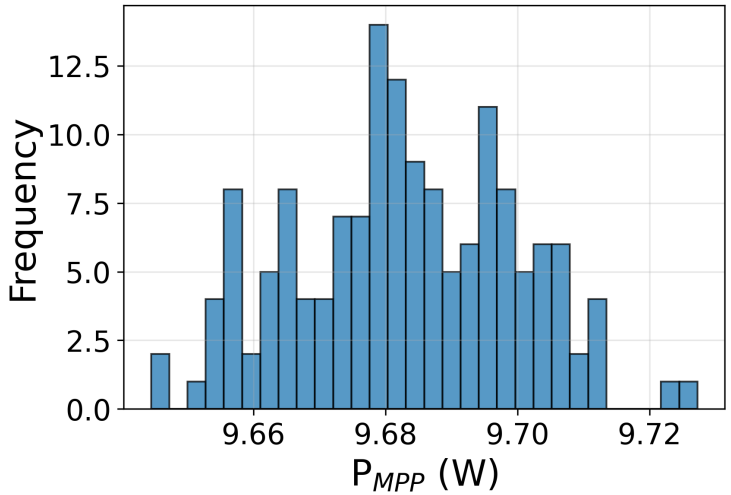
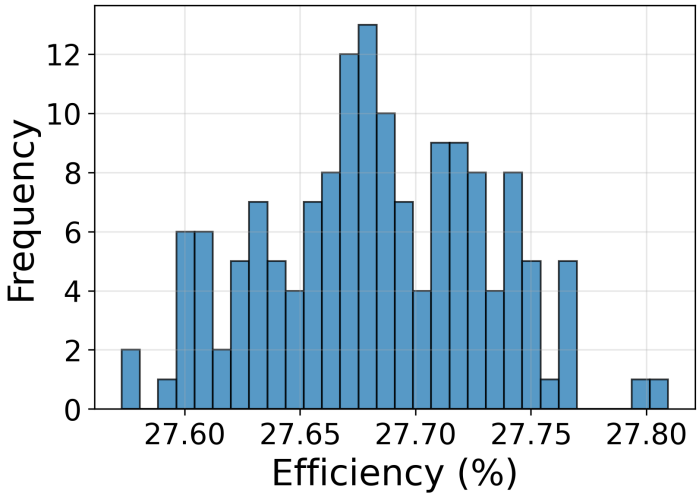
Pilot Production Data

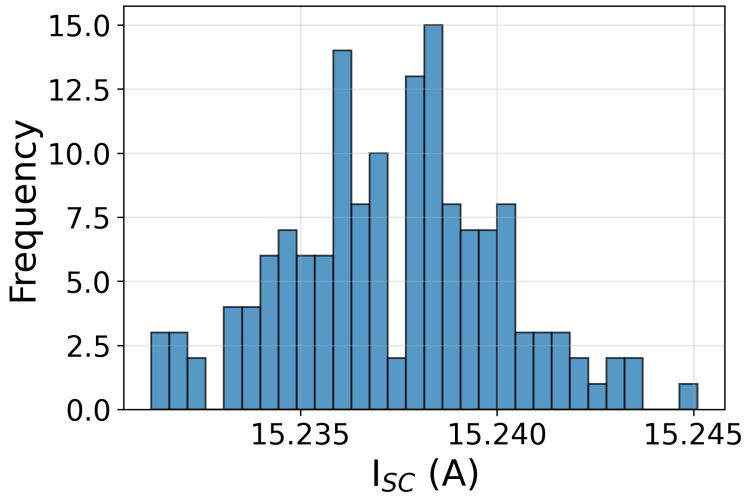


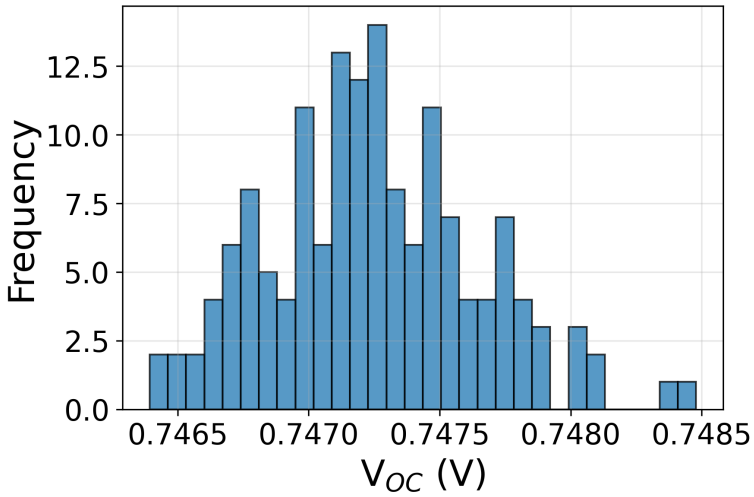


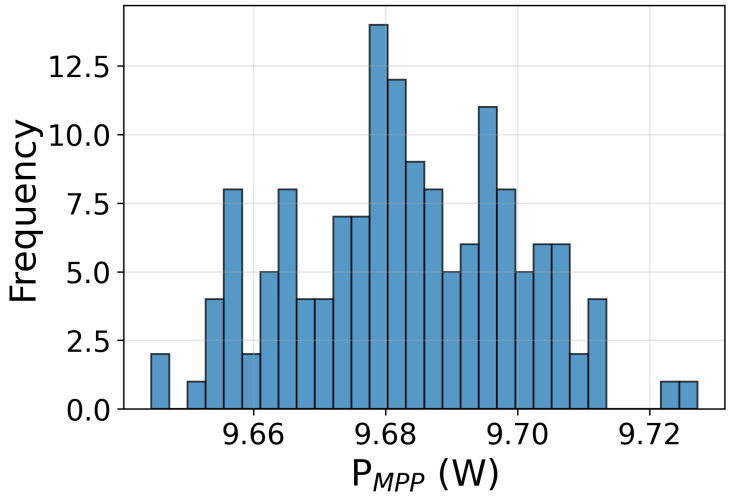


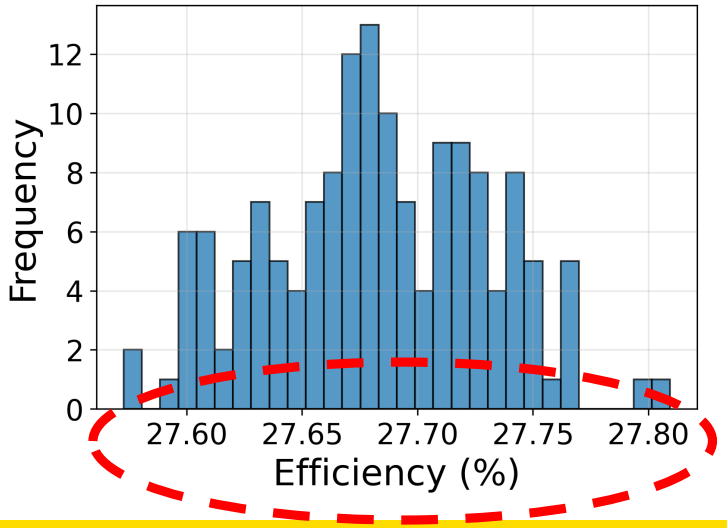


Pilot Production Data

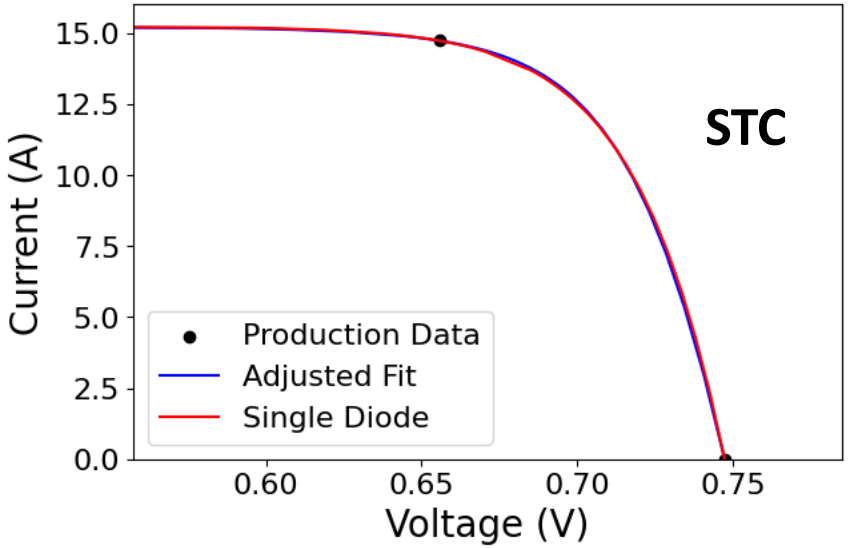


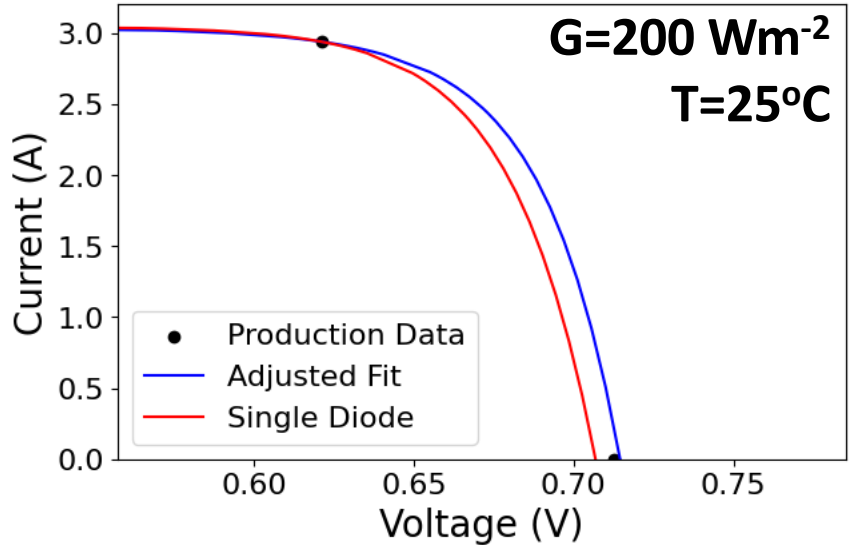


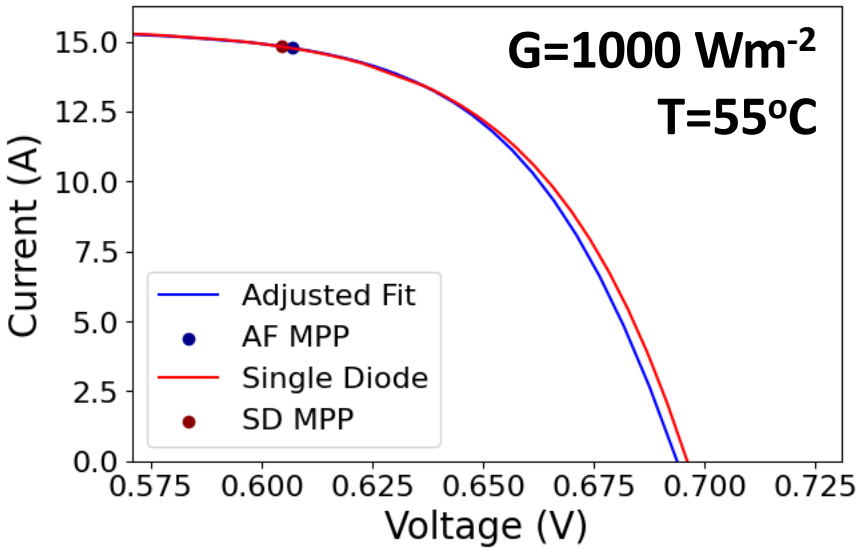




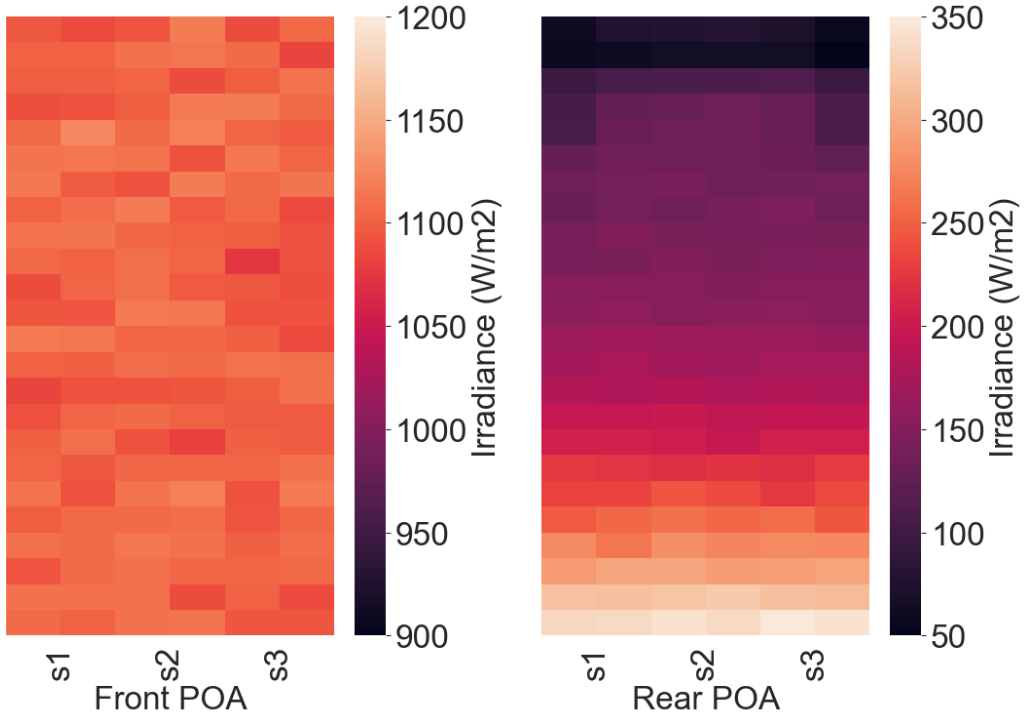
Fitting Results

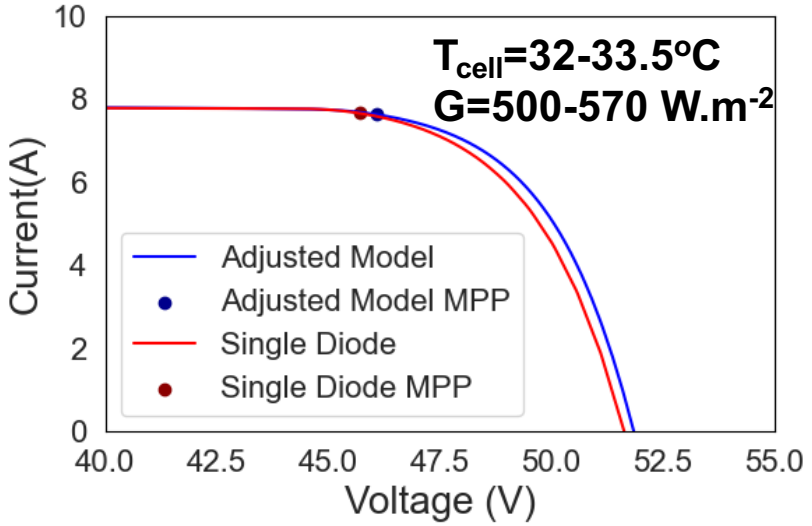


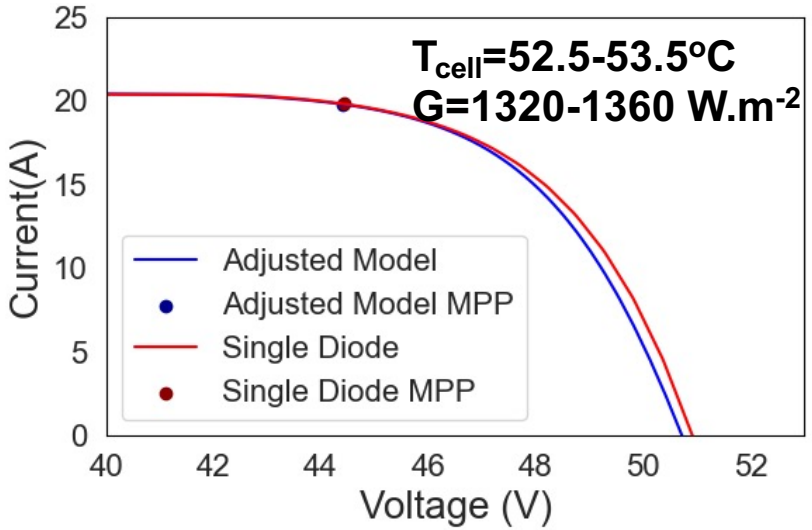




Convert to Module - SunSolve

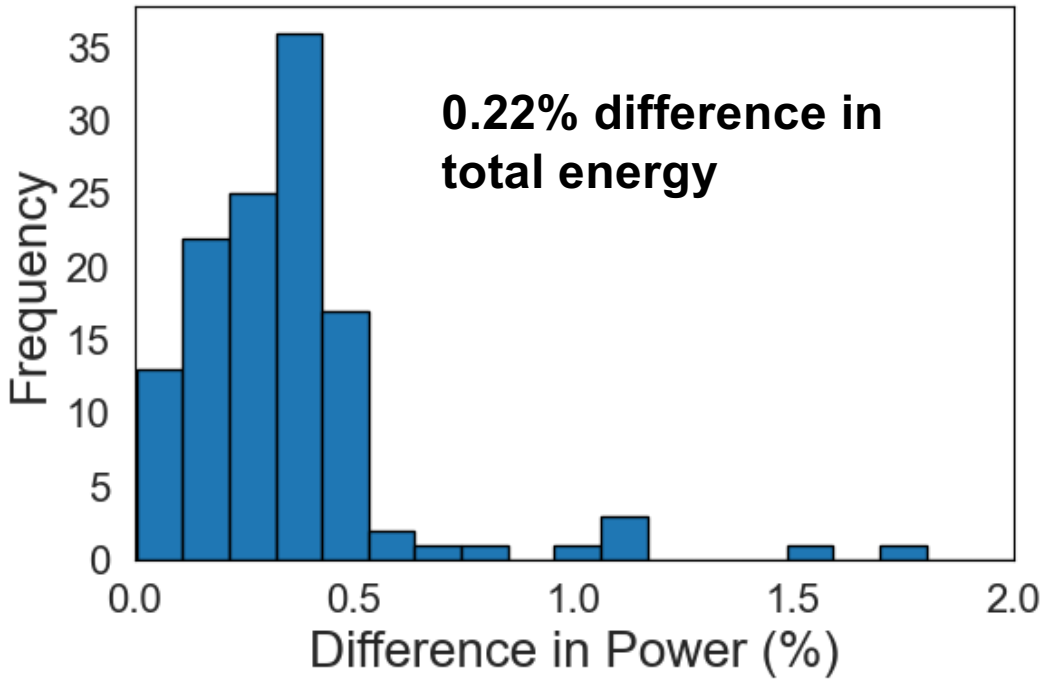


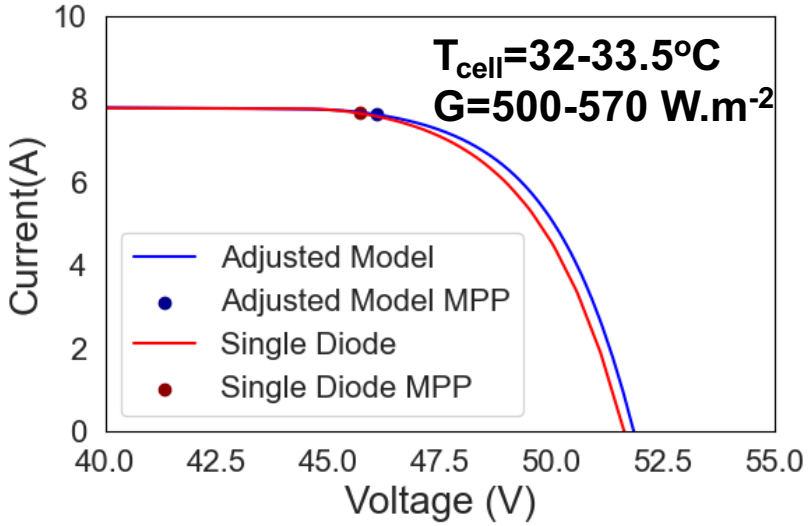


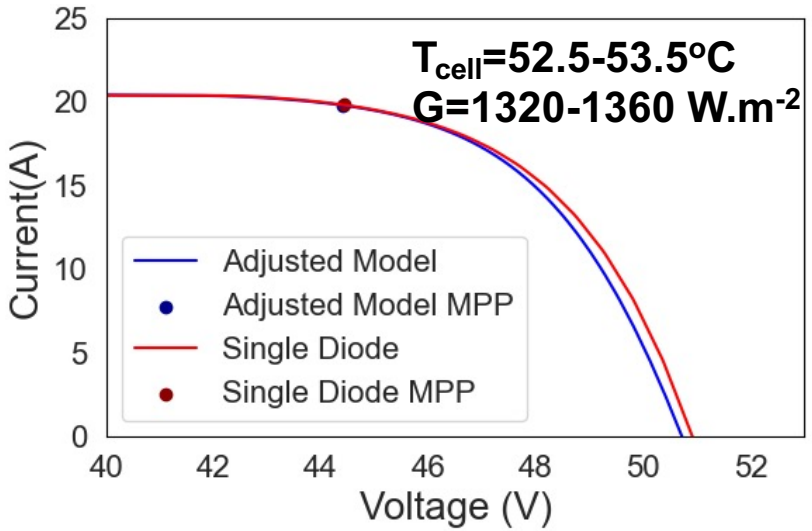


PVLighthouse, SunSolve Yield,
https://www.pvlighthouse.com.au/sunsolve-yield/,

Convert to Module - SunSolve



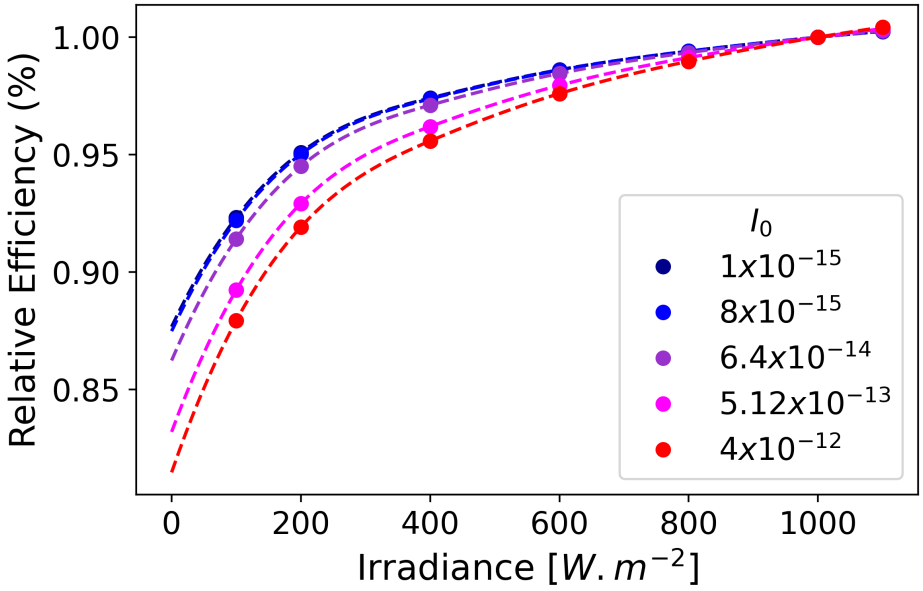




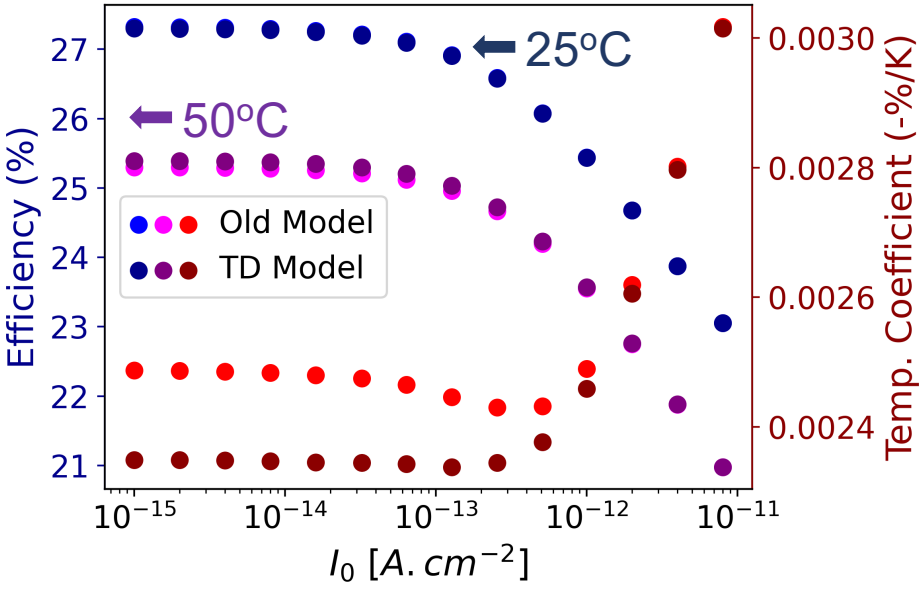
PVLighthouse, SunSolve Yield,
https://www.pvlighthouse.com.au/sunsolve-yield/,

Implications of the Model

Low Light Performance



Temperature Performance



I_0 = the dark saturation current of the residual diode

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Summary and acknowledgement

- Silicon solar cells are rapidly approaching the intrinsic limit
- Explicitly accounting for intrinsic recombination allows more accurate fitting of the *entire* IV curve
- This has implications for simulations of V_{OC} and under mismatch conditions

We want to hear about PV modelling challenges!

p.hamer@unsw.edu.au

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