

EXACT ANALYTICAL CALCULATION OF THE ONE-DIODE MODEL PARAMETERS FROM PV MODULE DATA SHEET INFORMATION

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ABSTRACT: This paper portrays a novel and enhanced unambiguous procedure that is suitable for the calculation of the six unknown one-diode parameters from PV-module data sheets. Before applying our proposed method to the manufacturer's data of more than 2000 solar panels, the most crucial information was integrated with the simulation environment known as INSEL[®]. After using the parameter identification procedure, whose routine was also implemented as a block in INSEL, negative resistances were practically absent and the simulated solar cell characteristics did not seem to differ drastically from the exact calculations of a two-diode fit. When calculating at high irradiances with the depicted procedure, the simulated performance showed negligible prediction errors within an order of magnitude of around -0.2%, nonetheless at lower levels (< 200 W/m²) underestimation errors as from around -23% took place. At a prediction level of approx. -3%, energy yield prognoses can reliably be simulated using the proposed parameter identification procedure.

Keywords: simulation, one-diode model, curve fitting, photovoltaic cells.

1 INTRODUCTION

Nowadays, significance has been attached to the quality of the computational results from simulation tools to prognosticate energy yields of PV-systems. The decision whether the PV-system can be considered or not as a profitable project in real-world contexts, is mostly thrown back on the results of the yields report.

Beyond question, the knowledge of mean monthly global radiation values of many years at the project location becomes the most crucial factor. If such values are off the mark around five percent, there is no simulation software in the world that computes energy yield prognoses with a calculation error slighter than five percent. Modeling of the PV-Generator per se depicts the second most important factor.

When calculating energy yields prognoses for crystalline silicon solar cells, nobody computes I-V sweeps with a more accurate emulation than the one known as two-diode model. The main problem hereby consists of the fact that such parameters are exclusively known only for a few PV-modules.

Curve fitting based on the two-diode model parameter procedure from experimental I-V solar cell characteristics can accurately simulate PV-modules. However, experimental I-V characteristics, which can be obtained from conventional flash solar cell testers, are normally unavailable. Additionally, the six unknown two-diode model parameters are not commonly given by manufacturers.

While neglecting charge carrier recombination inside the junction space-charge zone, the one-diode model can alternatively be used to simulate I-V solar cell curves. Some physically senseless results like negative series resistances or exaggerated diode ideality factors have been reported while using the classical equivalent circuit model [1,5]. The series resistances calculated by our method as shown in Figure 1 do not confirm this statement!

There are, however, fast fit procedures which numerically determine the two-diode model parameters using for instance flash solar cell testers during the solar cell production.

After all, what is known about certain types of PV-modules are the data sheets that portray the module behavior under STC (at 1000 W/m² irradiance, cell junction temperature of 25°C, AM1.5g solar spectrum) as well as the voltage and current temperature coefficients. The one-diode model works well for the most admissible simplification of the two-diode model and has often been taken as reference in simulation software tools for calculation of energy yields prognoses.

Duffie and Beckman reported since 1991 that these parameters could relatively easily be computed from the data sheet information [1]. However, assumptions must thereby usually be made (e.g. the surmise of an initially infinitely high parallel resistance) which inevitably lead to hardly estimable errors when generating energy yield prognoses.

We report an exact analytical procedure to calculate the one-diode model parameters that is purely based on the data sheets of the module manufacturers and which unambiguously simulates such information. For that matter, this paper portrays within which order of magnitude lay the error between prognosticating energy yields of PV-systems for many years using the proposed parameter identification procedure in comparison to the curve fitting of the two-diode model.

2 TWO-DIODE MODEL

Crystalline silicon solar cells are wide-area diodes whose physics could be explained according to the Shockley theory. In consequence, the current-voltage characteristic of ideal solar cells can be described by the following diode equation:

$$i_s = c_s T^3 \exp\left(-\frac{E_g}{kT}\right) \left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

where c_s , the Shockley saturation diode parameter, is the unique free parameter obtained from fitting.

The other physical constants beside it are: Band gap of the semiconductor material E_g , Boltzmann constant k , Elementary charge q as well as the voltage V , photocurrent losses due to charge carrier diffusion or also called Shockley current density i_s - and temperature T .

According to the Shockley theory, the one-diode model neglects the ever-present recombination opportunities of the energetically excited charge carriers in the junction space-charge region.

Nevertheless, if carrier recombination of the material is considered, the resulting current is given by:

$$i_r = c_r T^{5/2} \exp\left(-\frac{E_g}{2kT}\right) \left(\exp\left(\frac{qV}{2kT}\right) - 1\right)$$

where c_r , the photocurrent losses due to charge carrier recombination, is a temperature coefficient obtained using parameter fitting and.

The hereinafter equation, which represents the so-called two-diode model and whose solution can only be solved using iterative loops, is obtained from the mathematical relationship between temperature and the irradiance-dependent photocurrent $i_{ph} = (c_{ph} + c_r T)G$ in compliance with leakage currents characterized by the Shunt resistance r_p and the consideration of the voltage drop across the series resistance r_s ,

$$i = i_{ph} - i_s - i_r - \frac{V + ir_s}{r_p}$$

where c_{ph} is the photocurrent coefficient and the term ir_s , known as the voltage drop across the series resistance r_s , should be considered over the current densities i_s and i_r , i.e. voltage across the internal photodiode $V+ir_s$ should be used with all parallel components of the circuit instead of only considering voltage at the consumer V also called outside voltage measured at the contact of the solar cell.

Hence, the physical behavior of crystalline silicon solar cells can be depicted with the six one-diode model parameters c_{ph} , c_r , c_s , c_r , r_s and r_p - this also applies for CIS solar cells and in the case of amorphous silicon (a-Si), the voltage dependence of the photocurrent must be considered.

The difficulty in determining the parameters for a well-defined solar cell or PV-module could basically be solved in two ways:

If one or more experimental I-V characteristics are available, the six unknown parameters of the two-diode model can be adjusted to measured data using a fitting procedure that is already integrated in the simulation environment INSEL and which minimizes the deviations between measured and fitted data.

By using this parameter procedure, the PV-module can be simulated across the whole radiation range at the chosen location within an error of less than 0.5 percent.

Mostly, however, the data sheets of the PV-module manufacturer are the only available information. In this case, the parameters must be computed using analytical equations, for example using the one-diode model. The authors have derived equations to calculate all six parameters required for the one diode equation.

3 ONE-DIODE MODEL

Despite the fact that the Shockley and recombination current are linearly independent, both currents are frequently joined together under the introduction of a non-physically diode ideality factor n_s and this concept is also known as one-diode model.

$$i = i_{ph} - c_s T^3 \exp\left(-\frac{E_g}{kT}\right) \left(\exp\left(\frac{q(V + ir_s)}{n_s kT}\right) - 1\right) - \frac{V + ir_s}{r_p}$$

The one-diode model for simulation of I-V sweeps of solar cells and PV-modules has a reputation of insufficient when trying to describe the real behavior of the solar cells. Based on expert literature, it is insinuated that the one-diode parameter determination leads to physically senseless values like negative series resistances [1].

Furthermore, it is usual accepted, that it is not possible to calculate the six two-diode model parameters from the five parameters obtained from manufacturer's information and as a side effect, the modeled nominal power can not suit with the previously given power. The five parameters based on the data sheet of the module manufacturers are: nominal power (V_m , I_m), short-circuit current I_{sc} and its temperature coefficient α_r , open-circuit voltage V_{oc} and its temperature coefficient α_v . But, indeed, from these counterarguments it could be derived, that the use of the MPP-condition has so far been disregarded. Since the derivative of the power to the voltage at MPP has to be zero $dP/dV = 0$, the data sheets of PV-module manufacturers comprise the sixth linearly independent equation for the parameter determination. Thus, the six unknown one-diode model parameters including the shunt resistance could unambiguously be calculated from the data sheet given by module manufacturer's information.

With little algebraic analysis and mathematical effort one comes to an equation system -to find the six unknown parameters- that could simply be solved using a pocket calculator. This work shows how the proposed procedure has been applied on a Database [3], which comprises information of more than two thousand PV-modules. Subsequently, the most relevant information has been integrated with the simulation environment INSEL [4]. Figure 1 shows clearly, how negative series resistances did not practically occur using the proposed parameter identification procedure.

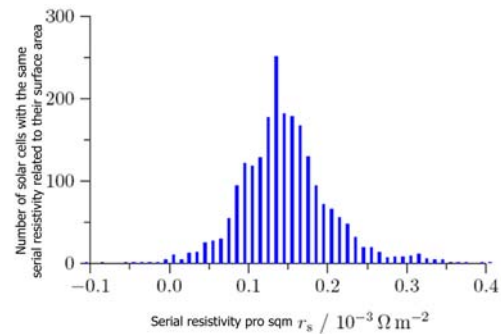


Figure 1: Serial resistivity over the surface area of more than 2000 solar panels from the Photon Solar Module Market Review 2006 [3].

But the problem therein consists in using data sheets of the PV-module manufacturers, which do not normally specify the behavior of the current drop curve within voltage intervals near MPP. This error can only be avoided by means of a curve fitting of the two-diode model to an experimental I-V characteristic.

The measured current-voltage characteristic of a reference solar cell and its corresponding performance curve are portrayed in Figure 2. The best curve fitting of the two-diode model to the measured data is additionally plotted on the same Figure. To the naked-eyed, both curves on Figure 2, are barely distinguishable each other.

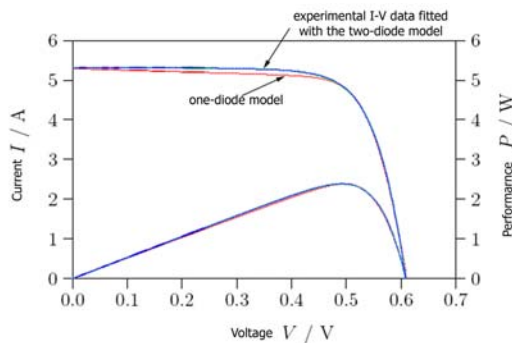


Figure 2: Simulation of the reference solar cell characteristics under STC to portray the adjustment of the six unknown parameters of the two-diode model to measured data by means of INSEL.

The third couple of curves -with lower current and performance - were analytically calculated according to the above-mentioned parameter identification procedure.

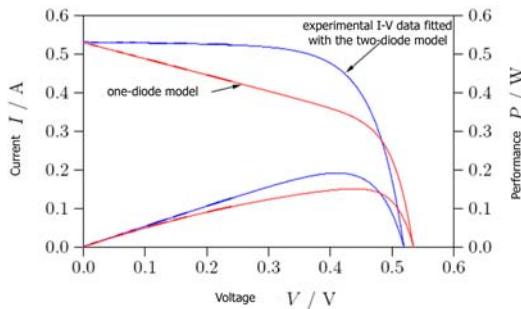


Figure 3: Simulation of the reference solar cell characteristics at low irradiances levels of approx. 100 W/m² and cell temperature of 25°C to depict a comparison of the proposed method and the experimental curves adjusted to the two-diode model using INSEL.

The employed data sheet's information for the parameter adjustment from PV-module data sheet were: open circuit voltage 0.60881 V, short circuit current 5.3125 A, voltage at maximum power point 0.49223 V and its matching current 4.8329 A, temperature coefficient of the short circuit current 0.003397 A/K, temperature coefficient of the open circuit voltage -0.002222 V/K. As a result, the nominal power of the solar cell using the proposed parameter identification procedure amounted approx. 2.3789 W.

Owing to small rounding errors, the nominal power of the solar cell using the accurate curve fitting of the two-diode model to experimental data amounted to

2.3839 W, ergo the nominal power using the proposed parameter identification procedure was underestimated around 0.2 percent comparatively to the curve fitting of the two-model to the measured data. At high irradiances, the deviations between the three cases seemed to be negligible.

However, as shown in Figure 3, by putting the curves under the microscope at lower irradiances (100 W/m²), the substantial divergence between the real solar cells - i.e. simulated curves using the perfect fitting of the two-diode model to measured data- and the analytically calculated characteristic -i.e. simulated curves by means of manufacturer's data sheets- attracts attention. As shown in Figure 4, the deviation of the power by operation at MPP lay approx. 44.1 mW or around 23.1%.

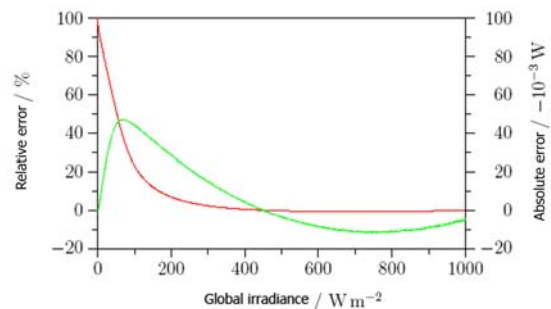


Figure 4: Relative and absolute errors between using curve fitting of the two diode model to measured data and using the analytical calculation of the one-diode model parameters from module data sheets.

4 EXPERIMENTAL RESULTS

4.1 Munich, Germany.

For eight years (from 1998 until 2005) we have calculated, to what degree the divergences between both approaches in question impact on the energy yield simulation of a grid-connected PV-system made up of the reference cell in Munich.

Starting points of the meteorological data were the mean monthly solar radiation published on the German Magazine called "Sonnenenergie" by the Germany's National Meteorological Service, also known as Deutscher Wetterdienst (DWD), as well as the mean monthly ambient temperature that the DWD brings out on the home page www.wetter.com.

Hence, the mean hourly global solar radiation on a south facing tilted surface with 30° slope was calculated using the standard procedure of the simulation environment INSEL. Moreover, the hourly energy yield at the MPP of the solar cell has also been calculated using both parameter-based models, whose routines are already implemented as INSEL-blocks.

The energy yield of the solar cell due to the curve-fitting of the two-diode model to measured data amounted to 23,2 kWh and using the analytical calculation of the one-diode model parameters from PV-module data sheets around 22,4 kWh, i.e. the proposed procedure underrated the energy yield prognoses before the inverter by 3.30% comparatively to the calculations based on the two-diode model.

When converting such energy yield into 1 kW peak power, the values added up to around 1219 or otherwise 1176 kWh/kWp. It should hereby be considered, that this information was only energy yield before the inverter and that the hot summer 2003 was comprised within the simulation period.

After the commercial inverter (in this case, we have normalized the performance curve of a Conergy IPG 280K on the reference solar cell) reached an energy yield of about 22,01 kWh and 21,28 kWh or in other words 1157 and 1116 kWh/kWp, i.e. only 3.34 percent less energy yield than without the inverter's simulation.

4.2 Scharnhäuser Park Ostfildern, Germany.

The Scharnhäuser Park area in Ostfildern, Germany is mostly connected to the local district heating system which is fed by a biomass-fueled combined heat and power station (BCHP), whose roof-integrated PV-system and BIPV-façade supply to the system around 35 kWp additionally to the 1.2 MWel delivered by the wood chip cogeneration plant. As shown in Figure 5, an array of 70 PV-modules SunTechnics STM200F powered by SunPower's A-300 solar cells are integrated on the building façade and boast around 14 kWp. The roof of the BCHP-station carries 99 modules STM 210F rated at 210 Wp each. The whole PV-system powers seven SMA-inverters, whose performances are online monitored at the University of Applied Sciences Stuttgart.



Fig.5: BIPV in Scharnhäuser Park Ostfildern with 70 dark backsheet modules STM200F (SunTechnics).

The following facts were analyzed before modeling the PV-system in INSEL: both models of panels are composed of 72-series connected A-300 solar cells made by SunPower Corp. and which deliver a panel conversion efficiency of around 17%. Single-band gap A-300 solar cells have an efficiency up to 21.5%, $J_{SC}=39.5 \text{ mA/cm}^2$, $V_{OC}=678 \text{ mV}$, $FF=803$. Similar properties of high efficiency CIGS solar cells ($V_{OC} = 701 \text{ mV}$, $J_{SC} = 34.6 \text{ mA/cm}^2$, $FF = 80\%$, efficiency = 19%) have been reported by NREL, whose results suggested band gaps of about 1.2 eV. [6] A-300 solar cells are made of photovoltaic grade float zone silicon (PVFZ-silicon) with extraordinary lifetime properties of approx. $> 1 \text{ ms}$ [7]. The dielectric SiO_2 -passivation layer enhances the longwavelength response of the cell (power generated within a spectrum of light between 330-1170 nm [8] against just 1100 nm from crystalline silicon [9]) and is commonly used in BIPV applications.

The voltage temperature coefficient of such solar cells amounts to $-1.87 \text{ mV/}^\circ\text{C}$ that leads to a temperature coefficient on power around $-0.38\%/^\circ\text{C}$, i.e. the dP/dT is with 24% more optimal than typical silicon solar cells [10].

Conversely, SunPower cells are doped with low-iron glass with solar transmittance $>91\%$ and lightly-textured glass is used to minimize harsh reflections from the front surface of the glass. A TPE (Tedlar/Polyester/EVA) layer protects the module against environmental stress. The light trapping effect of the A-300 solar cell enhances its thickness about six times [11].

Since the A-300 solar cell has a much broader spectral response than conventional crystalline silicon solar cells, the simulation in INSEL was carried out considering a band gap bigger than 1.124 eV and an optical absorption coefficient of approx. 90%.

Experimental IV-swepts of SunPower solar panels from data sheet information and from technical papers [12] were adjusted to the two-diode model using the INSEL-block PVFIT2. The SunPower modules SPR-210 and SPR-200 were taken as reference due to their similarities with the data sheets of the SunTechnics PV-modules that were fabricated using the same 72-series connected A-300 solar cells.

From the data sheets of the SunTechnics modules, the most relevant information depicted in Table I was extracted in order to calculate the one-diode model parameters using the INSEL-block PVDET1. Subsequently, a simulation was made to depict the physical behaviour of the PV-system. Figure 6 depicts IV-characteristics and power curves obtained by using both parameter approaches.

Description	roof-integrated	BIPV-Façade
Module data	STM210F	STM200F
Number of cells	cells	72 A-300 cells
Cell manufacturer	SunPower	SunPower
Total cell area [m ²]	0.0148904	0.0148904
Open Circuit Voltage [V]	47.8	47.8
Short Circuit Current [A]	5.7	5.4
Rated Voltage [V]	40	40
Rated Current [A]	5.25	5
Peak power [W]	210	200
Voltage temperature coefficient [mV/K]	-138.142	-138.142
Current temperature coefficient [mA/K]	2.268	2.268
Power temperature coefficient [%/K]	-0.38	-0.38
Module efficiency [%]	16.83	16.03

Table I: Manufacturer data of the PV-modules

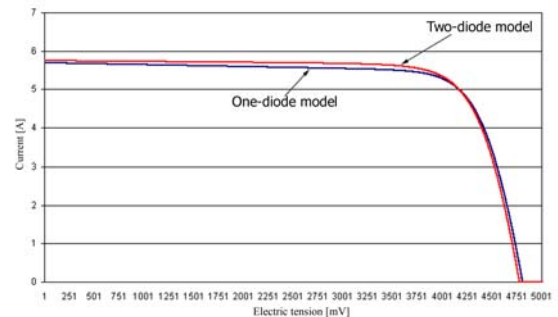


Fig.6: Comparison of IV-curves under STC of the solar panels STM210F and SPR210-WHT calculated by using both parameter-based procedures.

The online monitoring of both PV-devices took place using the state of the art of SMA-data technology with the aim of transmitting measured channels to the Zaff.net Research Centre by using a FTP. Measured meteorological data were used as inputs of the INSEL-model to simulate the 14KWp BIPV- and the 21KWp roof-integrated PV-system. As shown in Figure 7, simulated channels like energy harvest and AC-power for a sunny day in July 2007 were computed in INSEL by using the PVI-Block under NOCT-mode; the results were compared with measuring channels from the data logger and with a curve fitting to the two-diode model from a similar I-V swept, namely from the experimental I-V data written on the data sheets from the SunPower panels SPR-200 and 210.

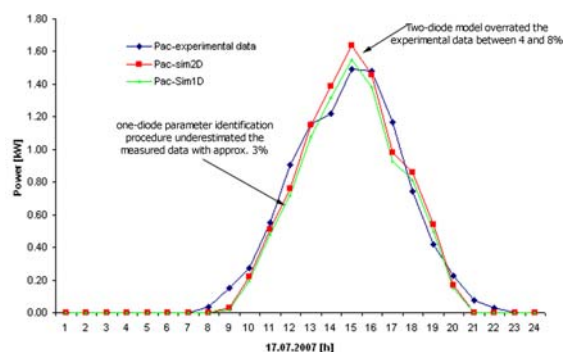


Fig. 7: AC-Power comparison between simulated and experimental-data (hourly step) from a SMA-Inverter SB3000 of the roof-integrated PV-installation at the BHP-station in Scharnhäuser Park Ostfildern, Germany

The simulated results of the seven PV-generators using the proposed approach averagely differed by 3% from measured energy production. As portrayed in Table II, the two-diode model overestimated the energy yields between 4% and 8% due to different voltage and current temperature coefficients in comparison to the solar panels taken as reference and due to different peak power tolerances between North American (+/-5%) and European Markets (+/-3%).

The former PV-modules STM200F and 210F had even peak power tolerances of approx. -0/+3% and the next models STM210FBS/WS were launch on the market with +/- 3% [13].

NOCT Inverter	Qty.	PV-array	Experimental data [KWh]	Simulated data			
				1-diode model	2-diode		
SMC6000	3	roof-integrated	901	865	-4.00%	937	4.00%
			860	865	0.58%	937	8.95%
			845	865	2.37%	937	10.89%
			Total	2606	2595	-0.42%	2811
SB3000	3	BIPV-Facade	221	217	-1.81%	231	4.52%
			231	217	-6.06%	231	0.00%
			207	217	4.83%	231	11.59%
SB2800i	1	BIPV-Facade	204	193	-5.39%	205	0.49%
PV-system	7	Total	863	844	-2.20%	898	4.06%

Table II: Results of an INSEL-Simulation with both parameter procedures under NOCT-conditions related to experimental data (July 2007) from the PV-installation at the BHP-station in Ostfildern, Germany.

5 CONCLUSION

All these facts point to the conclusion that:

When calculating the output yield of photovoltaic systems, solely by virtue of modeling solar cells – entirely aside from performance tolerances, shading, mismatch losses, ohmic losses caused by the electrical resistance of the wiring, snow-covered areas with high albedos, loss of effectiveness due to dirt as well as other irregularities - the prediction error is between three and four percent. In order to ensure an energy yield calculation with higher accuracy, the I-V characteristic of the PV-module must be known with more preciseness than the one simulated from the PV-module data sheet information.

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