

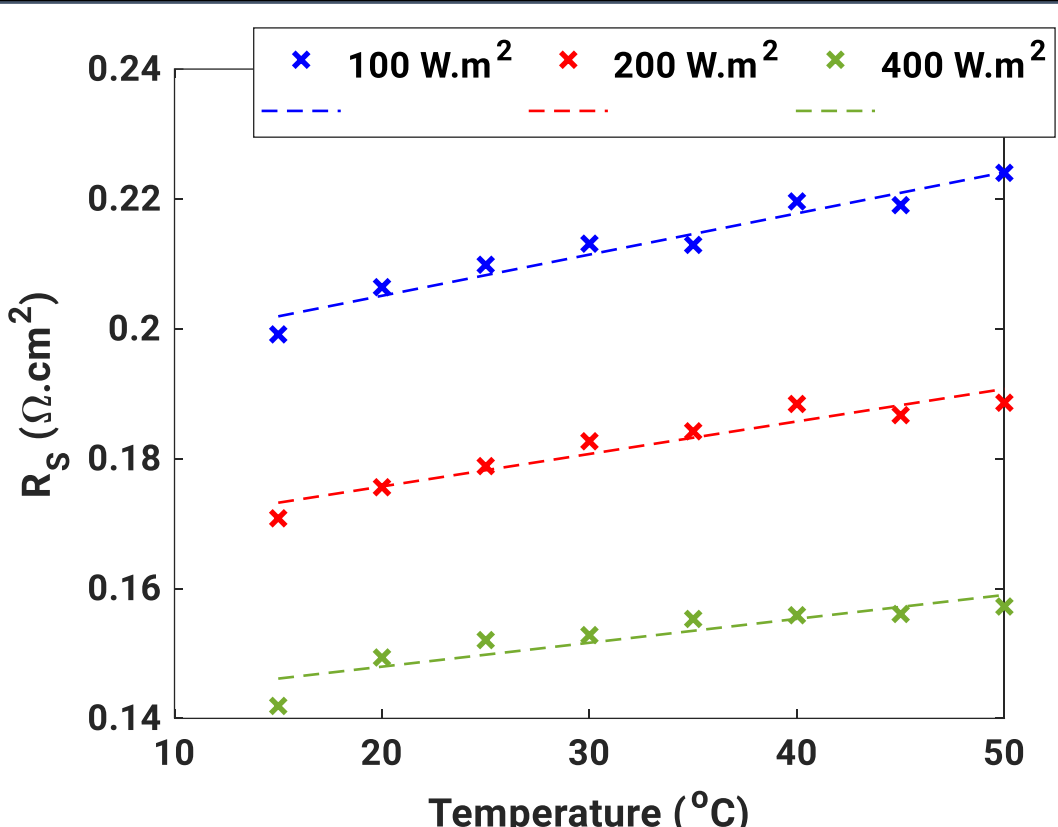
Ultra-High Efficiency Modules: The end of the single-diode model?

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Introduction

- Module technology is undergoing rapid evolution, with the PERC technology to be replaced by n-TOPCon and heterojunction (HJT) with cell efficiencies >26% in the next few years^[1].
- A key feature of these devices is extremely low carrier recombination, both in the silicon bulk and at the surfaces/contacts. This means that the solar cell is increasingly limited by intrinsic recombination, resulting in a significant boost to fill factor^[2].
- This presents a challenge for yield simulation^[3]. This poster investigates how well single-diode models can describe ultra-high efficiency cells, and how this can be improved by adjusting the fitting process to account for intrinsic recombination.

Methodology



This work focusses on fitting of solar cells, which can then be used to determine module parameters. The dataset for this study was simulated data from Quokka3^[4]. Simulations were performed using a model of the *previous* world record cell, with a 26.81% conversion efficiency under STC conditions. Data fitting for individual I-V curves was performed using the '2/3-Diode Fit' package^[6]. This package attempts to minimize the root mean square error (RMSE), rather than accuracy at MPP.

For several fitting processes, the series resistance is determined separately. We used the method of Bowden *et al.*^[7], as shown in Figure 1, to obtain an R_s value of 0.18 $\Omega.cm^2$ for STC, which is used unless otherwise stated.

Results are presented based on root-mean-square error, normalized by photocurrent (Normalized RMSE) and percentage difference in maximum power (MPP difference).

Figure 1: Plot of extracted R_s vs. temperature and low light intensity curve used in calculations

The Traditional Single-Diode Model

- High FF $\rightarrow$ single-diode model cannot accurately track MPP and V_{oc}
- This creates a trade-off:

Track MPP	Minimize RMSE
Good accuracy for MPP (Fig. 2D)	Error in MPP 0.5-2% (Fig. 4)
Error in Temperature coefficient for V_{oc} (Fig. 2B)	RMSE and V_{oc} acceptable between 20-50°C
Normalized RMSE between 3-10% (Fig. 2C)	Poor performance at low irradiances and high temperatures
Non-physical value of R_s (0.218 $\Omega.cm^2$)	Use "measured" R_s

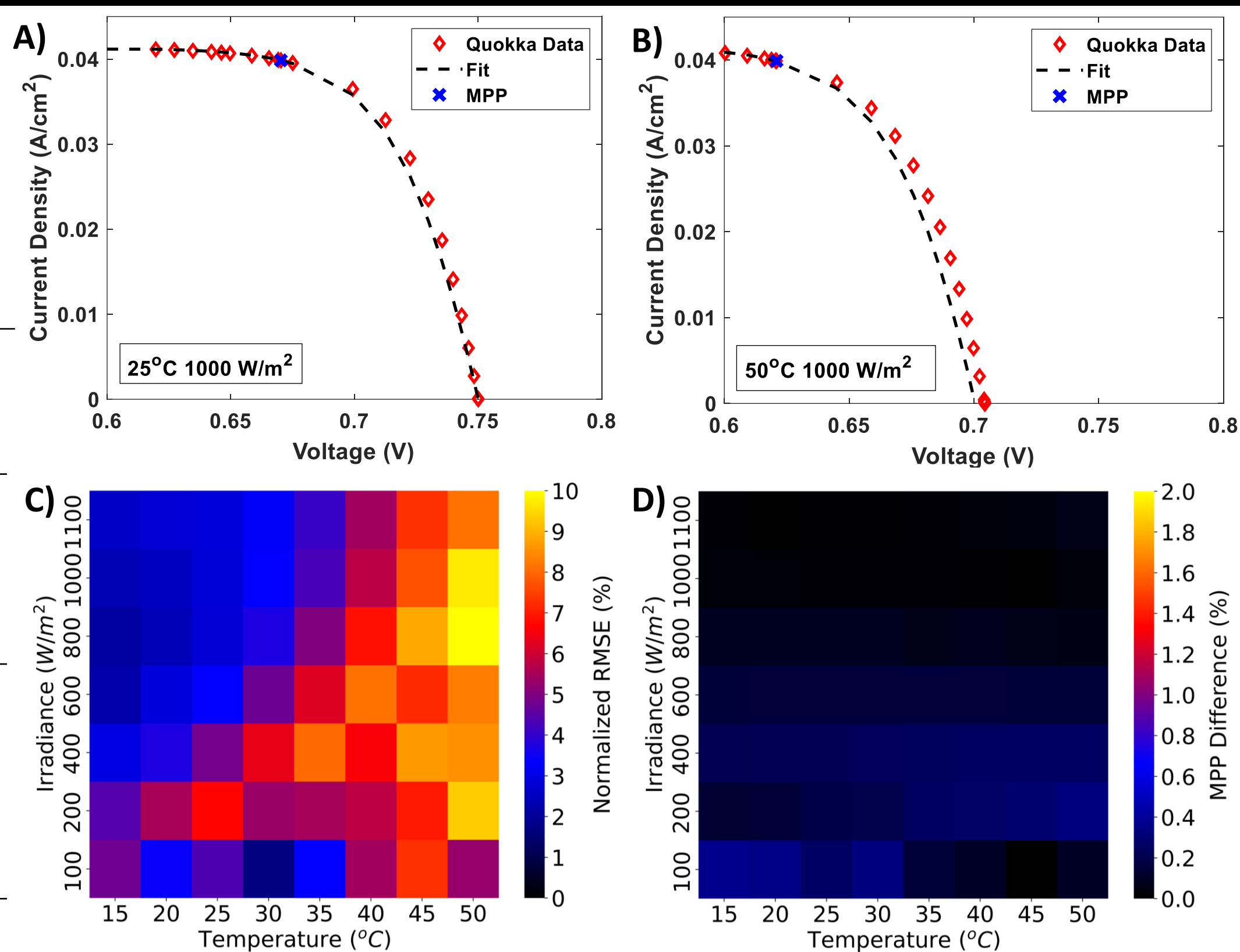
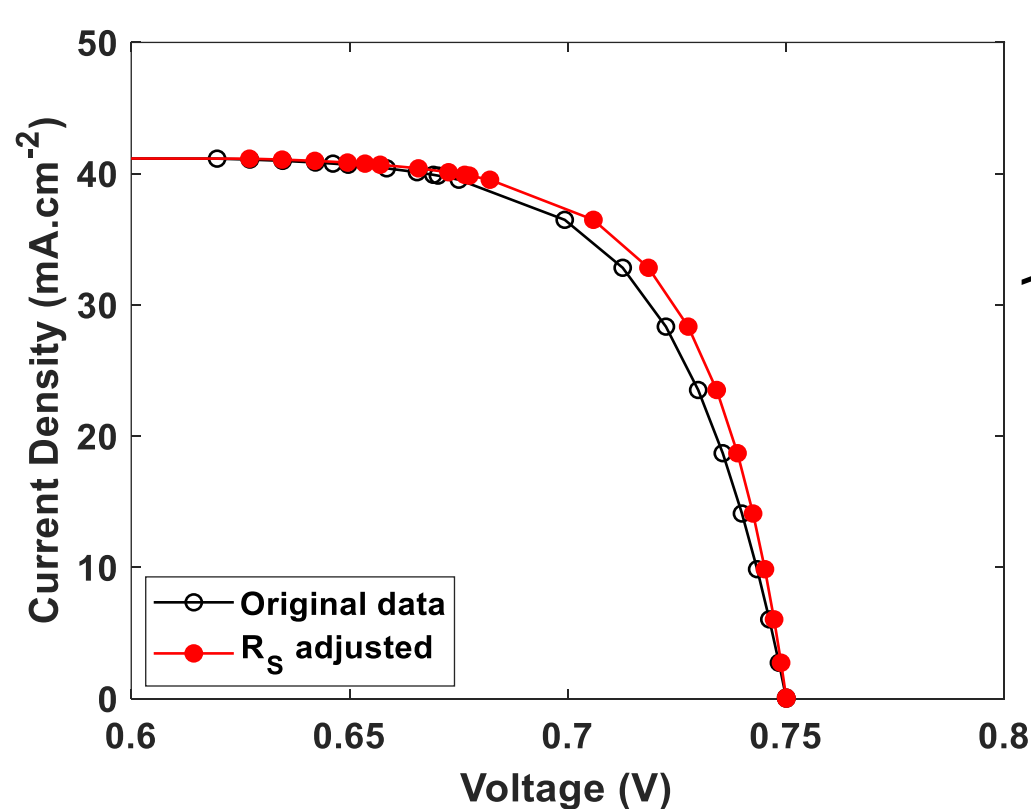


Figure 2: Results for the single-diode model configured for max. accuracy in MPP. A) Data and fit at STC, B) Data and fit at 50°C 1 sun, C) Normalized RMSE and D) MPP Difference for T=15-50°C and G=100-1100 W/m². Note that the scale for the normalized RMSE is double that elsewhere.

Adjusting for Intrinsic Recombination

Studies on recombination mechanisms within silicon have dealt with intrinsic recombination for decades, with improved parameterizations developed every few years^[8]. It is standard practice to adjust any recombination lifetime measurement to remove intrinsic effects. We apply a similar approach here. The steps of this fitting process are:

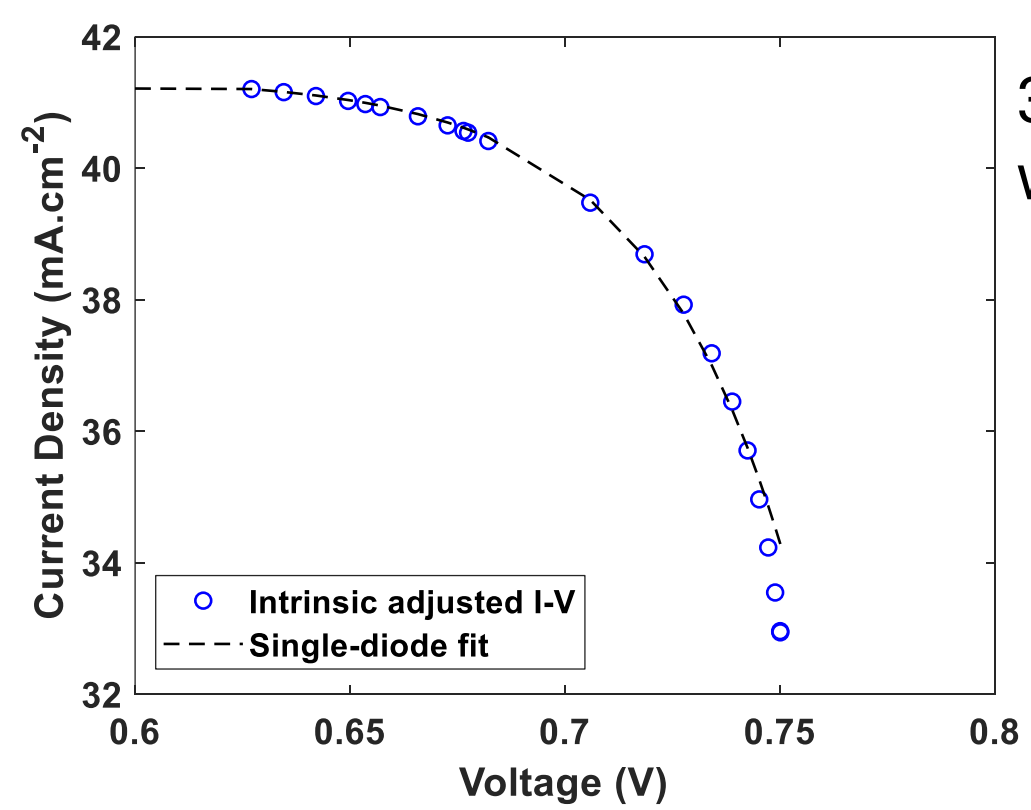


- Determine R_s and adjust voltage:

$$V_{adj} = V_{meas} + IR_s$$

- Calculate the recombination current due to intrinsic processes. Adjust current:

$$I_{adj} = I_{meas} + I_{auger,high_injection} + I_{auger,low_injection} + I_{radiative}$$



- Fit adjusted I-V dataset using the simple single-diode model, with R_s set to 0:

$$I_{adj} = I_{ph} - I_0 \left(e^{\frac{qV_{adj}}{nkT}} - 1 \right) - \frac{V_{adj}}{R_{SH}}$$

- Re-introduce the intrinsic recombination currents and R_s . An initial fit is performed at STC, with a secondary fit at 45°C, 1000 W.m⁻² to get the temperature dependence of n and I_{ph} .

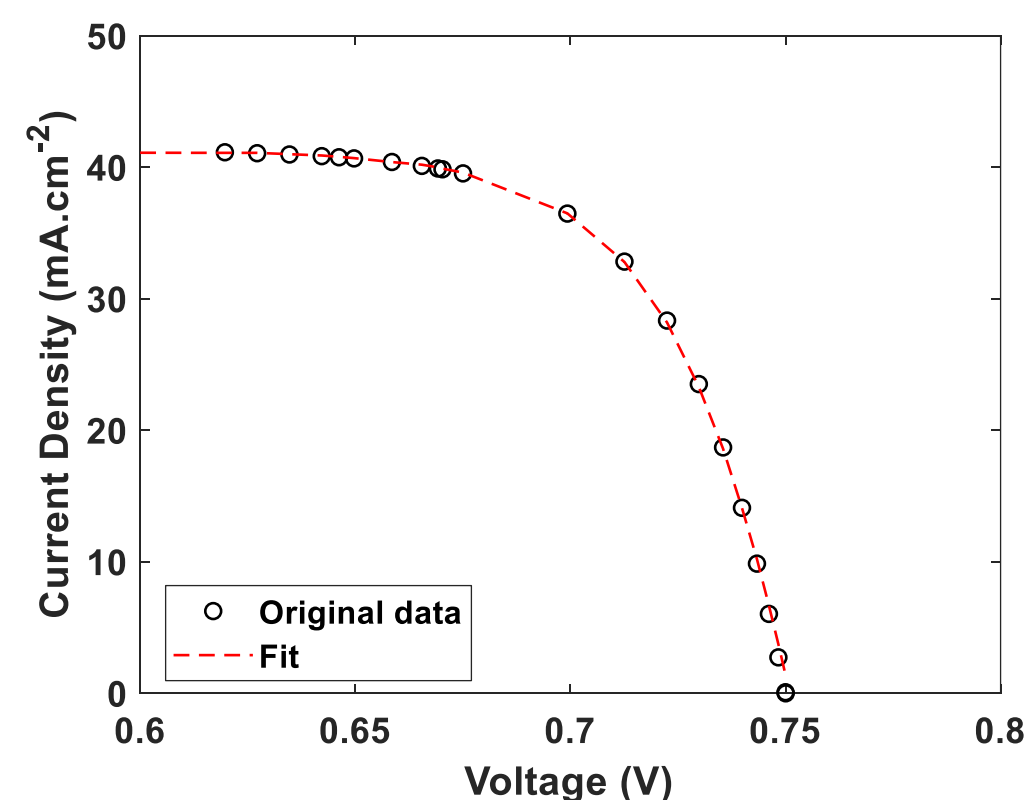
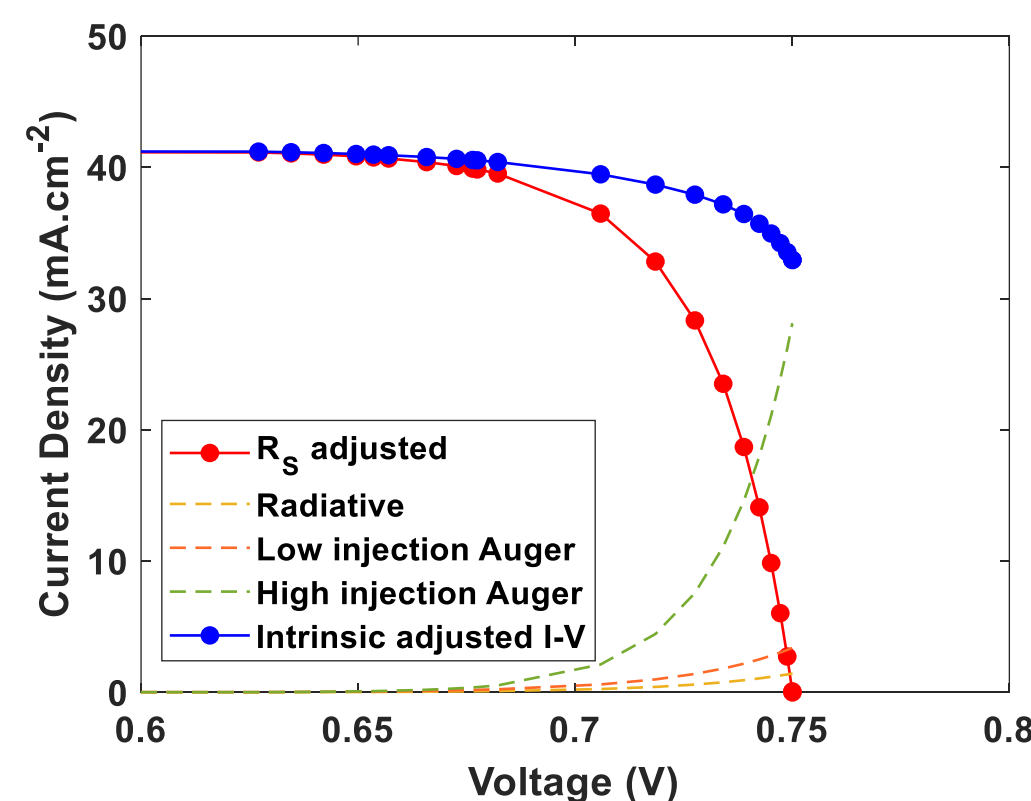


Figure 3: Fitting process for the adjusted single-diode model. Values for intrinsic recombination at STC from Lin *et al.*^[9]. Changes in intrinsic recombination with temperature/irradiance dependant solely on intrinsic carrier density as calculated following Couderc *et al.*^[10].

Results

Results are presented in Figure 4 below comparing results with and without the adjustment for intrinsic recombination. A further set of results is added for the case where the R_s value varied linearly with temperature, as derived from the I-V curves via the Bowden method above. The adjustment process clearly improves both the accuracy at MPP and the normalized RMSE values.

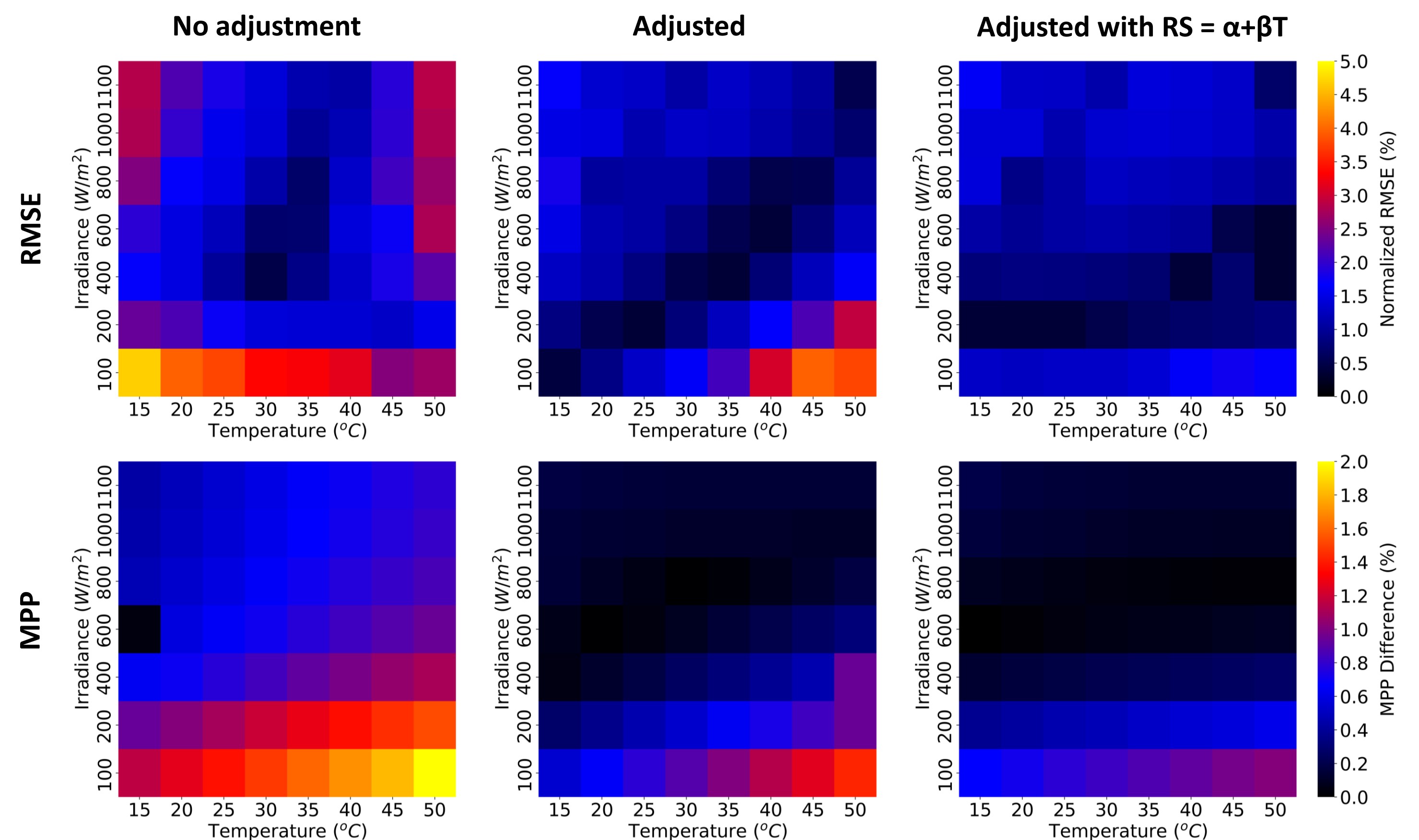


Figure 4: Normalized RMSE (top row) and MPP Difference (bottom row) for different models at T=15-50°C and G=100-1100 W/m².

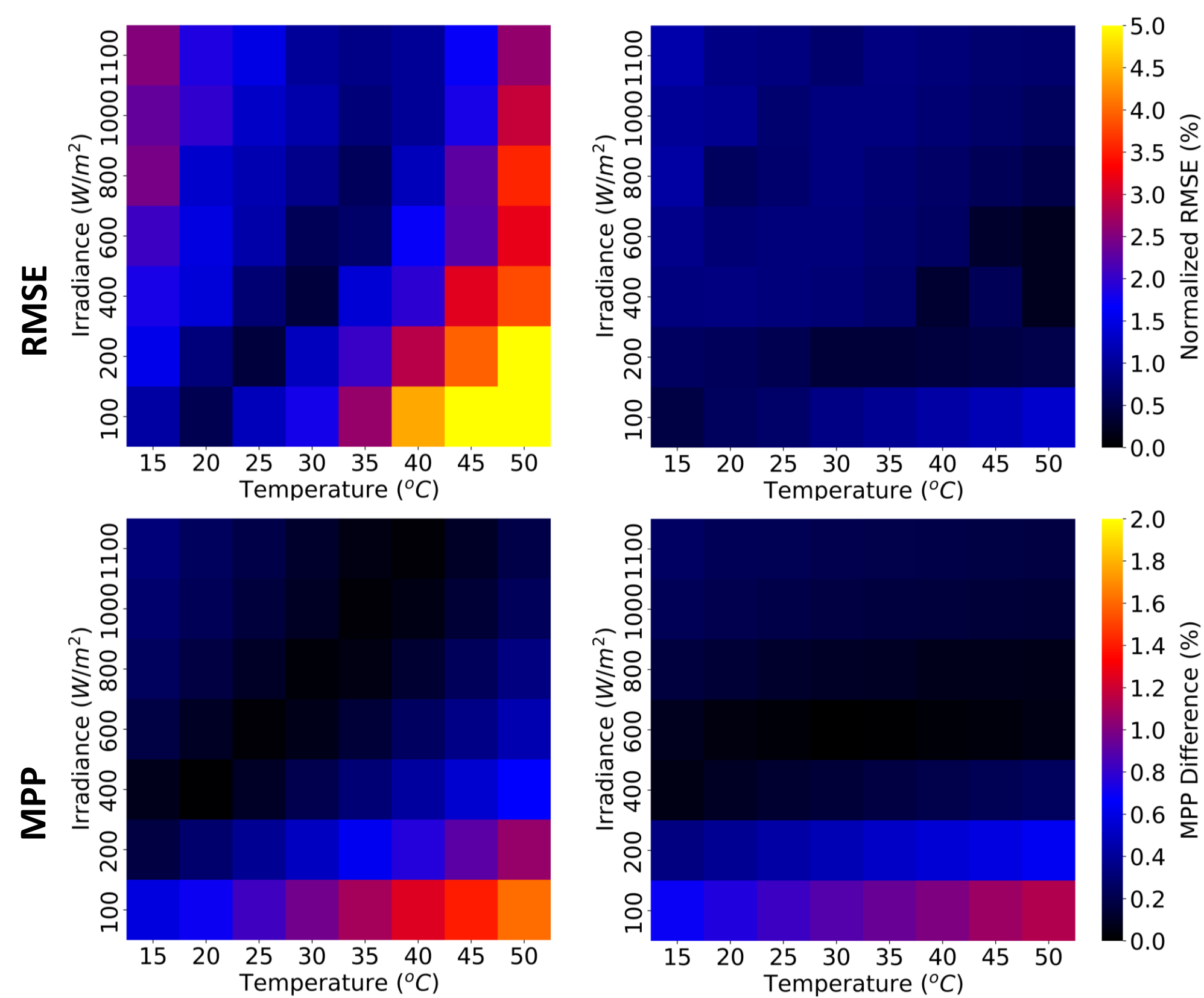
To calculate the intrinsic recombination we need:

- Cell thickness (important)
- Base doping (less important)

What happens if we don't know cell thickness exactly?

Figure 5 presents results when the intrinsic recombination currents are changed by $\pm 5\%$, equivalent to a similar change in cell thickness

Figure 5: Normalized RMSE (top row) and MPP Difference (bottom row) for fits where the intrinsic recombination was varied by $\pm 5\%$.



Conclusion and Future work

- Significant improvement in fitting accuracy when process is adjusted to account for intrinsic recombination
- Fitting to a simulation $\therefore$ intrinsic recombination behaves nicely. Actual temperature dependence for intrinsic recombination unverified
- Curve fitting (step 3) based on least squares, not weighted to MPP. Other methods to be explored
- Translation to module level and comparison of cell-level and module-level description to be carried out

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Acknowledgements

The authors would like to thank Pheng Phang and Daniel MacDonald from the Australian National University for supplying their Quokka model for the HJT cell. This work is supported by the Australian Centre for Advanced Photovoltaics (ACAP) and received funding from the Australian Renewable Energy Agency (ARENA). This project has also been assisted by the NSW Government through its Environmental Trust.

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