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New guidelines for a more accurate extraction of solar cells and modules key data from their current–voltage curves

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ABSTRACT

This paper investigates the optimisation of the fit procedures to determine with the highest accuracy the key data of photovoltaic cells and modules from their current–voltage characteristics. Our analysis is based on numeric current–voltage curves obtained by solving the two-diode equation in steady state. The established state-of-the-art fit procedures, such as the ASTM E948-09 standard, are shown to be outperformed by smart adjustments of the fit range and the regression type. As a result of this optimisation, the accuracy in determining the short-circuit current density is improved by up to 15 times, the open-circuit voltage by 3 to 10 times and the maximum power by 4 to 5 times, in comparison to state-of-the-art approaches. It is demonstrated that the signal-to-noise ratio of the experimental data strongly influences the fit accuracy, and therefore, the fit criteria must be adjusted according to the noise level of the measuring unit. Finally, our fit procedures were applied to experimentally measured current–voltage curves of 3000 silicon heterojunction solar cells. Notably, the established fit standards are shown to overestimate the maximum power by up to 0.2%, whereas our proposed fit yields more consistent values. In conclusion, novel fit guidelines are provided, aiming at enhancing the key data determination of high-efficiency photovoltaic cells and modules. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS

ASTM E948-09 standard; fitting; I – V curve; key data; polynomials; power rating; crystalline silicon; solar cell

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1. INTRODUCTION

The accurate rating of photovoltaic (PV) cells and modules under standard test conditions is an essential part of their characterisation. The key data—namely, the short-circuit current density (J_{sc}), the open-circuit voltage (V_{oc}), and the nominal peak power (P_{mpp}) at maximum power point (MPP)—are extracted from the measured current–voltage (I – V) characteristic of the device under test (DUT). Accurate key data are of fundamental importance for PV devices manufacturers and customers. Continuous improvements nowadays allow certification institutes to achieve better than 2% accuracy on key data measurements for crystalline silicon-based PV devices [1]. There exist abundant literature and international standards precisely defining the appropriate way to conduct PV devices rating, especially

regarding spectrum and irradiance of the light source [2] [3] [4] [5], DUT temperature control and monitoring [2] [4] [6], contacting of the DUT [2] [7], reference cells [8] [9] [10], to name a few. In contrast, the post-processing of the I – V data themselves, that is, how J_{sc} , V_{oc} and P_{mpp} are actually extracted, is covered in much less extent, be it in research papers [11] [12] or in international standards [13] [7]. The only existing international standard precisely describing a procedure for the key data extraction is the ASTM E948-09 norm [13]. K. Emery from NREL suggested alternative fit ranges and procedures in [14]. Notably, neither the ASTM norm nor the NREL paper provides an estimation of the accuracy obtained following their fit guidelines. In contrast, Dimberger and Kräling provide in [1] an exhaustive determination of the key data measurement uncertainties at Fraunhofer ISE CalLab, but

the precise details regarding the key data extraction are undisclosed.

In our recent paper [15], the determination of PV cells and modules P_{mpp} from their I - V characteristics has been investigated. Our analysis was based on synthetic I - V curves generated by numerically solving the two-diode equation in steady-state conditions. A broad population of synthetic I - V curves with different shapes and key data was generated, and the accuracy and robustness of the ASTM, the NREL and our P_{mpp} fits were assessed on this device population. Frequent shortcomings of the ASTM and the NREL fits were observed, namely, an overestimation of P_{mpp} up to 0.25%. A novel fit procedure has been proposed and optimised, where the fit boundaries are defined by two independent thresholds expressed as a fraction of P_{mpp} , and no longer based on J_{mpp} and V_{mpp} boundaries as advocated by the ASTM norm [13]. As a major achievement, our fit procedure resulted in 3 to 4 times more accurate values of P_{mpp} than those obtained following the ASTM or the NREL guidelines. More importantly, our fit performed equally accurate regardless of the device fill factor (FF). In contrast, the ASTM and the NREL fits yield P_{mpp} values overestimated by more than 0.1% for devices with FF of 78% or higher. This overestimation has been shown to be linked to an improper choice of the range where P_{mpp} was fitted. The effect of the polynomial order on the fit accuracy was also investigated. Finally, our results were validated by measuring actual PV single cells and full modules. Further details can be found in [15].

This paper aims at completing our previous study by investigating in more details the fit procedures not only for P_{mpp} , but also for J_{sc} and V_{oc} . The fit parameters for J_{sc} , V_{oc} and P_{mpp} are optimised, and their sensitivity to the measurement noise is discussed. The results are then compared to the ASTM and the NREL procedures. As a case study, the validity and robustness of our approach are assessed one step further by testing it on I - V curves experimentally measured on 3000 commercial-grade 6-in silicon heterojunction (SHJ) solar cells. The key data obtained with our fits are benchmarked against those extracted using the ASTM and the NREL guidelines, and the peculiarities of each procedure are discussed. Finally, general recommendations aiming at enhancing the accuracy of the solar cells and modules key data extraction from their I - V characteristics are provided.

2. EXPERIMENTAL

2.1. Synthetic I - V curve generation

The main points of our approach, also presented in more details in [15], are summarised in the succeeding texts. Synthetic I - V curves are generated using the commercial software Matlab [16]. The starting point of our approach is to numerically solve the two-diode equation in steady state, according to (1).

$$J = J_L - J_{01} \left\{ \exp \left[\frac{q(V + JR_s)}{n_1 kT} \right] - 1 \right\} - J_{02} \left\{ \exp \left[\frac{q(V + JR_s)}{n_2 kT} \right] - 1 \right\} - \frac{V + JR_s}{R_p} \quad (1)$$

In (1), k is Boltzmann's constant, T the DUT temperature, J_L the light generated current density, J_{01} and J_{02} the first and second diode saturation current densities, respectively, n_1 and n_2 the associated ideality factors, R_p the shunt resistance and R_s the series resistance. V is the input vector containing the voltage values where (1) is to be solved, and J is the output vector containing the calculated current density values for each element in V . In all the following, we set T to 298 K, n_1 to 1 and n_2 to 2. Note that we verified that the results presented in this paper and in [15] remain valid for $n_1 > 1$ and $n_2 > 2$ values. The vector V takes values between -0.5 and 1.0 V, with a sampling frequency of 1 mV^{-1} . Once known V and J , the full I - V curve is reconstructed. Moreover, solving the two-diode equation (1) for the specific case $V=0$ (resp. $J=0$), the theoretical value of J_{sc} (resp. V_{oc}) is determined. Finally, the theoretical value of P_{mpp} is extracted, and the FF is calculated. These values are named $J_{sc,th}$, $V_{oc,th}$, $P_{mpp,th}$ and FF_{th} , respectively. Note that the accuracy in determining the actual values of $J_{sc,th}$, $V_{oc,th}$, $P_{mpp,th}$ and FF_{th} is given by the numerical accuracy of the Matlab solving algorithms and is well below $10^{-5}\%$.

Applying this model, a virtual population of 500 I - V curves whose two-diode parameters (J_L , J_{01} , J_{02} , R_s , R_p) are randomly chosen into representative ranges for crystalline silicon-based solar cells is generated (see [15] and the references therein). The resulting distributions for $J_{sc,th}$, $V_{oc,th}$, FF_{th} and $P_{mpp,th}$ are plotted in Figure 1.

White Gaussian noise with variance σ_J is afterwards added to the current vector J to simulate the effects of an actual measurement. The noise vector on J is noted $J_{noise}(\sigma_J)$. The signal-to-noise ratio (SNR) in decibel (dB) for the current vector J is then calculated as:

$$SNR_{dB} = 10 \times \log_{10} \left(\frac{\overline{J^2}}{J_{noise}^2(\sigma_J)} \right) \quad (2)$$

Similarly, the noise vector for the voltage channel ($V_{noise}(\sigma_V)$), with variance σ_V , and the corresponding SNR, are calculated. The resulting SNR as a function of σ_J and σ_V is plotted in Figure 2. The noised I - V curves under study feature a wide variety of shapes and key data and serve as basis throughout this paper to evaluate the accuracy and the robustness of the ASTM, the NREL and our fit procedures in determining the key data.

2.2. Fit procedures for J_{sc} , V_{oc} and P_{mpp}

Table I details the fit ranges and methods used to extract J_{sc} , V_{oc} and P_{mpp} , according to the ASTM and the NREL guidelines, as well as the ones proposed in [15] and further

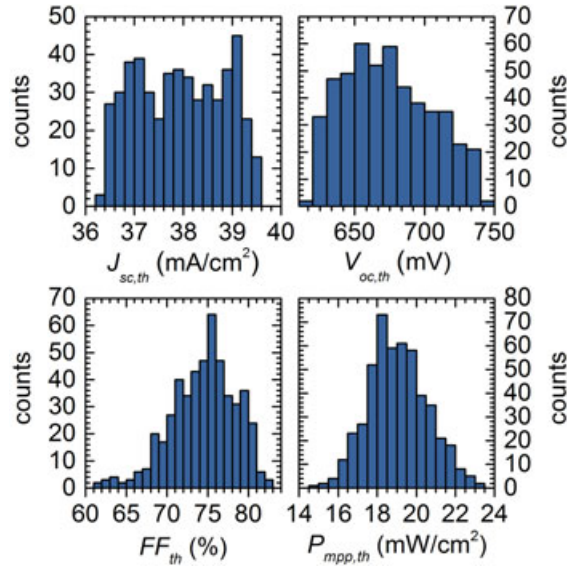


Figure 1. Histograms of the theoretical values of J_{sc} , V_{oc} , FF and P_{mpp} for the 500 synthetic *I-V* curves under study. [Colour figure can be viewed at wileyonlinelibrary.com]

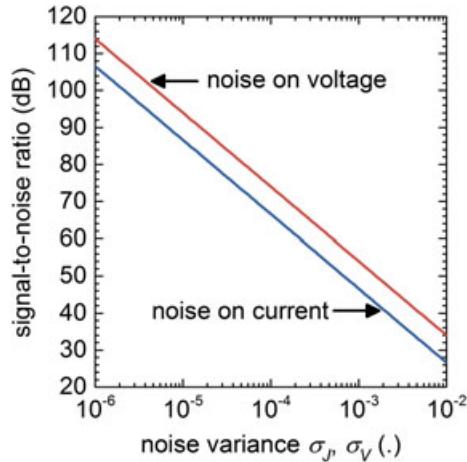


Figure 2. Resulting signal-to-noise ratio as a function of the noise variance. [Colour figure can be viewed at wileyonlinelibrary.com]

investigated in this paper. Each procedure is now briefly discussed and compared.

Regarding J_{sc} fit, ASTM proposes the simplest approach, namely, a linear interpolation of the two (J , V) points closest to zero voltage. NREL also recommends a linear fit but includes more data points in the fit range. We propose as well to use a linear fit, but on a somewhat different voltage range, namely, $\alpha \times V_{mpp} \leq V \leq \beta \times V_{mpp}$, where $-0.5 \leq \alpha < 0$ and $0 < \beta \leq 1$.

The ASTM and the NREL guidelines for V_{oc} fit are quite similar to those for J_{sc} : they both use a linear fit, on the two (J , V) points bracketing zero current in the case of ASTM,

and on a larger range in the case of NREL. In contrast, we compare the use of a linear vs. a second-order polynomial fits, on (J , V) points fulfilling the condition $\gamma \times J_{mpp} \leq J \leq \delta \times J_{mpp}$, where $-0.25 \leq \gamma < 0$ and $0 < \delta \leq 0.5$.

In the case of P_{mpp} , the ASTM fit and ours use a fourth-order polynomial fit, whereas NREL recommends the use of a polynomial fit of the fourth-order or higher. The major differences arise regarding the fit range: indeed, the ASTM norm defines the P_{mpp} fit range on (J , V) points based on V_{mpp} and J_{mpp} fractions. In contrast, following NREL, we define the P_{mpp} fit range on (P , V) points as a function of P_{mpp} fraction. However, whereas NREL uses a single P_{mpp} threshold, our P_{mpp} fit range is defined by two independent thresholds: $a_0 \times P_{mpp}$ for voltages smaller than V_{mpp} and $b_0 \times P_{mpp}$ for voltages greater than V_{mpp} , where a_0 and b_0 take values between 0 and 1.

For each guideline, the extracted key data are compared to the theoretical values (determined by solving the two-diode equation, see Section 2.1), and the absolute errors are calculated according to (3).

$$\varepsilon(X) = \left| \frac{X_{fit} - X_{th}}{X_{th}} \right| \quad (3)$$

In (3), $X = J_{sc}$, V_{oc} , or P_{mpp} . The mean value and the standard deviation of $\varepsilon(X)$, calculated on the 500 *I-V* curves under study, are also reported and noted $\bar{\varepsilon}(X)$ and $\sigma(\varepsilon(X))$, respectively.

2.3. Actual measurements of silicon heterojunction solar cells

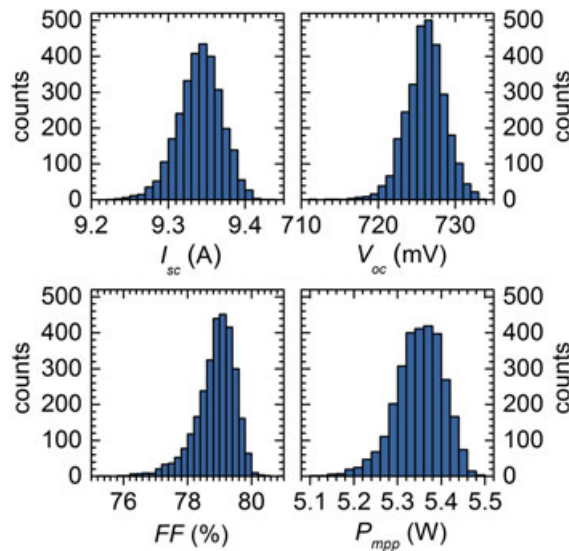
A total of 3000 6-in, commercial-grade SHJ solar cells were measured at our facilities using a class AAA Wacom steady-state solar simulator equipped with a Grid^{TOUCH} contacting system [17] in standard test conditions at 25 °C under AM1.5G equivalent illumination. The SNR is higher than 80 dB for our experimental set-up. The measured *I-V* curves are afterwards fitted with the ASTM, the NREL and our fit procedures, as described in Table I (Section 2.2), and the key data are extracted and compared. The histograms of the short-circuit current (J_{sc}), V_{oc} , FF and P_{mpp} values obtained using our fit criteria are displayed in Figure 3. The SHJ devices under study are tightly distributed around mean values of $J_{sc} = (9.34 \pm 0.06)$ A, $V_{oc} = (726 \pm 5)$ mV, $FF = (79 \pm 1)$ % and $P_{mpp} = (5.3 \pm 0.1)$ W.

As the actual values of the key data are not known *a priori* for these 3000 solar cells, the differences $\Delta^{ASTM}(X)$ between the key data determined using the ASTM guidelines and those using our fit criteria are calculated following equation (4), where $X = J_{sc}$, V_{oc} , or P_{mpp} . Similarly, the differences $\Delta^{NREL}(X)$ between the NREL fits and ours are calculated.

$$\Delta^{ASTM}(X) = \frac{X^{ASTM} - X^{this\ work}}{X^{this\ work}} \quad (4)$$

Table 1. Overview of the fit ranges and methods under study used to determine the solar cells and modules key data from their current–voltage curves.

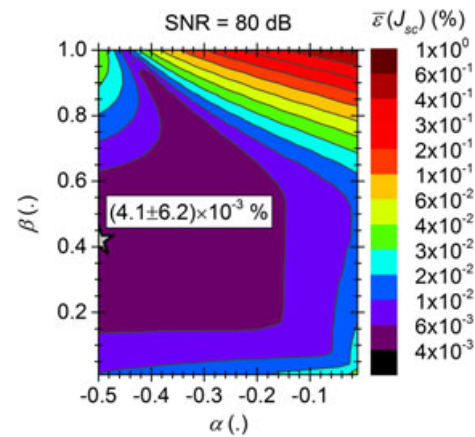
	Ref. Year	ASTM [13] 2009	NREL [14] 2011	This work 2016
J_{sc} fit	Type	Linear	Linear	Linear
	Range	Two (J, V) points closest to zero voltage	(J, V) points such that $ J < 0.04 \times J_{V=0}$ $ V < 0.2 \times V_{J=0}$	(J, V) points such that $\alpha \times V_{mpp} \leq V \leq \beta \times V_{mpp}$ with $-0.5 \leq \alpha < 0$ and $0 < \beta \leq 1$
V_{oc} fit	Type	Linear	Linear	Linear or second-order polynomial
	Range	Two (J, V) points closest to zero current	(J, V) points such that $ J < 0.2 \times J_{V=0}$ $ V < 0.1 \times V_{J=0}$	(J, V) points such that $\gamma \times J_{mpp} \leq J \leq \delta \times J_{mpp}$ with $-0.25 \leq \gamma < 0$ and $0 < \delta \leq 0.5$
P_{mpp} fit	Type	Fourth-order polynomial	\geq Fourth-order polynomial	Fourth-order polynomial
	Range	(J, V) points such that: $0.75 \times V_{mpp} < V < 1.15 \times V_{mpp}$ $0.75 \times J_{mpp} < J < 1.15 \times J_{mpp}$	(P, V) points such that: $P > 0.8 \times P_{mpp}$ $V > 0.8 \times V_{mpp}$	(P, V) points such that $P \geq a_0 \times P_{mpp}$ for $V < V_{mpp}$ $P \geq b_0 \times P_{mpp}$ for $V \geq V_{mpp}$ with $0 < a_0, b_0 < 1$

**Figure 3.** Histograms of the measured key data of 3000 6-in silicon heterojunction solar cells, determined using the fit criteria presented in this paper. [Colour figure can be viewed at wileyonlinelibrary.com]

3. RESULTS AND DISCUSSION

3.1. Short-circuit current density fit

Figure 4 plots the variation of $\bar{\epsilon}(J_{sc})$ as a function of the (α, β) boundaries in the case $SNR = 80$ dB. The minimum value of $\bar{\epsilon}(J_{sc})$ is obtained when $\alpha = -0.50$ and $\beta = 0.42$ and equals $(4.1 \pm 6.2) \times 10^{-3}\%$. Repeating this experiment for the other SNR values, the (α, β) boundaries minimising $\bar{\epsilon}(J_{sc})$ are determined in each case. The resulting minimum values of $\bar{\epsilon}(J_{sc})$ are plotted in Figure 5 and compared to the values obtained with the ASTM and the NREL fits.

**Figure 4.** Variation of the mean absolute error on J_{sc} ($\bar{\epsilon}(J_{sc})$) as a function of the (α, β) boundaries used for the fit range, in the case of a signal-to-noise ratio of 80 dB. The grey star indicates the position of the minimum for $\bar{\epsilon}(J_{sc})$. [Colour figure can be viewed at wileyonlinelibrary.com]

Overall, all fits perform better for higher SNRs, that is, lower noise level. Interestingly, in the no-noise limit (corresponding to the case $SNR \rightarrow \infty$), the ASTM fit, which uses only the two data points bracketing zero voltage to determine J_{sc} , performs the best. Nevertheless, this approach results very sensitive to noise, as the error given by the ASTM fit rapidly grows when the SNR decreases. Indeed, $\bar{\epsilon}(J_{sc})$ for the ASTM fit is already $7 \times 10^{-3}\%$ at 100 dB and up to 0.7% at 60 dB, whereas it is respectively $6 \times 10^{-4}\%$ and $3 \times 10^{-2}\%$ with our fit. The NREL fit also degrades with noise, even if its errors are for most SNRs slightly lower than with the ASTM fit. In contrast—even if also sensitive to noise—our fit yields higher accuracy than the ASTM and the NREL fits for SNRs of 100 dB and lower, thanks to its optimised fit range.

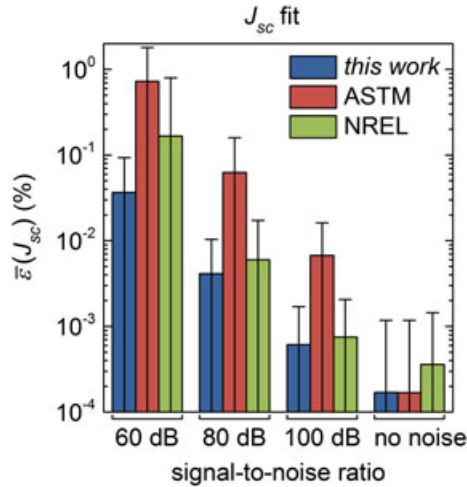


Figure 5. Comparison of the mean absolute error on J_{sc} ($\bar{\epsilon}(J_{sc})$) as a function of the signal-to-noise ratio. The error bars are the 2σ deviation of $\epsilon(J_{sc})$ for the 500 solar cells under investigation. [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

3.2. Open-circuit voltage fit

Following the same approach applied for J_{sc} fit (Section 3.1), the (γ, δ) boundaries minimising $\bar{\epsilon}(V_{oc})$ are determined for each SNR values, in the case of a linear regression and a second-order polynomial fit. The results in the case SNR = 80 dB are exemplary plotted in Figure 6. As can be seen, for this SNR value, the minimum values of $\bar{\epsilon}(V_{oc})$ obtained with the linear or the second-order polynomial fits are quite similar: $(4.5 \pm 6.9) \times 10^{-3}\%$ for the former and $(3.6 \pm 5.4) \times 10^{-3}\%$ for the latter. However, the two fits behave significantly differently as a function of the (γ, δ) boundaries. Indeed, in the case of the linear fit, the (γ, δ) zone yielding the lowest $\bar{\epsilon}(V_{oc})$ values is

sharply delimited, and $\bar{\epsilon}(V_{oc})$ rapidly grows outside this region, reaching up to $10^{-1}\%$ error. In contrast, the second-order polynomial fit yields $\bar{\epsilon}(V_{oc})$ values not higher than $10^{-2}\%$ regardless of the chosen boundaries. This suggests a higher robustness of the second-order polynomial fit regarding the chosen fit range.

Figure 7 compares the performances of our V_{oc} fit (linear and second-order polynomial) to the ASTM and the NREL ones (which both use a linear regression). Interestingly, among the linear fits, the simple two-point linear fit of ASTM performs the best in the no-noise limit. Nonetheless, for SNRs of 100 dB and lower, our optimised linear fit yields higher accuracy. Note that the NREL fit usually gives higher errors than ASTM and our work, but is remarkably insensitive to noise. Moreover, it was found

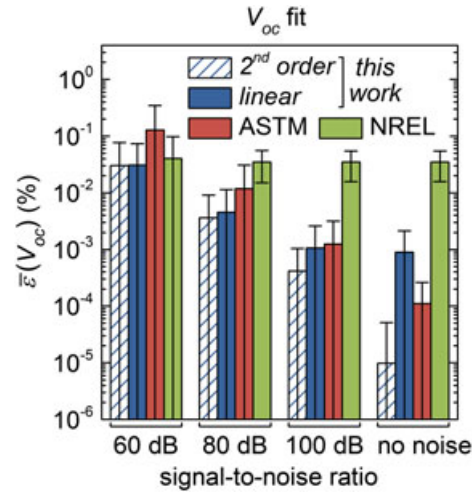


Figure 7. Comparison of the mean absolute error on V_{oc} ($\bar{\epsilon}(V_{oc})$) as a function of the signal-to-noise ratio. The error bars are the 2σ deviation of $\epsilon(V_{oc})$ for the 500 solar cells under investigation. [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

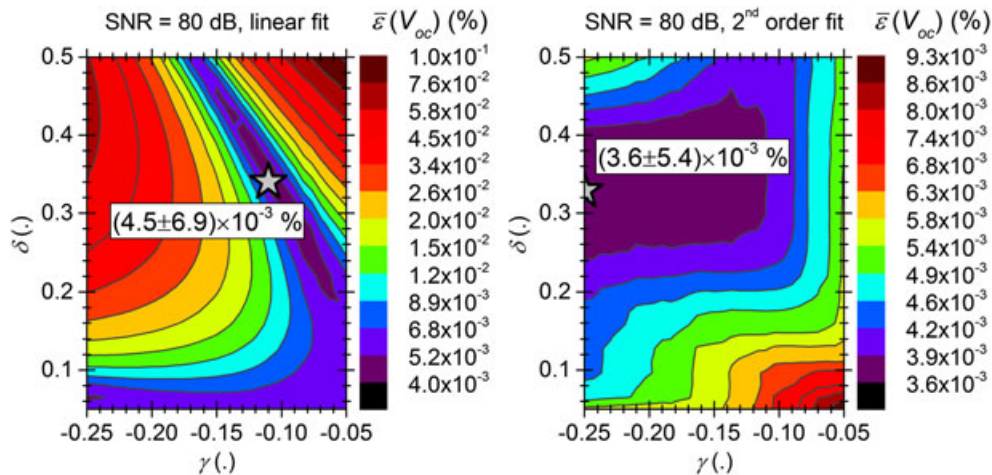


Figure 6. Variation of the mean absolute error on V_{oc} ($\bar{\epsilon}(V_{oc})$) as a function of the (γ, δ) boundaries used for the fit range, in the case of a signal-to-noise ratio of 80 dB, using a linear regression (left) and a second-order polynomial fit (right). The grey stars indicate the position of the minimum for $\bar{\epsilon}(V_{oc})$. [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

that the NREL fit procedure mainly yields underestimated V_{oc} values. This topic is addressed in more details at the end of this section.

Using a second-order polynomial fit as an alternative to the standard linear regression, the most accurate values of all benchmarked fits are obtained, even in the no-noise limit (see the blue hatched bars in Figure 7). One possible explanation for the superior results of the second-order polynomial fit compared to the linear regression is that

the former better accommodates to the curvature of the I - V curve close to V_{oc} . However, as seen in Figure 7, the superiority of the second-order polynomial fit rapidly reduces when noise increases. Indeed, whereas in the no-noise case, the second-order polynomial fit is almost two orders of magnitude more accurate than the linear one, this improvement drops to only 3 times at SNR = 100 dB. At 80 dB, the accuracy gain of the second-order polynomial fit is marginal, and at 60 dB, it performs similarly to the

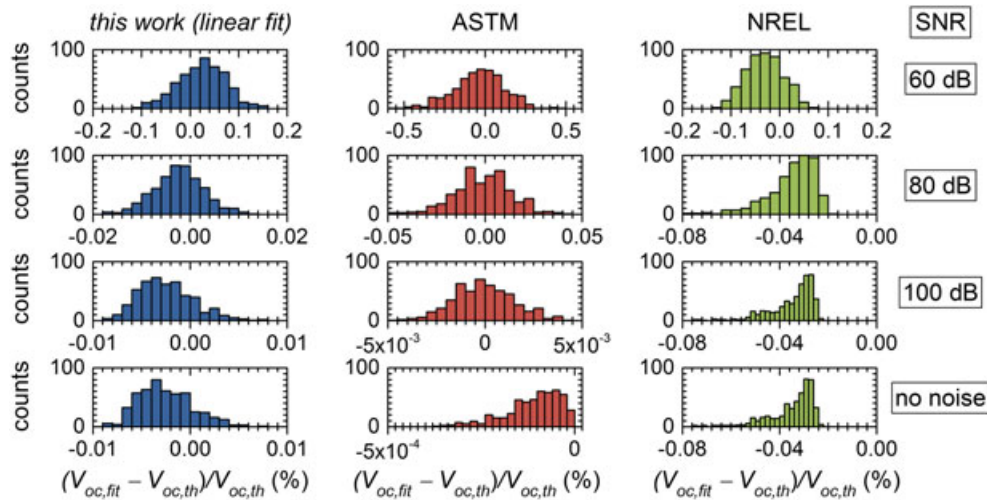


Figure 8. Histograms of the signed error on V_{oc} ($(V_{oc,fit} - V_{oc,th})/V_{oc,th}$) as a function of the signal-to-noise ratio. [Colour figure can be viewed at wileyonlinelibrary.com]

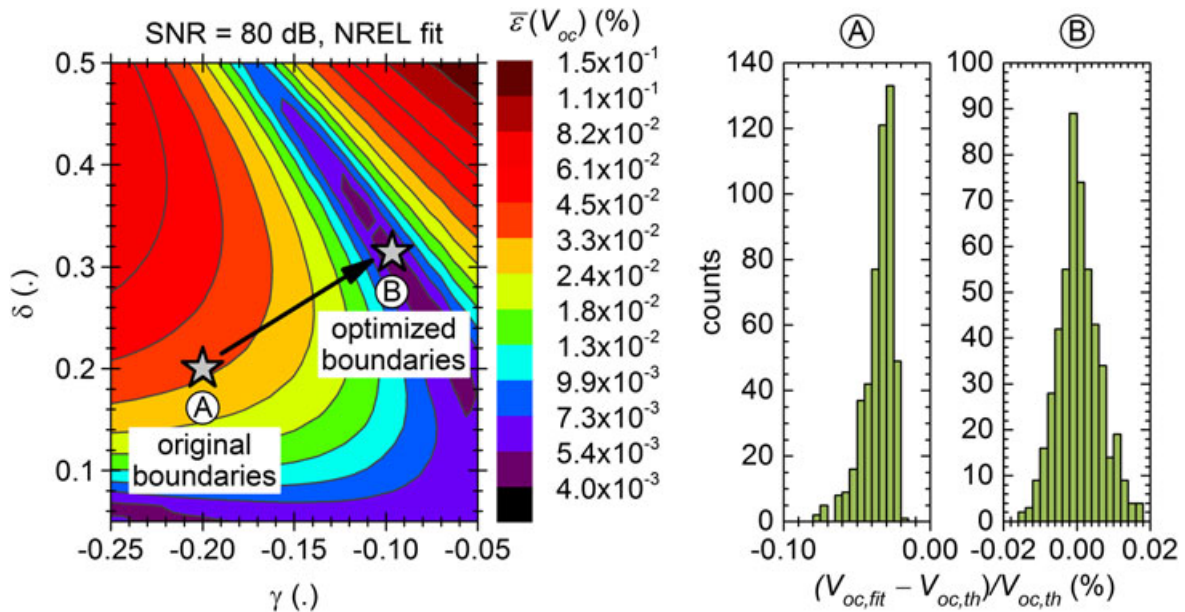


Figure 9. Illustration of the fit range influence on the systematic error in determining the V_{oc} with the NREL fit. Using the original NREL boundaries yields a mean absolute error on V_{oc} of $(3.5 \pm 2.0) \times 10^{-2}\%$ together with a systematic underestimation of the actual V_{oc} value (see the 'A' histogram featuring only negative values). In contrast, the optimised boundaries allow reducing the mean absolute error to $(4.5 \pm 7.2) \times 10^{-3}\%$ with no systematic error (see the 'B' histogram evenly distributed around zero). [Colour figure can be viewed at wileyonlinelibrary.com]

linear regression. Last but not least, using a second-order polynomial fit for V_{oc} determination does not go without new challenges. Indeed, second-order polynomials usually have two roots: determining which one actually is the 'true' value of V_{oc} can reveal quite delicate. A first approach would be to compare the two V_{oc} roots of the second-order polynomial to the V_{oc} value obtained using the linear regression: the one of the two roots closest to this latter value might be assumed to be a more accurate estimation of the actual V_{oc} . Further investigations are however needed to fully assess the validity of this approach.

Figure 8 plots the histograms of the signed error on V_{oc} (calculated as $(V_{oc,fit} - V_{oc,th})/V_{oc,th}$) obtained with the ASTM, the NREL and our linear fit for all SNRs. In contrast to $\varepsilon(V_{oc})$ (see (3) in Section 2.2), which is always

positive, the signed error on V_{oc} can take positive or negative values: a positive value indicates an overestimation of the actual V_{oc} , whereas a negative value indicates an underestimated V_{oc} . As can be seen in Figure 8, for all SNRs but 60 dB, the histograms of the signed error on V_{oc} of the NREL fit take only negative values. This indicates that the V_{oc} determined using the NREL procedure is lower than the actual one, as already briefly mentioned in the discussion of Figure 7. In contrast, the histograms of the ASTM fit and our linear fit are evenly distributed around zero, indicating no systematic deviation in their V_{oc} estimation. (A notable exception is however the ASTM fit in the no-noise limit.)

As NREL uses a linear regression similarly to our V_{oc} fit procedure, we can hence affirm that the peculiar behaviour

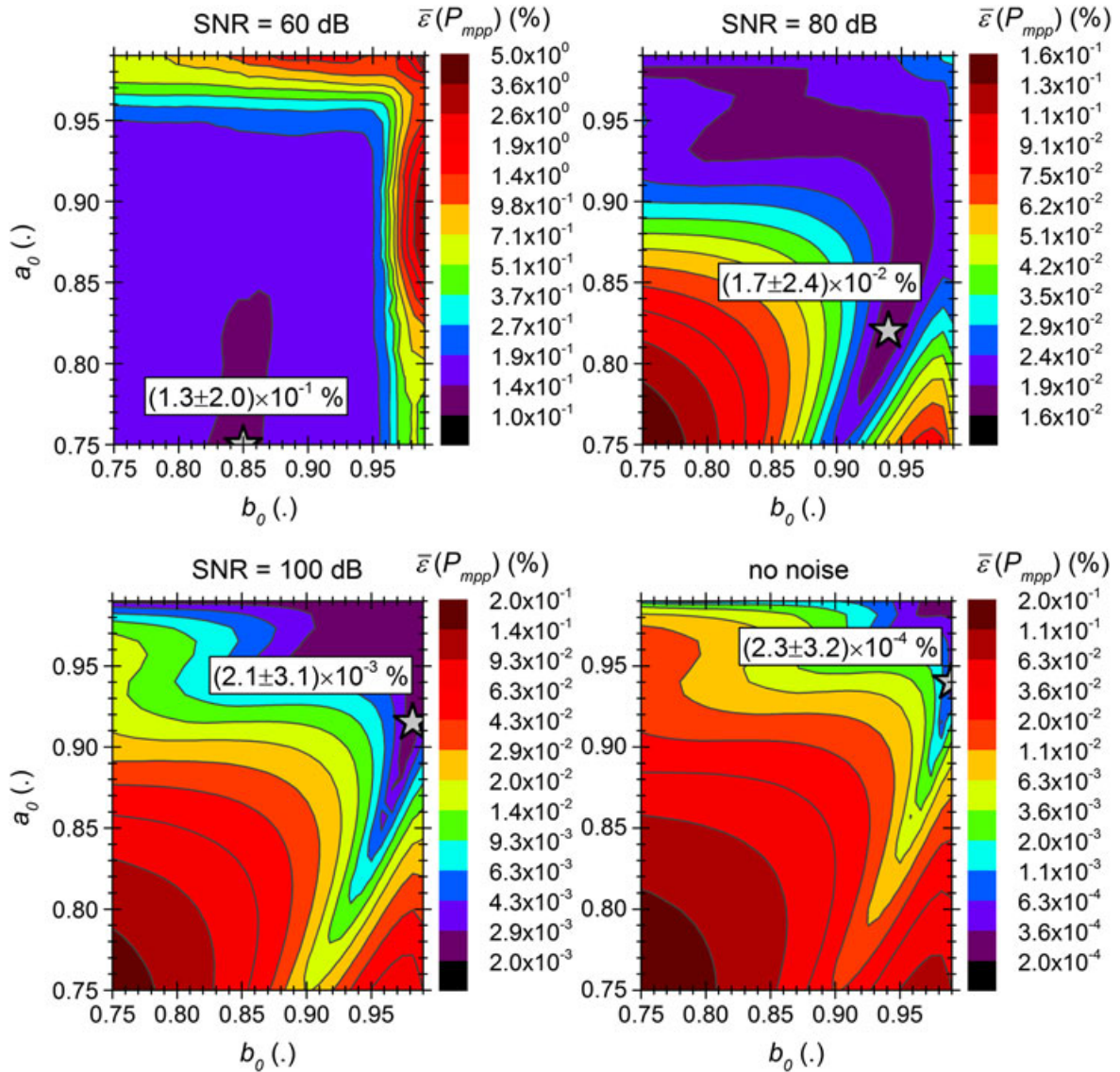


Figure 10. Variation of the mean absolute error on P_{mpp} ($\bar{\varepsilon}(P_{mpp})$) as a function of the (a_0, b_0) boundaries used for the fit range, for three signal-to-noise ratios and in the no-noise limit. The grey stars indicate the position of the minimum for $\bar{\varepsilon}(P_{mpp})$. [Colour figure can be viewed at wileyonlinelibrary.com]

of the NREL fit rather originates from a non-optimised choice of the fit boundaries. To illustrate this point, the NREL V_{oc} fit boundaries were redefined in a similar fashion to our fit, namely, as (J, V) points fulfilling the condition $\gamma \times J_V = 0 \leq J \leq \delta \times J_V = 0$ (where $-0.25 \leq \gamma < 0$ and $0 < \delta \leq 0.5$), still keeping the additional condition $|V| \leq 0.1 \times V_J = 0$. The original NREL fit is then retrieved using $\gamma = -0.20$ and $\delta = 0.20$ (see Table I). The value of $\bar{\varepsilon}(V_{oc})$ is then calculated for all (γ, δ) values. The results are plotted in Figure 9 in the case $\text{SNR} = 80$ dB. The colour map is very similar to the one obtained with our linear fit (see Figure 6, left). This was expected, as the NREL fit boundaries are now almost identical to ours. However, the map clearly reveals that the original NREL boundaries ($\gamma = -0.20$ and $\delta = 0.20$) can be advantageously replaced by the values $\gamma = -0.10$ and $\delta = 0.31$: doing so, $\bar{\varepsilon}(V_{oc})$ is reduced from $(3.5 \pm 2.0) \times 10^{-2}\%$ to $(4.5 \pm 7.2) \times 10^{-3}\%$ (compare the 'A' and 'B' grey stars on the map). Moreover, comparing the histograms of the signed error on V_{oc} obtained for conditions 'A' and 'B' shows that when using the original boundaries, the histogram features only negative values, indicating underestimated V_{oc} values, as already observed in Figure 8. In contrast, with the optimised boundaries, the histogram is evenly distributed around zero, indicating that any systematic error in the V_{oc} determination has been cancelled. We can hence conclude that the original NREL V_{oc} fit suffers from an improper fit range, resulting in a systematic error (here an underestimation) in the value of the fitted parameter.

3.3. Maximum power fit

Figure 10 plots the variation of $\bar{\varepsilon}(P_{mpp})$ as a function of the (a_0, b_0) boundaries for three different SNRs and in the no-noise limit. It is worth observing that both the minimum value of $\bar{\varepsilon}(P_{mpp})$ and its position change with the noise level: the lower the noise, the lower $\bar{\varepsilon}(P_{mpp})$ and the narrower the optimum (a_0, b_0) range. For instance, at 60 dB, the minimum value of $\bar{\varepsilon}(P_{mpp})$ is not lower than $(1.3 \pm 2.0) \times 10^{-1}\%$ and requires $a_0 = 0.75$ and $b_0 = 0.85$. In contrast, in the no-noise case, $\bar{\varepsilon}(P_{mpp})$ is as low as $(2.3 \pm 3.2) \times 10^{-4}\%$ and a much narrower fit range has to be used, namely, $a_0 = 0.94$ and $b_0 = 0.99$. Conversely, using a too narrow fit range with low SNR can yield strongly inaccurate P_{mpp} values: if for instance one uses the no-noise fit range in the case $\text{SNR} = 60$ dB, $\bar{\varepsilon}(P_{mpp})$ would reach $1.9 \pm 2.5\%$, a value 10 times worse than what would be obtained using the ASTM fit.

The accuracies on P_{mpp} determination for the fit procedures under investigation are reported in Figure 11. Our optimised fit performs better than the ASTM and the NREL ones regardless of the noise level. In the no-noise limit, our fit is even more than two orders of magnitude more accurate than the ASTM and the NREL ones. In

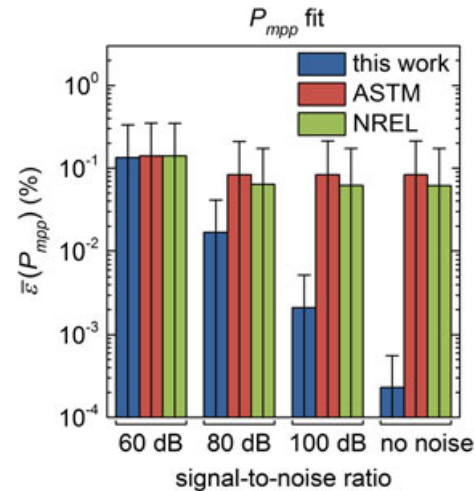


Figure 11. Comparison of the mean absolute error on P_{mpp} ($\bar{\varepsilon}(P_{mpp})$) as a function of the signal-to-noise ratio. The error bars are the 2σ deviation of $\varepsilon(P_{mpp})$ for the 500 solar cells under investigation. [Colour figure can be viewed at wileyonlinelibrary.com]

[15], it has already been demonstrated that the main reason for the ASTM and the NREL P_{mpp} fits inaccuracy originates in their too large fit range, usually leading to overestimated P_{mpp} values. Moreover, it was highlighted that the P_{mpp} overestimation increased with the FF of the DUT. At that time however, this phenomenon was investigated for a single SNR value equal to 80 dB. Figure 12 completes this study by plotting the variation of $\varepsilon(P_{mpp})$ for various SNRs. As can be seen, the ASTM and the NREL fits exhibit a marked FF dependency for all SNRs higher than 80 dB: the higher the DUT FF , the higher $\varepsilon(P_{mpp})$. Moreover, the higher the SNR, the more visible this dependency: compare, for example, the data at $\text{SNR} = 80$ dB with those in the no-noise limit. In contrast, when using our fit procedure, no correlation is visible between $\varepsilon(P_{mpp})$ and the DUT FF : our fit performs equally well for DUT with FF of 60% or 80%.

The results obtained in this section as a function of the SNR complete the outcomes of [15], showing (i) the P_{mpp} fit range must be adapted to the ambient noise level, a rule of thumb being that high SNRs allow a narrow fit range with improved accuracy, and (ii) for a given SNR, the P_{mpp} fit accuracy can be strongly dependent on the DUT FF if a non-optimised fit procedure is used, as was evidenced for the ASTM or the NREL ones. In contrast, our P_{mpp} fit procedure proves robust against noise level and DUT FF variation. Guidelines detailing the appropriate P_{mpp} fit parameters are provided in Table II, Section 3.5.

3.4. Case study: key data measurement of 3000 silicon heterojunction solar cells

Figure 13 plots the differences in determining the key data of the 3000 SHJ solar cells with the fits under study. The ASTM and the NREL fits were performed as described in Table I. For our fits, the parameters yielding the highest

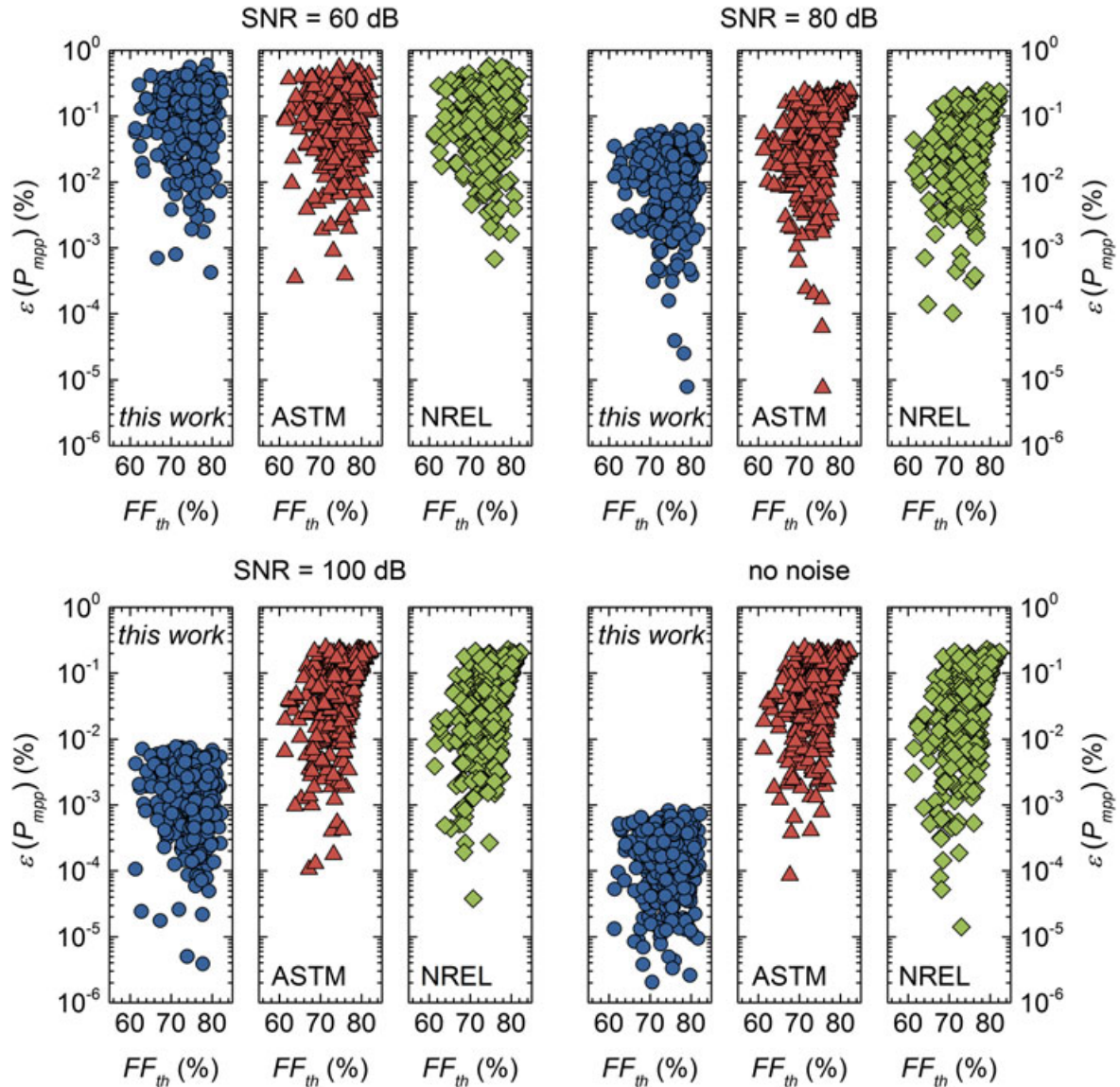


Figure 12. Variation of the absolute error on P_{mpp} ($\varepsilon(P_{mpp})$) as a function of the theoretical FF of the device under test, for three signal-to-noise ratios and in the no-noise limit. Each data point represents one single *I*-*V* curve within the 500 under study. [Colour figure can be viewed at wileyonlinelibrary.com]

accuracy according to the results of Sections 3.1 to 3.3 were used, namely, a linear I_{sc} fit on the range $-0.50 \times V_{mpp} \leq V \leq 0.42 \times V_{mpp}$, a second-order polynomial V_{oc} fit on the range $-0.25 \times I_{mpp} \leq I \leq 0.33 \times I_{mpp}$ and a fourth-order polynomial P_{mpp} fit using $a_0 = 0.82$ and $b_0 = 0.94$. Note that all $\Delta^{ASTM}(X)$ and $\Delta^{NREL}(X)$ values discussed in the succeeding texts in this section are larger than the typical errors expected from the calculations on synthetic *I*-*V* curves (Sections 3.1 to 3.3) for the signal-to-noise ratio of our experimental set-up (>80 dB) and can hence be considered meaningful.

Looking first at I_{sc} fits, it is to be seen that the medians of $\Delta^{ASTM}(I_{sc})$ and $\Delta^{NREL}(I_{sc})$ are very close to zero. This means that there is no systematic deviation between these

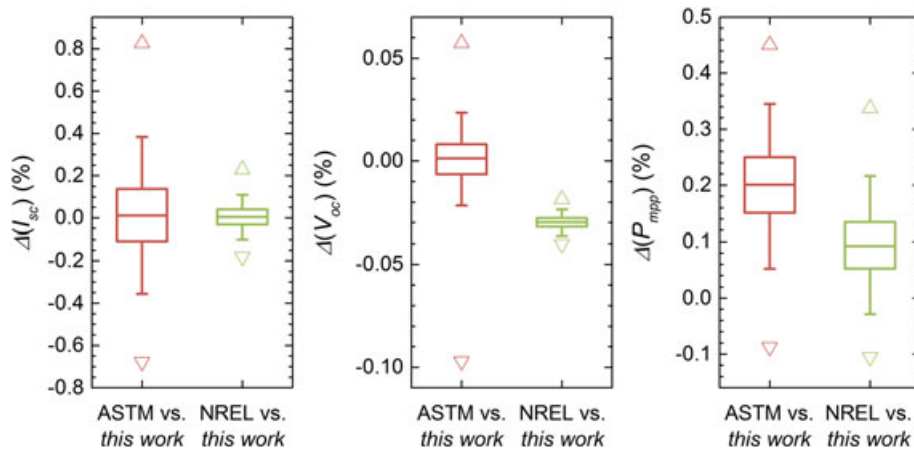
fits and ours, but rather random differences. Moreover, the 2σ deviation of $\Delta^{ASTM}(I_{sc})$ is approximately 4 times larger than those of $\Delta^{NREL}(I_{sc})$. This is consistent with the results of Figure 5: indeed, at SNR = 80 dB, the NREL fit and ours yield similar accuracy, whereas the ASTM fit was found to be less accurate. Overall, the differences between our fit and the ASTM one go up to $\pm 0.8\%$, whereas it is only $\pm 0.2\%$ when compared to NREL.

Different behaviours are observed for $\Delta(V_{oc})$. The median of $\Delta^{ASTM}(V_{oc})$ are again close to zero, indicating random differences between our V_{oc} fit and the ASTM one. In contrast, the median value of $\Delta^{NREL}(V_{oc})$ is negative: this indicates that the V_{oc} values determined using the NREL procedure are systematically lower than with ours. This is

Table II. Fit types and ranges to be applied for the determination of crystalline silicon-based PV devices key data.

SNR	Parameter	Fit type	Fit range	Expected error (%)
60 dB	J_{sc}	Linear	$-0.50 \times V_{mpp} \leq V \leq 0.55 \times V_{mpp}$	$(3.7 \pm 5.7) \times 10^{-2}$
	V_{oc}	Linear	$-0.20 \times J_{mpp} \leq J \leq 0.50 \times J_{mpp}$	$(3.1 \pm 4.3) \times 10^{-2}$
	P_{mpp}	Second-order polynomial	$-0.25 \times J_{mpp} \leq J \leq 0.50 \times J_{mpp}$	$(3.0 \pm 4.6) \times 10^{-2}$
		Fourth-order polynomial	$P \geq 0.75 \times P_{mpp}$ for $V < V_{mpp}$ $P \geq 0.85 \times P_{mpp}$ for $V \geq V_{mpp}$	$(1.3 \pm 2.0) \times 10^{-1}$
80 dB	J_{sc}	Linear	$-0.50 \times V_{mpp} \leq V \leq 0.42 \times V_{mpp}$	$(4.1 \pm 6.2) \times 10^{-3}$
	V_{oc}	Linear	$-0.11 \times J_{mpp} \leq J \leq 0.34 \times J_{mpp}$	$(4.5 \pm 6.9) \times 10^{-3}$
	P_{mpp}	Second-order polynomial	$-0.25 \times J_{mpp} \leq J \leq 0.33 \times J_{mpp}$	$(3.6 \pm 5.4) \times 10^{-3}$
		Fourth-order polynomial	$P \geq 0.82 \times P_{mpp}$ for $V < V_{mpp}$ $P \geq 0.94 \times P_{mpp}$ for $V \geq V_{mpp}$	$(1.7 \pm 2.4) \times 10^{-2}$
100 dB	J_{sc}	Linear	$-0.31 \times V_{mpp} \leq V \leq 0.73 \times V_{mpp}$	$(6.1 \pm 10.8) \times 10^{-4}$
	V_{oc}	Linear	$-0.20 \times J_{mpp} \leq J \leq 0.05 \times J_{mpp}$	$(1.1 \pm 1.5) \times 10^{-3}$
	P_{mpp}	Second-order polynomial	$-0.25 \times J_{mpp} \leq J \leq 0.24 \times J_{mpp}$	$(4.2 \pm 6.3) \times 10^{-4}$
		Fourth-order polynomial	$P \geq 0.92 \times P_{mpp}$ for $V < V_{mpp}$ $P \geq 0.98 \times P_{mpp}$ for $V \geq V_{mpp}$	$(2.1 \pm 3.2) \times 10^{-3}$
No noise	J_{sc}	Linear	$-0.04 \times V_{mpp} \leq V \leq 0.01 \times V_{mpp}$	$(1.7 \pm 10.1) \times 10^{-4}$
	V_{oc}	Linear	$-0.20 \times J_{mpp} \leq J \leq 0.05 \times J_{mpp}$	$(9.0 \pm 12.3) \times 10^{-4}$
	P_{mpp}	Second-order polynomial	$-0.05 \times J_{mpp} \leq J \leq 0.05 \times J_{mpp}$	$(9.9 \pm 41.5) \times 10^{-6}$
		Fourth-order polynomial	$P \geq 0.94 \times P_{mpp}$ for $V < V_{mpp}$ $P \geq 0.99 \times P_{mpp}$ for $V \geq V_{mpp}$	$(2.3 \pm 3.2) \times 10^{-4}$

PV, photovoltaic; SNR, signal-to-noise ratio.

**Figure 13.** Boxplots of the differences between the key data determined using the ASTM and the NREL fits procedures against ours, in the case of 3000 silicon heterojunction solar cells. The boxes give the 25%, 50% and 75% percentiles; the whiskers are the 2σ deviations; the upward triangles give the maxima and the downward triangles the minima. [Colour figure can be viewed at wileyonlinelibrary.com]

consistent with the outcomes of Section 3.2, where it was evidenced that the NREL fit underestimates the actual V_{oc} values. This difference is however less than -0.05% .

Regarding P_{mpp} fit, the median values of $\Delta^{ASTM}(P_{mpp})$ and $\Delta^{NREL}(P_{mpp})$ are of 0.2% and 0.1% , respectively. This suggests that the ASTM and the NREL fits overestimate the actual P_{mpp} value of the 3000 SHJ solar cells under study by these same figures. These values are in line with the outcomes of our investigations on synthetic I - V curves with FF of 78–80% presented herein in Section 3.3 and in

[15], which clearly point towards an overestimation of the actual P_{mpp} with the ASTM and the NREL fits, owing to their non-optimal fit ranges. The origins of this behaviour are thoroughly unveiled in [15], to which the reader is referred for further details.

Figure 14 plots $\Delta^{ASTM}(P_{mpp})$ and $\Delta^{NREL}(P_{mpp})$ as a function of the SHJ solar cells measured FF . For an easier interpretation of the data, the mean values of $\Delta^{ASTM}(P_{mpp})$ and $\Delta^{NREL}(P_{mpp})$ were calculated on FF ranges of 1% width, for example, 76–77%, and similarly up to the 80–81%

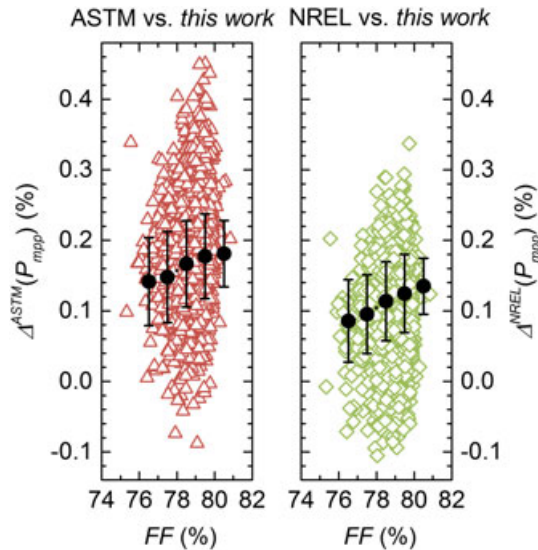


Figure 14. Variation of the differences between the P_{mpp} values determined using the ASTM and the NREL fit procedures against ours, as a function of the FF of the 3000 silicon heterojunction solar cells under study. Each open triangle and diamond represents one individual device. The black dots are the mean values of $\Delta(P_{mpp})$ calculated by increment of $1\%_{abs} FF$, and the error bars are the corresponding standard deviation values. [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

range. These values are plotted as black dots in Figure 14. As can be seen, the mean values of $\Delta^{ASTM}(P_{mpp})$ and $\Delta^{NREL}(P_{mpp})$ get higher for higher FF . This is again consistent with the observations reported in Section 3.3 and in [15] on synthetic *I-V* curves: the higher the device FF , the larger the P_{mpp} overestimation of the ASTM and the NREL fits. This is further confirmed by Figure 15, where the *P-V* curve of a SHJ device with $FF = 79.5\%$ is displayed. As can be seen, the ASTM and the NREL fits obviously overestimate the position of P_{mpp} , whereas our fit procedure yields a P_{mpp} value better in line with the experimental data.

3.5. Recommendations for accurate fits

The results presented in this paper show that for J_{sc} , V_{oc} and P_{mpp} extraction, the state-of-the-art ASTM and NREL fit procedures can most of the time be outperformed by thorough adjustments of the fit range and the regression type (e.g. linear vs. second-order polynomial). This conclusion holds for *I-V* curves featuring a wide variety of shapes and key data, as well as for noise levels typically encountered in laboratory or production environments. Gathering the outcomes of the present paper and those of our previous paper [15], we provide the following recommendations to perform accurate key data extraction:

- *J_{sc} fit:* Including points with negative voltage in the J_{sc} fit range enhances the accuracy and robustness of

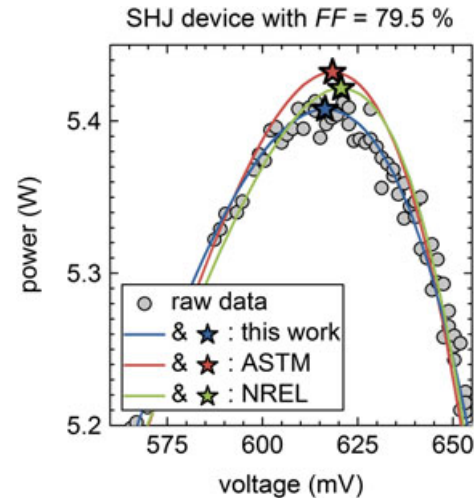


Figure 15. Comparison of the polynomial fits (solid lines) and the maximum power points (stars) obtained using the P_{mpp} fit criteria proposed in this paper, compared to those given by ASTM [13] and NREL [14], in the case of the experimentally measured *P-V* curve of a 6-in silicon heterojunction solar cell with $FF = 79.5\%$. [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

the fit. For instance, at $SNR = 80$ dB, the expected error of our fit is $4 \times 10^{-3}\%$. This represents a 15-fold (resp. 1.5-fold) accuracy improvement compared to the ASTM (resp. NREL) fit. However, this approach will obviously fail if nonlinear effects affect the negative voltage range of the *I-V* curve. Whereas this is unlikely to happen when measuring a single solar cell, in the case of PV modules, several nonlinear effects are known to appear close to J_{sc} , especially those linked to bypass diodes, or if a passive load is used. This problem was already pointed out in [11,14]. Adapting the J_{sc} fit procedure taking into account these parasitic effects requires further investigations and is out of the scope of this paper.

- *V_{oc} fit:* Similarly to J_{sc} , including points with negative current within the V_{oc} fit range yields a better accuracy. Our linear fit with optimised boundaries provides a threefold (respectively eightfold) accuracy improvement compared to ASTM (resp. NREL) at $SNR = 80$ dB. Alternatively, replacing the linear regression by a second-order polynomial fit further enhances the fit performances, especially in the case of low noise environments. For instance, at $SNR = 100$ dB, using our second-order polynomial V_{oc} fit improves the accuracy by almost two orders of magnitude compared to NREL. Nevertheless, as for J_{sc} , these fit procedures might result problematic for some PV modules, for example, those including blocking diodes [11]. Further investigations are also needed to address this issue, but are as well out of the scope of this paper.
- *P_{mpp} fit:* Re-defining the P_{mpp} fit range using two independent boundaries expressed as a fraction of P_{mpp}

already provides an important accuracy enhancement. At 80 dB, our fit is 5 times more accurate than ASTM, and 4 times than NREL. Even better, this fit range can itself be adapted to the FF of the DUT, as suggested in [15]. Even if primarily developed for single solar cells, our P_{mpp} fit procedure should also be relevant in the case of full PV modules, provided that the transient effects linked to the measurement of capacitive modules are thoroughly corrected [18] [19].

- **Noise level:** The ASTM guidelines give accurate key data in the case of ideal measurements without any noise, but rapidly fail as the SNR decreases. In contrast, adapting the fit range to the SNR allows a robust and more accurate key data determination. A careful evaluation of the ambient noise is therefore a prerequisite to perform accurate fits.

Finally, Table II summarises the fit types and ranges to be used for crystalline silicon-based PV devices in order to obtain accurate key data based on the outcomes of this paper.

As a final outlook, the generalisation of our fit guidelines to other established or emerging PV technologies remains an open question. Indeed, whereas the two-diode model is widely accepted for crystalline silicon-based PV devices, numerous deviations to this simple model have been observed for other PV materials, such as copper indium gallium selenide (CIGS) [20], thin-film amorphous silicon [21] and perovskite [22]. How the key data fit guidelines have to be consequently modified requires further investigation.

4. CONCLUSION

In this paper, we reported on the optimisation of the fit procedures to extract crystalline silicon-based solar cells and modules key data from their I - V curves. Our analysis is based on numeric I - V curves obtained by solving the two-diode equation in steady state. Smart adjustments of the fit range and the regression type were shown to allow obtaining J_{sc} , V_{oc} and P_{mpp} values more accurately than following the established state-of-the-art standards. Our fit criteria were demonstrated to be robust against noise. The validity of our approach was assessed on I - V curves experimentally measured on 3000 SHJ devices. Finally, we provide novel fit criteria and general requirements aiming at enhancing the key data determination accuracy for high-efficiency crystalline silicon-based PV devices.

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