ASIA-PACIFIC SOLAR RESEARCH CONFERENCE

PEER REVIEWED
ASIA-PACIFIC SOLAR RESEARCH CONFERENCE

Improving the Accuracy of Fill Factor Empirical Expressions for Modern Industrial Solar Cells

Gaia Maria Javier, Yoann Buratti, Priya Dwivedi, Thorsten Trupke, and Ziv Hameiri

The University of New South Wales, Sydney, Australia

The fill factor (*FF*) is one of the most critical parameters in assessing the performance of solar cells.[1] Identifying the different loss mechanisms associated with the *FF* assists researchers and manufacturers in improving the efficiency of their cells.[2]

Empirical expressions that correlate the *FF* with other key electrical parameters have been developed by Green.[3–5] They determine the *FF* using the normalised values of the open-circuit voltage (V_{oc}), series resistance (R_s), and shunt resistance (R_{sh}) as defined in Table I. Green obtained the expressions by simulating current-voltage (*I-V*) curves using the one-diode model[4] with a broad range of parameters,[5] wider compared to the current industrial range. Thus, there may be gaps when these expressions are used in predicting the *FF* of modern industrial solar cells. This study, therefore, aims to: (1) recalculate the empirical coefficients assuming the typical ranges of electrical parameters in solar cell production lines, and (2) assess the suitability of the developed expressions to determine the measured *FF* of modern industrial solar cells.

Table I. Normalised electrical parameters

Variable	Description	Formula
$\boldsymbol{v_{oc}}$	normalised V_{oc}	V_{oc}/nV_T, where n is the ideality factor and V_T is the thermal voltage
$\boldsymbol{R_{ch}}$	characteristic resistance	V_{oc}/I_{sc}, where I_{sc} is the short-circuit current
$\boldsymbol{r_s}$	normalised R_s	R_s/R_{ch}
$\boldsymbol{r_{sh}}$	normalised R_{sh}	R_{sh}/R_{ch}

A total of 750,000 *I-V* curves were simulated using the pvlib library[6] in Python. The *I-V* curves were generated based on the one-diode model:

$$I = I_L - I_0\left[exp\left(\frac{V + IR_s}{nV_T}\right) - 1\right] - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{1}$$

where I_L is the light generated current, I_0 is the dark saturation current, n is the ideality factor, V is the voltage, and I is the current. Two ranges of inputs are used: (1) the original ranges of Green,[5] and (2) the ranges of solar cells from our industry partners. The *FF*, as well as the V_{oc} and I_{sc}, are then extracted from the resulting *I-V* curves.

Analytical expressions for the *FF* are listed in Table II. FF_0 refers to the *FF* in the absence of resistance effects. FF_s accounts for the effect of the series resistance; FF_{sh} accounts for the effect of the shunt resistance; and FF_{pred} accounts for both. Empirical coefficients, represented as C_x in Table II, were fitted using the non-linear least squares method.[7] The accuracy of the empirical expressions was determined by the relative mean absolute error (RMAE) as defined in Equation 2. Lower RMAEs signify more accurate expressions.

$$\text{RMAE} = \frac{1}{N}\sum\left|\frac{FF_{\text{pred}} - FF_{\text{act}}}{FF_{\text{act}}}\right| \tag{2}$$

where N is the number of samples; FF_{pred}, as previously mentioned, is the predicted *FF* using the empirical expression accounting for both the shunt and series resistance; and FF_{act} is the measured/simulated value.

The fitting limits and the extracted coefficients are summarised in Table II. Despite the slight variations in C_3 and C_4, similar coefficients were derived using the original ranges of Green.[5] The difference in the computed C_4 could come from rounding errors while the difference in the computed C_3 still needs to be investigated. As modern industrial cells are associated with higher V_{oc}, lower R_s, and higher R_{sh} values, we also fitted the coefficients using the tuned electrical ranges. Note that the coefficients were calculated assuming a range of ideality factor ($1 \le n \le 1.2$). It was found that C_2 remains constant while the other coefficients marginally increase.

Table II. Fill factor empirical coefficients and limits

Explicit expression	Green's range			Industrial range	
	Limits of expression	Green's empirical coefficients	This work's empirical coefficients	Limits of expression	This work's empirical Coefficients
$FF_0 = \frac{v_{oc} - \ln(v_{oc} + C_1)}{v_{oc} + 1}$	$v_{oc} > 10$	$C_1 = 0.72$	$C_1 = 0.72$	$v_{oc} > 18$	$C_1 = 0.78$
$FF_s = FF_0(1 - C_2 r_s) + \frac{r_s^2}{C_3}$	$r_s < 0.4$ $r_{sh} > 2.5$	$C_2 = 1.1$ $C_3 = 5.4$	$C_2 = 1.1$ $C_3 = 6.3$	$r_s < 0.1$ $r_{sh} > 23$	$C_2 = 1.1$ $C_3 = 7.7$
$FF_{sh} = FF_0\left[1 - \frac{v_{oc} + C_4}{v_{oc}}\left(\frac{FF_0}{r_{sh}}\right)\right]$	$r_s + \frac{1}{r_{sh}} < 0.4$	$C_4 = 0.7$	$C_4 = 0.8$	$r_s + \frac{1}{r_{sh}} < 0.1$	$C_4 = 0.9$
$FF_{pred} = FF_s\left[1 - \frac{v_{oc} + C_4}{v_{oc}}\left(\frac{FF_s}{r_{sh}}\right)\right]$		$C_4 = 0.7$	$C_4 = 0.8$		$C_4 = 0.9$

The simulated and predicted *FF* values within the industrial range are compared in Fig. 1(a). Green's expressions yielded an RMAE of 0.019%, whereas the revised expressions showed a slightly lower RMAE of 0.016%. Hence, both expressions demonstrate low errors and can effectively predict the *FF* generated by the one-diode model up to the first decimal point (in %).

The explicit expressions were also applied on 15,000 *I-V* measurements from our industry partner's production line. The measured and predicted *FF* values are shown in Fig. 1(b). The RMAE for Green's and the recalculated coefficients are 0.658% and 0.646%, respectively. The deviation of the predicted values from the measurements indicates that the original and modified expressions do not capture all the actual fill factor losses. The additional losses could be attributed to: (1) an ideality factor above unity; (2) junction and/or edge recombination (a two-diode model behaviour); (3) the non-uniformity in the solar cell design (e.g. shading and recombination associated with the front grid); (4) additional non-uniform recombination due to the presence of material or processing induced defects; or (5) errors in the *I-V* measurements and therefore in the extracted experimental parameters. Figure 1(c) presents the predicted *FF* using the modified expressions for the case of $n > 1$. Here, 100 solar cells were randomly selected from the 15,000 cells. The effective ideality factor of these cells was estimated to be 1.05 using the Newton-Raphson method.[8] As can be seen, the modified expressions with $n = 1.05$ represent the measured *FF* more accurately with a lower RMAE of 0.138%.

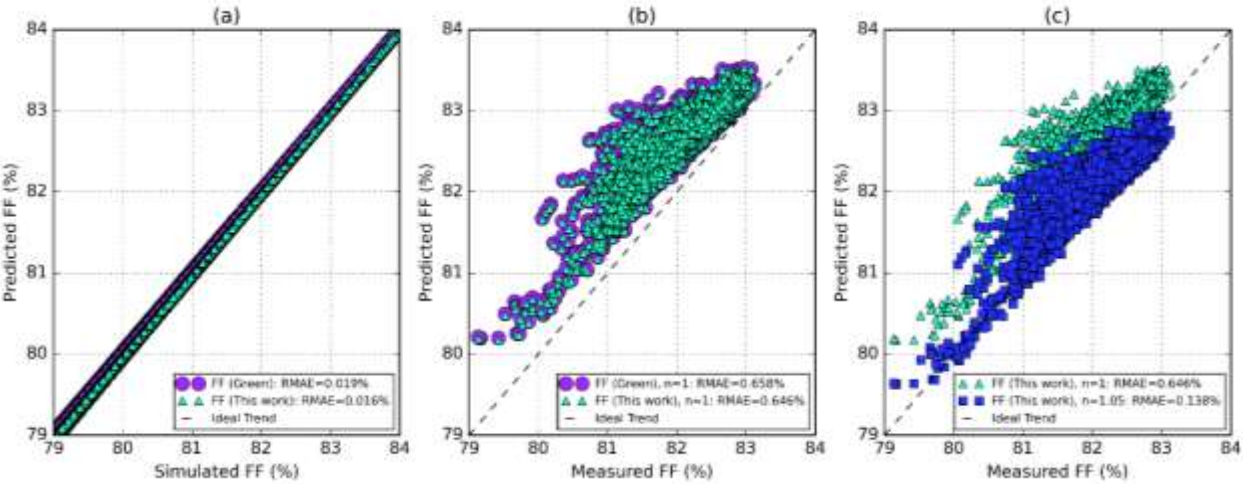

Figure 1. (a) Predicted *FF* as a function of the simulated *FF*, and predicted *FF* as a function of measured *FF* using empirical expressions with (b) $n = 1$, and (c) $n = 1.05$.

The empirical expressions were also used to investigate the impact of each variable on the *FF*. It was observed that V_{oc} and the ideality factor are crucial in setting the upper limit of the *FF* for a given solar cell. Additionally, R_s accounts for 97-99% of the resistive losses in the measured industrial solar cells.

Extending the expressions to include the two-diode model will be presented in the conference. We will also present our investigations using electroluminescence[9] and photoluminescence[10] images to correlate the deviation from the model with the non-uniformity of the cells.

To summarise, in this study, methods to modify Green's *FF* expressions for modern industrial solar cells were presented. Empirical coefficients were recalculated using the one-diode model in the typical parameter range of industrial cells. It is shown that the revised expressions predict the *FF* with an RMAE of 0.016%. Nevertheless, both the original and revised expressions have relatively large deviations (0.646-0.658%) when compared with actual measurements. Using the modified expressions with an ideality factor larger than unity reduces the RMAE to 0.138%. Future work will include developing empirical equations using the two-diode model and adding luminescence image metrics to account for the non-uniformity of the investigated cells. This study provides techniques to improve the prediction of *FF* in solar cell production lines, making it easier for manufacturers and researchers to optimize the performance of modern solar cells.

Acknowledgement
This work was supported by the Australian Government through the Australian Renewable Energy Agency [ARENA Project 2020/RND016]. The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

References

1. M. A. Green, 2016, "Accurate expressions for solar cell fill factors including series and shunt resistances," *Appl. Phys. Lett.*, 108, p081111.
2. A. Khanna, T. Mueller, R. A. Stangl, B. Hoex, P. K. Basu, and A. G. Aberle, 2013, "A fill factor loss analysis method for silicon wafer solar cells," *IEEE J. Photovolt.*, 3, p1170–1177.
3. M. A. Green, 1977, "General solar cell curve factors including the effects of ideality factor, temperature and series resistance," *Solid-State Electron.*, 20, p265–266.
4. M. A. Green, 1981, "Solar cell fill factors: General graph and empirical expressions," *Solid-State Electron.*, 24 , p788–789.
5. M. A. Green, 1982, "Accuracy of analytical expressions for solar cell fill factors," *Sol. Cells*, 7, p337–340.
6. W. F. Holmgren, C. W. Hansen, and M. A. Mikofski, 2018, "pvlib python: a python package for modeling solar energy systems," *J. Open Source Softw.*, 3, p. 884.
7. M. R. Osborne, 1976, "Nonlinear least squares — the Levenberg algorithm revisited*," *ANZIAM J.*, 19, p343–357.
8. J. Verbeke and R. Cools, 1995, "The Newton-Raphson method," *Int. J. Math. Educ. Sci. Technol.*, 26, p177–193.
9. T. Fuyuki, H. Kondo, T. Yamazaki, Y. Takahashi, and Y. Uraoka, 2005, "Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence," *Appl. Phys. Lett.*, 86, p262108.
10. T. Trupke, R. A. Bardos, M. C. Schubert, and W. Warta, 2006, "Photoluminescence imaging of silicon wafers," *Appl. Phys. Lett.*, 89, p044107.