ABSTRACT
This paper presents a method for extracting physically meaningful parameters from measured I-V curves of PV modules. The 7-parameter double-exponential model is applied in the modeling. The method is based on linear fitting of semi-logarithmic plots. The paper demonstrates a new technique to estimate the series resistance of a module with high accuracy from such plots. As a result, also the reverse saturation current and the quality factor of the diffusion diode can be determined. The method is applied to outdoor I-V data from a test station with three similar, but not identical, polycrystalline-Si modules. The values of the series resistances found with this method deviate somewhat from the values found by indoor measurements by an independent laboratory. The quality factors of the diffusion diodes were in this case found to be somewhat larger than 1, indicating a good, but not perfect quality of the material.

INTRODUCTION
The present paper describes a method to extract physically correct parameters from outdoor-illuminated forward I-V curves of PV modules analyzed by the 7-parameter double-exponential model. Our approach avoids complex non-linear curve fitting by linear fitting of relevant portions of semi-logarithmic plots. No prior knowledge or initial guess of the parameters is required. A similar method has previously been applied for determining parameters of cells, but here the method is adapted for PV modules. We further introduce a novel technique for the estimation of series resistance with high accuracy.

The method is applied in the analysis of outdoor I-V data from three similar polycrystalline-Si PV modules. One of the modules is based on solar-grade Si (SoG-Si) produced from a metallurgical route, and the other two are made of classical poly-Si purified by the chemical route. The test station is located at latitude N58°09' in Southern Norway. To our knowledge, this paper represents the first application of the double-exponential model to a PV module made of SoG-Si from a metallurgical route.

The paper first gives a review of the double-exponential model and some of its variants. Existing approaches for parameter-extraction are discussed. Thereafter, the experimental setup is explained. It is then shown which mathematical manipulations on the I-V data are necessary in order to obtain semi-logarithmic plots with partial linearity. This method is then applied to the three polycrystalline-Si modules of the setup. Details of the novel technique for precise evaluation of the series resistance are presented, and we briefly discuss the values obtained for the parameters.

REVIEW OF THE DOUBLE-EXPONENTIAL MODEL
In the available literature, the double-exponential model has mostly been applied to crystalline-Si PV cells [1-7], most of which have been monocrystalline, due to the fact that this technology dominated the market for the initial half century of the modern photovoltaic age [8,9]. There are few reports on the application of the model for polycrystalline cells.

A few papers on parameter-extraction from I-V data of Si modules have been published [4,10]. However, since there are many tens of individual cells in an average size module, the double-exponential model may not always be applicable since the cells may not be perfectly matched. Besides, modules incorporate additional semiconductor elements that further complicate their description; bypass diodes are normally connected across substrings of cells to handle partial-shading conditions and to prevent hot-spots and cell damage [11]. However, with cells that are nearly identical, the double-exponential model can be applied.

Details of the Model and Some Variants
A general form of the double-exponential model is given by Eq. (1). The equation is consistent with the double-diode lumped-circuit model of a PV cell shown in Fig. 1. The terminal current $I$ of the cell can be divided into four components, as shown in Eq. (1): the photogenerated current ($I_{ph}$), the current through the shunt resistance ($I_{s}$), the diffusion-diode current ($I_{D1}$), and the recombination-diode current ($I_{D2}$). The 7 independent parameters in the model are: the photogenerated current $I_{ph}$; the series resistance $R_s$; the shunt resistance $R_s$; the reverse saturation current $I_{01}$ and the quality factor $n_1$ of the diffusion diode; and the reverse saturation current $I_{02}$ and the quality factor $n_2$ of the recombination diode. $n_1$ is often assumed to be equal to 1 by many authors, in accordance with the diffusion theory of p-n junctions [12], whereas $n_2$
is sometimes set equal to 2, in accordance with the theory of recombination via traps [13]. The thermal voltage \( V_T = k_B T/q_e \), where \( T \) is the p-n junction temperature (considered a known or controlled quantity), \( k_B \) is Boltzmann’s constant, and \( q_e \) is the elementary charge. The parameters in the double-exponential model depend on the irradiance and cell temperature [5,6,7].

\[
I(V) = I_{PH} - I_p - I_{D1} - I_{D2} = \frac{V + IR_S}{R_p} - I_{01}\left(e^{\frac{V + IR_S}{n_1 q_e T}} - 1\right) - I_{02}\left(e^{\frac{V + IR_S}{n_2 q_e T}} - 1\right) \tag{1}
\]

\[
I(V) = \frac{V + IR_S}{R_p} - I_{01}\left(e^{\frac{V + IR_S}{n_1 q_e T}} - 1\right) - I_{02}\left(e^{\frac{V + IR_S}{n_2 q_e T}} - 1\right) \tag{2}
\]

There exist a few variants of the lumped-circuit model. Watson (1960) first proposed a double-diode model, but with identical exponents for both junctions [3]. Wolf and Rauschenbach (1963) focused on distributed-series-resistance effects in PV cells, and arrived at an equation similar to Eq. (1) [3], but they ignored the shunt current due to the high parallel resistance \( R_p = 13.8 \, \text{k} \Omega \) in their experimental 2-cm² monocrystalline-Si cell.

Müllejans et al. (2004) preferred a 5-parameter model, setting \( n_1=1 \) and \( n_2=2 \) [4]. They report \( R_p \)-values of practical (large-area) poly-Si PV cells as low as 6.6 \( \Omega \). Other authors have also applied 5-parameter versions of the model [5,7,10]. Some of them have made a priori assumptions for the recombination factors of the two diodes, while others have considered the recombination diode negligible. However, Coors and Böhm (1997) have pointed out advantages of using the 7-parameter model in correction of I-V curves [6] and found it superior to IEC-891 and Blaesser’s procedure. Ouennoughi and Chegaar (1999) have used the single-exponential (single-diode) approximation [10]. They have applied the same equation to a PV module, leaving the quality factor to also account for the number of cells in series. Thus, they have estimated quality factors for modules that differ by orders of magnitude compared to those of single cells. Such an approach makes the direct comparison of p-n-junction parameters for cells and modules more difficult. Lo Brano et al. (2010) have used a quality factor that incorporates both the elementary charge and Boltzmann’s constant, such that its dimension becomes Volts/Kelvin [14]. By proper scaling of their quality-factor estimates for two PV modules, we have arrived at classical (dimensionless) quality factors of 0.87 and 0.73. These values are not physical, and neither are their corresponding reverse saturation currents.

**Figure 1** Lumped-circuit, double-diode model of a PV cell.

When cells are connected in series to form PV modules, one can apply the double-exponential model assuming that all cells are nearly identical. Eq. (1) must then be modified to the form shown in Eq. (2), where \( V \) and \( I \) are now understood to be the terminal voltage and current of the module, respectively. \( N_S \) is the number of cells in series.

Most authors seem to prefer non-linear curve-fitting approaches when it comes to extracting cell parameters [1-7]. Some assume a priori integer values \( n_1=1 \) and often also \( n_2=2 \). Appelbaum et al. (1993), after reviewing many earlier works on non-linear fitting, concluded that there can be wide parameter sets all resulting in satisfactory curve fitting [1]. A question then arises about the physical significance of the parameters obtained using one or another technique since the double-exponential model represents the physical mechanisms of conduction in crystalline-Si PV cells. Besides, some of the parameters, such as \( R_S \), may vary depending on the operating point on the I-V curve. If care is not taken to find a representative value, incorrect values for the other parameters fitted will be obtained [5,15,16]. The non-linear fitting procedures are also quite complicated both mathematically and in terms of computer code, a complexity that should be avoided if possible. Gottschalg et al. (1997) calculated the linear parameters \( (I_{PH}, 1/R_S, I_01 \text{ and } I_02) \) and fitted only the non-linear ones \( (R_S, n_1 \text{ and } n_2) \) [2]. However, this approach is difficult to program and computationally intensive.

The reverse I-V characteristics can be used to determine some of the parameters [3]. Dark I-V curves are also widely applied, often in combination with illuminated characteristics. An example of an inherent problem with this approach makes the direct comparison of p-n-junction parameters for cells and modules more difficult. Lo Brano et al. (2010) have used a quality factor that incorporates both the elementary charge and Boltzmann’s constant, such that its dimension becomes Volts/Kelvin [14]. By proper scaling of their quality-factor estimates for two PV modules, we have arrived at classical (dimensionless) quality factors of 0.87 and 0.73. These values are not physical, and neither are their corresponding reverse saturation currents.

Some authors have used semi-logarithmic plots of I-V data for p-n junctions [3,10,18,19]. It has been possible to distinguish linear portions of semi-logarithmic plots when one of the exponential terms dominates. The key is that if the plots are not correctly compensated for series-resistance effects, characteristic deviations from linearity at higher current levels will be observed [3,18]. The method was for example used by Wolf and Rauschenbach (1963), who thereby found that the quality factor of the
recombination diode was close to 3 and temperature-dependent [3]. The next Sections describe how we have adapted the methodology.

**TEST SETUP AND DATA ANALYSIS**

Fig. 2 shows non-shaded outdoor I-V curves of 3 PV modules tested by the University of Agder. We have applied the double-exponential model for modules, given by Eq. (2), in the analysis of I-V data collected for these modules. It should be noted that activation of bypass diodes at high currents is apparent in the I-V curve of the module denoted A10162. This indicates slight current mismatch of its cells. However, this takes place at a region of the I-V curve that is not so relevant for our analysis, as will be seen below.

![Figure 2 Outdoor I-V curves of the 3 polycrystalline-Si PV modules tested.](image)

The modules tested are polycrystalline-Si modules consisting of $N_S=60$ screen-printed series connected cells of size 156x156 mm$^2$. 5 bypass diodes are used, each connected across a substring of 12 cells. One of the modules is based on SoG-Si produced from Elkem Solar’s metallurgical route (denoted Elkem Solar Silicon® by the manufacturer), and the other two are made using classical poly-Si purified by the Siemens chemical route. Cells and modules were manufactured by Q-Cells. The modules are installed at the roof of a building at latitude N58°09' in the city of Kristiansand, Norway, facing South, at an inclination angle of 60° from the horizontal (optimized for spring and autumn generation). I-V curves of the modules are simultaneously recorded by the data acquisition system in approximately 280 ms, and one curve contains about 4000 data points. This high number of data points allows for the efficient filtering of noise. The sweep time must be low since any variation in the irradiance during the sweep will lead to a non-constant photocurrent, which in this work is approximated by the short-circuit current. An even shorter sweep time than that used here, would have been desirable. Crystalline-Si modules allow for sweep times down to a few milliseconds [20]. However, a much higher limit was imposed by the hardware and software used in our setup.

The multichannel electronic load system Dynaload MCL488 controlled by custom-made Labview code is applied in the test setup. The system only permits backward I-V sweeps (starting from Open Circuit) of sufficient voltage resolution. The electronic loads have on-state resistances of about 0.15 Ω. This prevents complete shorting of the modules, which can be seen in Fig. 2. The data acquisition board used is NI PCIe-6363. A SolData 80spc polycrystalline-Si reference cell measures the in-plane irradiance during sweeps.

**Semi-logarithmic Plots: Basic Approach**

The zero-voltage ($V=0$) form of Eq. (2) shows that a good approximation for the short-circuit current is $I_{SC} \approx I_{PH}$ since $R_S$ typically is several orders of magnitude smaller than $R_P$, and since the reverse saturation currents have very small values at typical irradiance levels [1].

Eq. (2) can be re-written as shown in Eq. (3).

$$I_{PH} - I = \frac{V + IR_S}{R_P} + I_01e^{\frac{V + IR_S}{N_SN_1k_BT}} + I_02e^{\frac{V + IR_S}{N_SN_2k_BT}}$$

(3)

Because $n_2$ is about twice the value of $n_1$ [1] or more [3], the first exponent in the right-hand side of Eq. (3) eventually dominates over the other two terms at higher voltages. The equation can be made dimensionless by dividing both sides by $I_{PH}$. One can now apply the natural logarithm on both sides and take the high-voltage approximation:

$$\ln\left(\frac{I_{PH} - I}{I_{PH}}\right) \approx \ln\left(\frac{I_{PH} - I}{I_{PH}}\right) + \frac{V + IR_S}{N_SN_1k_BT}$$

(4)

If the value of $R_S$ is known, the plot of $\ln\left(\frac{I_{PH} - I}{I_{PH}}\right)$ over

$$V + \frac{IR_S}{N_S}$$

will be linear at higher voltages. The slope of the linear fit will equal $q/(n_1k_BT)$ from which $n_1$ can be deduced, given that the Equivalent Cell Temperature (ECT) of the module during the I-V curve sweep is known. The vertical-axis intercept of the linear fit will equal $\ln(I_{01}/I_{PH})$ from which $I_{01}$ is easily derived.

An erroneous value of $R_S$ will result in a semi-logarithmic plot deviating from linearity at higher voltages (see Figs. 3-5). From a given I-V curve measurement, a proper algorithm can find the value of the series resistance that results in the best linearity of the corresponding semi-logarithmic plot at higher voltages (see Fig. 6).
Our analysis was done on I-V data sets taken at irradiance levels above 400 W/m². Direct temperature measurements were not available, but we calculated the Equivalent Cell Temperatures (ECTs) of all the modules during the I-V curve sweeps. This was done after the procedure given in IEC 904-5:1993 [21] using the in-plane irradiance, the open-circuit voltage \( V_{OC} \), its temperature coefficient \( \beta \), and the value of \( q_e/(n_1 k_B T) \) extracted from the semi-logarithmic plots. (In fact, this procedure assumes a one-diode model, which is consistent with the approximation we have done by disregarding the recombination diode. It is only applicable to non-shaded I-V curves taken at irradiance above 200 W/m².)

The three PV modules that we have measured have also recently been tested indoors at an independent, certified laboratory in Germany. The laboratory applied Standard Test Conditions, and the measurements provided the main data for the modules, as well as \( R_S \) (using the EN 60891), \( R_P \) and the temperature coefficients for all three modules.

**RESULTS AND DISCUSSION**

Fig. 3 shows the semi-logarithmic plots for the three modules with the STC-values of \( R_S \) provided by the independent laboratory. The \( R_S \)-values provided were 0.40, 0.17 and 0.46 \( \Omega \) for the modules A10156, A10160, and A10162, respectively.

Figure 3 Semi-logarithmic plots using STC-values of \( R_S \) provided by the independent lab.

Only in the plot of one of the modules denoted A10156 did we get the linear portion that was expected. For the other two modules, bending of the curves near open-circuit conditions is apparent. The STC-value of the series resistance does therefore not represent the whole range of possible operating conditions. In fact, it was found that the series resistance varied with irradiance, temperature and time of day. Besides, copper, silver and other metals that are used in the making of Si PV modules have positive temperature coefficients of resistivity. It can therefore be argued that the value of the series resistance should be evaluated for a range of representative environmental conditions.

It is also interesting to observe the “bulging” of the curve corresponding to the module denoted A10162 at the other end, closer to short-circuit conditions (see Fig. 3). The slight cell-current mismatching that was pointed out in connection with Fig. 2, is exaggerated by these semi-logarithmic plots. A further analysis of this phenomenon is however outside the scope of the present paper.

Figure 4 Semi-logarithmic plots with \( R_S \) set to zero for all the modules.

To further emphasize the effect that \( R_S \)-values have on the curves plotted, Figs. 4, 5 and 6 give the semi-logarithmic
plots when $R_S$ is set to 0, 0.80 and 0.40 $\Omega$, respectively, for all the modules. It is seen that a value of 0.40 $\Omega$ is quite representative for all the modules. Especially for one of the modules, this is a significant deviation from the STC-value measured by the independent laboratory (0.17 $\Omega$). Below, we present a method for accurate determination of $R_S$ for an individual I-V curve measurement.

**Figure 6 Semi-logarithmic plots with $R_S$ set to 0.40 $\Omega$ for all the modules.**

**Estimation of the Series Resistance**

For each I-V curve measured, the resulting value of $R_S$ was the one that gave the best linearity in the corresponding semi-logarithmic plot. We developed a computer algorithm to find the best fit for each curve. A range of $R_S$-values are used, and for each value the least squares residual of the best linear fit is stored. The $R_S$-value that gives the smallest residual is then the most representative value for the curve under analysis. Fig. 7 shows a plot of the least squares residual as a function of $R_S$ near its optimum. There is an apparent quadratic underlying polynomial on the large scale. The minimum of this function corresponds to the best estimate of $R_S$ for the given I-V data set. This value is then used to find $I_{01}$ and $n_1$ from the linear part of the semi-logarithmic plot.

It can be seen from Fig. 7 that a very high accuracy (relative error of 0.1%) can be achieved when estimating $R_S$ with this method, even for noisy I-V data, which is apparent in the Figure. Since thousands of I-V curves are processed, the procedure becomes computationally demanding when a high resolution of $R_S$-values is used. We have therefore developed a much faster algorithm requiring only up to seven iterations to find the best $R_S$-value for each I-V curve: For each iteration, semi-logarithmic plots are computed for eight values of $R_S$ from a given range, and a linear fit is found for each of the eight values. The two values that result in the smallest least squares of the linear fit are then chosen as the range for the next iteration.

**Figure 7 The least squares residual as a function of $R_S$ for an individual I-V curve.**

It can be seen from Fig. 7 that a very high accuracy (relative error of 0.1%) can be achieved when estimating $R_S$ with this method, even for noisy I-V data, which is apparent in the Figure. Since thousands of I-V curves are processed, the procedure becomes computationally demanding when a high resolution of $R_S$-values is used. We have therefore developed a much faster algorithm requiring only up to seven iterations to find the best $R_S$-value for each I-V curve: For each iteration, semi-logarithmic plots are computed for eight values of $R_S$ from a given range, and a linear fit is found for each of the eight values. The two values that result in the smallest least squares of the linear fit are then chosen as the range for the next iteration.

Once the series resistance has been accurately determined, also the ideality factor and the reverse saturation current of the diffusion diode can be derived.

During the course of a single sunny day in May 2010, all the three parameters exhibited complicated (including hysteresis) variations with temperature. The analysis of the temperature dependence is however beyond the scope of this paper. For the module denoted A10156, $R_S$ varied between 0.29 and 0.43 $\Omega$, whereas the values found for $n_1$ and $I_{01}$ ranged from 1.15 to 1.4, and from $1 \times 10^{-8}$ to $8 \times 10^{-8}$ A, respectively. The three modules tested did not differ significantly in terms of these parameters.

**CONCLUSIONS**

We have presented a simple method, based on linear fitting of data and data array manipulations, for extraction of three of the seven parameters of the double-exponential model for crystalline-Si PV modules with reasonable accuracy. The parameters found are the series resistance, the reverse saturation current and the quality factor of the diffusion diode. The photocurrent is assumed equal to the short-circuit current. The method is based on a verified physical model of PV cells adapted to modules. The results do not indicate a variation of the series resistance along the operating point on the high voltage portion of the I-V curves. We conclude that each module has cells that are nearly identical such that the 7-parameter, double exponential model is indeed valid for the modules. The diffusion-diode quality factor has been found to vary and is larger than 1 for the three modules that were tested. It is therefore not correct to set this value a priori to 1, as is done in some five- or six-parameter models. In further work, we will further refine the method, and also investigate its applicability for finding the remaining three parameters of the seven-parameter model.
ACKNOWLEDGEMENT

The authors acknowledge financial support by Elkem Solar, the Research Council of Norway and the Municipality of Kristiansand. We further thank Torfinn Buseth and Jan Ove Odden at Elkem Solar for technical expertise, valuable discussions, and sharing of PV module reference data as measured by the independent laboratory in Germany. Special thanks are due to Erling Andresen as well as the technical staff and the students from Kvadraturen Skolesenter in Kristiansand. They have contributed in an important way to the project by building the mechanical frames and support structures for the PV modules, and by doing the electrical cabling, all done very professionally.

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