PERFORMANCE ASSESSMENT OF A SIMULATION MODEL FOR PV MODULES OF ANY AVAILABLE TECHNOLOGY

André Mermoud, Thibault Lejeune
Institute for Environmental Sciences / Energy Group, University of Geneva,
Battelle, Bât. D, 7, route de Drize, CH-1227 Carouge – Switzerland
andre.mermoud@unige.ch – thibault.lejeune@unige.ch

ABSTRACT: From long-term detailed measurements of several PV modules of all commercialized technologies, this work aims to analyze the results of the "standard" one-diode model, and suggests some modifications for improving it, especially for amorphous, microcrystalline and CdTe modules. We found that for any module an exponential behaviour of the shunt resistance parameter should be taken into account. We identified two other corrections (recombination losses and spectral correction) in order to improve the modelling of amorphous technology modules. These improvements have been implemented in the PVsyst software developed at the University of Geneva.

Keywords: Modelling, Performance, Thin film.

1 INTRODUCTION

Thin film photovoltaic (PV) modules (amorphous a-si:H, CIS, CdTe or µC-a:Si technologies) present the most promising opportunity to significantly decrease the prices of PV in the future, as they need a very limited quantity of pure materials, and the manufacturing processes may be simplified. Their energetic return time is usually lower than one year.

Their commercial development is rapidly growing. Therefore any simulation tool should be able to accurately evaluate their performances in a PV system in real conditions, and to compare them with the traditional Si-crystalline solution

Many teams report measurements of whole PV systems equipped with thin film modules, and observe seasonal, irradiance or temperature behaviours different from crystalline modules. But there is no consensus on how to interpret these data and "a fortiori" how to model them.

The aim of this study is to establish a consistent model that can be used in software dedicated to PV systems simulation (like PVsyst).

2 MEASUREMENTS

Our approach is mainly phenomenological, based on detailed comparisons of outdoor measurements of the I/V characteristics and model predictions. Our PV module test facility is located on the roof of our building at the Geneva University, and operates since 2004 (Mermoud [4]). Outdoor measurements are recorded every 10 minutes in order to provide a significant sample containing all irradiance and temperature conditions. These measurements are performed on 8 modules simultaneously – one mono-crystalline for calibrations, one CIS, and others of various technologies.

Each record includes 30 points distributed along the I/V curve and measurements of irradiances with pyranometers (global in the module plane, $Glob_P$, global and diffuse in the horizontal plane, $Glob_H$ and $Diff_H$ respectively), as well as the module's and external temperatures. In addition, irradiances measured by a PV-cell are recorded before, at the middle and at the end of the measurement in order to check the stability of the irradiance (the pyranometer has a time constant of ~ 30 sec). After a selection process – mainly according to irradiance stability – our sample contains several thousand of records for each module.

3 ESTABLISHING THE "STANDARD" MODEL

A valid model should reproduce the electrical behaviour of a PV module under any external conditions (irradiance, temperature, incidence angle, spectral contents). Furthermore, in order to be applied in a simulation software, the model should be established with a minimum number of "extra" parameters not usually provided by the present-day manufacturer's datasheets.

The starting point of this study is the usual one-diode model (hereafter referred as the "standard" model), established for a crystalline-Si cell and extended to the whole module (Duffie *et al.* [2]):

$$I = I_\Phi - I_0 \left[e^{\left(q \frac{V + I \cdot R_S}{N_{CS} \cdot \gamma k T_C} \right)} - 1 \right] - \frac{V + I \cdot R_S}{R_{Sh}} \qquad (1)$$

where

I, V: Current and voltage at module's terminals,

I_Φ: Photocurrent at the measured irradiance G_{meas}, proportional to irradiance ($I_{\phi,ref}$ at the reference diance G_{ref})

I_0: Diode saturation current, varies exponentially with temperature, ($I_{0,ref}$ at the reference temperature T_{ref}).

R_{Sh}: Shunt resistance, inverse of the slope around short-circuit (I_{sc}) point,

R_S: Series resistance (may vary between 0 and a R_S^{MAX} value),

γ: Diode ideality factor (should normally lie between 1 and 2 per junction),

q: Charge of the electron,

N_{CS}: Number of cells in series

For the generalization to other technologies, we try to identify the modifications required to match the measured data (cf. Mermoud [4] for a complete description of our approach). The final objective is to describe the module behaviour under any operating conditions, from a unique set of parameters.

The 5 basic parameters ($I_{\phi,ref}$, $I_{0,ref}$, R_{Sh}, R_S, γ) are established using one I/V characteristics, chosen in our sample as a reference curve. For the corresponding reference conditions (G_{ref}, T_{ref}), we can directly establish the R_{sh} parameter (slope around I_{sc}), and write the equation (1) at 3 points (I_{SC}, 0), (V_{mp}, I_{mp}), (0, V_{oc}). Then, setting the R_S parameter, we can solve the equations in order to determine $I_{\phi,ref}$, $I_{0,ref}$, and γ. We adjust R_S with the value that provides the best match of I/V curve.

This provides the model for expressing the full I/V characteristics at reference conditions.

Now we use the following expressions for extending the model to any Irradiance and Temperature conditions:

$$I_\phi = \left(\frac{\phi}{\phi_{ref}}\right) \cdot \left[I_{\phi,ref} + \mu I_{SC} \cdot \left(T_C - T_{C,ref}\right)\right] \qquad (2)$$

And for the diode saturation current:

$$I_o = I_{0,ref} \cdot \left(\frac{T_C}{T_{C,ref}}\right)^3 \cdot e^{\left[\left(\frac{q\varepsilon_G}{\gamma k}\right)\left(\frac{1}{T_{C,ref}} - \frac{1}{T_C}\right)\right]} \qquad (3)$$

where ε_G is the Gap energy of the material (1.12 eV for Si).

4. MODEL QUALITY CHARACTERIZATION

Now we can apply the model for each (G_{meas}, T_{meas}) measurement, and compare the model results to the measured I/V characteristics. For the assessment of the model, three distributions are analyzed:

- the maximum power P_{MAX}, which is of course the basic result expected for use in the simulation of systems with MPP tracking,
- the short circuit current, I_{SC}, whose value is quasi-identical to the photocurrent,
- the open circuit voltage, V_{OC}, whose evolution is strongly determined by the internal behaviour of the model, especially according to temperature.

We avoid using the V_{MP} and I_{MP} distributions as final indicators, because they are not determined with high accuracy (they depend on the curve shape) and are strongly correlated (only their product P_{MAX} is relevant).

Observed distributions of differences between measured and predicted data (often called “errors”) are analysed as function of the relevant variables (irradiance, temperature) and quantified by the Mean Bias Differences (MBD, noted μ) and the standard deviation (the Root Mean Square Differences RMSD, noted σ). MBD and RMSD are usually expressed as percentage of the nominal value (at STC).

These differences – measurement *minus* model – include not only the model inaccuracies, but also experimental uncertainties (irradiance and temperature measurements, misalignment, variable albedo, shadings, dirt, snow, etc).

The RMSD is representative of the spread of the results in different operating conditions. It is an indicator of the validity of model when conditions are varying. The MBE is sensitive to the primary parameters (I_{SC}, V_{OC}, V_{MP}, I_{MP}), i.e. on the chosen reference I/V characteristics. NB: These indicators are referred as percentage of the nominal values on each “measurement”. For getting an error relatively to the energy yield, i.e. the average power P_{aver} they should be renormalized by P_{nom}/P_{aver}, with P_{aver} usually about half of P_{nom}.

When using the model in a simulation software, the (I_{SC}, V_{OC}, V_{MP}, I_{MP}) parameter set will be the manufacturer’s specified STC values. As they will not be exactly representative of your module, you may have significant errors. But these errors are related to the parameter’s uncertainties, not to the model quality. The MBD can be significant, but if the model is good (with correct parameters) the RMSD should remain low (thin distributions). Therefore do not confuse **Model Accuracy** and **Parameter Accuracy**!

4.1 Incidence angle correction

The irradiance on the module is determined by the plane pyranometer measurement $\mathrm{Glob_P}$. But we should apply an Incident Angle correction (named IAM for “Incidence Angle Modifier”) to the beam component, accounting for the Fresnel’s laws about reflexions on the cover glass. We use the parameterization proposed by ASHRAE, i.e.

$$F_{IAM} = 1 - b_o\,(1/\cos i - 1) \qquad (4)$$

with i = incidence angle, and the parameter b_0=0.05.

We could not check this expression experimentally as this information is too difficult to extract from the data (the irradiance level effect mixes with this little effect). The Global and Diffuse horizontal measurements are used for the determination of the beam component.

5. RESULTS

5.1 Methodology check with crystalline modules

As a general “calibration” of our measurement procedure, we used several crystalline modules, for which the “standard” model is reputed to be developed.

We measured a Siemens M55 (Si-monocrystalline) during one year, an Atlantis M55 (Si-mono) during 2.5 years, as well as a Kyocera (Si-poly) during 5 years (up to now).

Results of the pure “Standard model” for the Siemens M55 are shown on Fig 1. We observe that the model underestimates the data at low irradiances.

But when analysing the shunt resistance (which may be measured on each I/V characteristics), we observe that it increases quasi-exponentially when the irradiance diminishes. If we model this behaviour (see next paragraph about amorphous), we obtain a flatter distribution, and better difference indicators, for P_{MAX} as well as for V_{OC} errors. (see comment of the Fig. 1).

The exponential R_{Sh} behaviour seems to be a general rule: we observed it on all modules we have analysed. This has an effect on the low-light irradiance performance: higher R_{Sh} diminishes the associated loss, therefore increasing the efficiency. This efficiency enhancement is more pronounced when the R_{Sh} at STC is low, as there are higher losses to be recovered.

The model’s parameters (R_S and R_{Sh}) are completely determined from the measured reference I/V characteristics. But when dealing with manufacturer’s data the slope around I_{SC} is not available, neither the full I/V curve, so that we have to make hypothesis on these parameters.

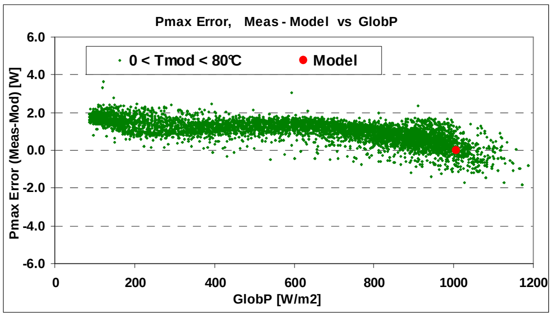


Figure 1: Errors distribution on P_{MAX} as function of $Glob_P$ for the Si-monocrystalline module M55.

Pure "standard" model:	**μ** = 1.9 % and **σ** = 1.1 %	on P_{MAX}
	μ = 1.1 % and **σ** = 1.0 %	on V_{OC}
With R_{Sh} correction:	**μ = 0.2 %** and **σ = 1.2 %**	on P_{MAX}
	μ = 0.4 % and **σ = 0.5 %**	on V_{OC}

5.2 Modelling a CIS module

We installed a CIS module (Shell ST40) since the beginning of the project. Surprisingly, this module is quasi-perfectly described by the "standard" model, even better than the crystalline one. CIS modules also need a R_{Sh} exponential correction, of the same order of magnitude as the crystalline modules. The results (measured-model differences), shown on Fig. 2 for a 6-years period, are impressive. They provide a valuable assessment of the long-term stability of our experimental setup (the March-April 2005 deviation on fig. 2 is due to a displacement of the temperature sensor).

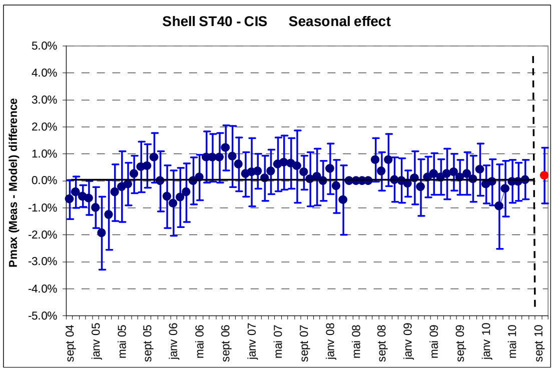


Figure 2: Error distribution for ST40 (CIS) over 6 years.

"Standard" model	**μ = 0.2 %** and **σ = 1.0 %**	on P_{MAX}
(with R_{Sh} correction):	**μ** = 0.0 % and **σ** = 0.9 %	on V_{OC}
	μ = 0.5 % and **σ** = 0.8 %	on I_{SC}

5.3 Amorphous triple junction

The primary objective of this work was the modelling of amorphous modules. Our first object of study was a triple-junction Unisolar tile module (SHR-17). With 3 superposed cells (sensitive in the blue for top, green-yellow for middle and red for bottom), these modules are not the simpler ones, but we had already some preliminary results about them.

In a first step, we tried to apply the "standard" model to such a complex system. A first observation was that for any measured I/V characteristics, it is possible to find a set of parameters of the standard model, for which the model perfectly matches the measured I/V curve. That means that the "standard" model is able to well represent the electrical behaviour. But, the problem is that a different set of parameters is required for each (G, T) conditions.

In a second step, we tried to find how the model parameters behave according to external conditions. Or more generally, we looked for possible corrections to the model for matching our data. Three (sometimes four) main modifications of the "standard" model are necessary.

1) Shunt resistance exponential behaviour

As for crystalline modules the measured R_{Sh} is strongly dependent on the irradiance level. The high-irradiance R_{Sh} value is much lower with amorphous technologies (the I/V slope around I_{sc} is high), so that the associated losses are very high. But the exponential improvement toward low irradiances is also much more pronounced (by a factor of 12 for the $R_{Sh}(0)/R_{Sh}(\mathrm{STC})$ ratio, against 4 for crystalline modules).

The R_{Sh} distribution is shown on Fig. 3. We tried to approximate it with a simple exponential expression:

$$R_{Sh} = R_{Sh}(G_{ref}) + \left(R_{Sh}(0) - R_{Sh}(G_{ref})\right) \times e^{-R_{Sh}^{Exp}\cdot\left(\frac{G}{G_{ref}}\right)}, \qquad (5)$$

where G_{ref} is the irradiance for the reference I/V curve.

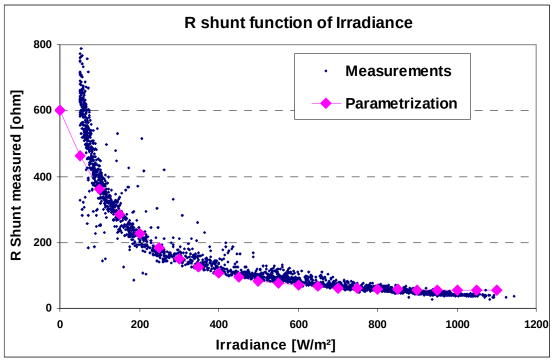


Figure 3: Amorphous triple-junction module SHR-17, ured R_{Sh} distribution and parameterization with an exponential factor $R_{Sh}^{Exp} = 5.5$ and $R_{Sh}(0) = 600\ \Omega$.

We found that the value $R_{Sh}^{Exp} = 5.5$ actually provides a good approximation of the R_{Sh} data for *most modules of different technologies* we have tested. Hence, the only parameter left in Eq. (5) is $R_{Sh}(0)$. However this is different for CdTe ($R_{Sh}^{Exp} \cong 2.0$) and micro-crystalline ($\cong 3.0$).

Using this corrected R_{Sh} when computing the model in a simulation is the most effective correction to the "standard" model for representing amorphous modules.

The measurement of the R_{Sh} value and its irradiance behaviour are very easy, using any I/V measured curve. These data are key parameters of the model, and should be part of the module's specifications in the future.

2) Recombination losses

While the standard model reproduces very well the V_{oc} and V_{mp} voltages for crystalline modules, it fails to predict the correct values for amorphous junctions. An additional term in the general I/V equation was proposed by Merten *et al.* [3] in order to explicitly take the recombination losses in the -*i*- layer of the *p-i-n* junction into account. In this region, where takes place the main part of the photocurrent generation, the recombination of pairs is rather intense, fostered by the presence of dangling bonds which act as recombination centres. This recombination current is in first approximation proportional to the charge carrier concentration, and hence to the photocurrent. On the other hand, it is related to the electrical field in the i layer. This leads to the following expression for the recombination current:

$$I_{rec} = I_{\varphi} \cdot d_i^2 / [\mu\tau_{eff} \cdot (V_{bi} - (V - I \cdot R_S))] \quad (6)$$

with

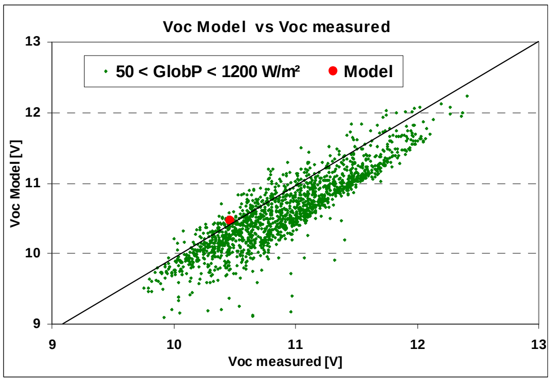
d_i^2: Thickness of the i layer (of the order of 0.3 μm),

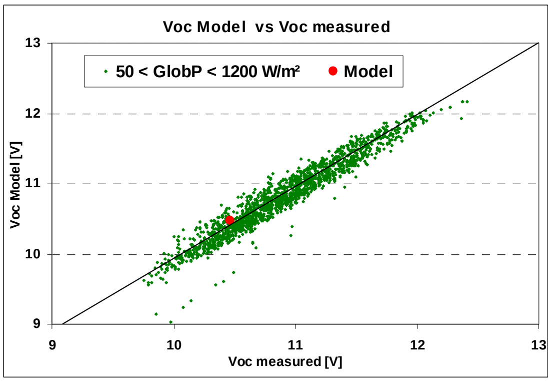
$\mu\tau_{eff}$: Effective diffusion length of the charge carrier,

$$\mu\tau_{eff} = 2\,\frac{\mu_n\tau_n \cdot \mu_p\tau_p}{\mu_n\tau_n + \mu_p\tau_p}$$

V_{bi} : Intrinsic potential of the junction (“Built-in” voltage). Its value may be considered as constant, about 0.9 V per junction (i.e. 2.7 V for triple junction).

The recombination current is a loss, which should be subtracted from the photocurrent. This corresponds to an additional term in the “standard” model. As it is voltage-dependent it modifies the shape of the I/V curve (which does not match anymore exactly the I/V measurement), and therefore is not a “perfect” correction. But we keep it as it improves drastically the errors distribution, as it can be seen in Figs. 4a and 4b.





Figures 4a and 4b: Distribution of the V_{oc} errors before and after applying the recombination correction for the SHR-17 module.

In our model, the “quantity” of recombination correction is defined by the parameter $d_i^2/[\mu\tau_{eff}]$ which we consider as a new model parameter that we named $d^2\mu\tau$. In our phenomenological approach, we establish its value by minimizing the errors, especially on the V_{OC} distribution, but which also acts on P_{MAX}.

When establishing the model for amorphous modules, we have now to determine 3 inter-dependent parameters (R_{Sh}, R_s and $d^2\mu\tau$), with a complex definition domain. We observed in all our modules that the $d^2\mu\tau$ parameter optimal value is high, around 80% to 90% of its maximum value. But this maximum value is itself strongly dependent on the R_{Sh} and R_S choices.

NB: The $d^2\mu\tau$ parameter corresponding to our data does not fit the theoretical value proposed by Merten *et al.* [3]. Until now, we do not have any explanation for that.

3) Spectral correction

In a-Si:H junctions, the gap energy E_{GAP} is around 1.6 eV, and therefore the spectral response of single amorphous junctions is only sensitive to photons of higher energy, i.e. with wavelength $\lambda < 0.73$ nm. Far red and IR photons are not energetic enough for creating an electron-hole pair.

Because we could not perform spectral measurements in our experiment, we used a correction model proposed by CREST[1] of the University of Loughborough (Betts *et al.* [4]). This model is based on an estimation of the spectrum energy contents in the incident irradiance, through the so-called APE variable (Average Photon Energy). Using one-year of spectral data, a “Utilizing Factor” UF, fraction of the spectrum really effective, is derived from the APE and the amorphous spectral response function. This UF may be parameterized according to known variables, i.e. the air mass and Kt_C (Clearness Index normalised to “Clear Day”), as shown in Fig. 5.

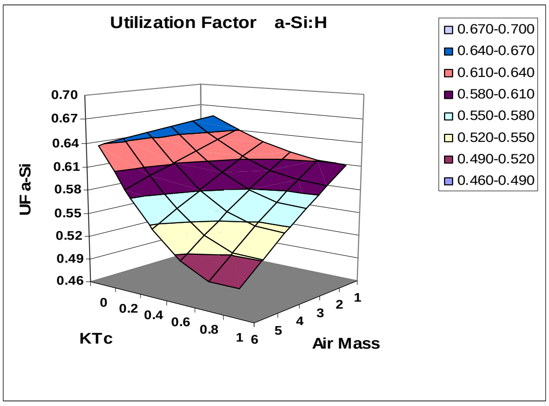


Figure 5: Utilisation Factor parameterization.

This correction is indeed not computed specifically for the triple-junction spectral response. Nevertheless, we decided to keep it as it slightly improves the final simulation accuracy (improvement of 0.6% on μ and 0.4% on σ).

The final results on this triple-junction amorphous module are the following (full year 2009):

μ = **0.1 %** and **σ** = **2.3 %** on P_{MAX}
μ = 0.3 % and **σ** = 0.5 % on V_{OC}
μ = 0.0 % and **σ** = 1.6 % on I_{sc}

Annealing seasonal effect

This is of course not as good as than for crystalline modules. But this technology is also subject to the Staeb-

[1] Centre for Renewable Energy Systems Technology

ler-Wronski annealing seasonal variations, which is not yet taken into account in our model. This effect is apparent on the 6-years evolution of the module's performance on Fig. 6. It is higher, or of the same order of magnitude, as the "monthly" accuracy σ of our model.

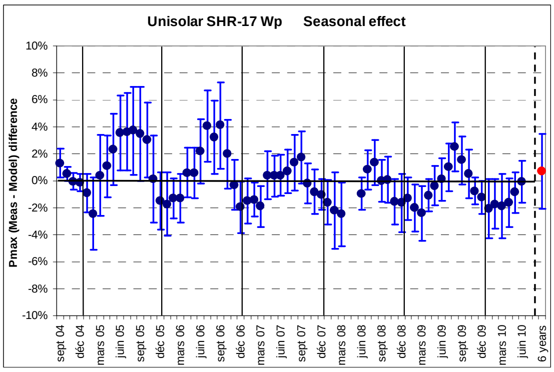


Figure 6: SHR-17 results over 6 years, annealing effect.

Global results: **μ = 0.7 %** and **σ = 2.8 %** on P_{MAX}

μ = 0.7 % and **σ** = 0.7 % on Voc

4) Temperature correction (eventual)

The temperature behaviour on P_{MAX}, noted μP_{MPP} [%/°C] is normally a result of the model. But this does not always match the specification of the manufacturer (although it is probably a better estimation). Many people require that the model is perfectly in accordance with the specifications. Therefore we defined an additional correction, i.e. a linear correction of the Gamma factor as function of the temperature, which affects the temperature behaviour of the P_{MAX} and the V_{OC} values. This correction allows to obtain any desired μP_{MPP} value, but usually degrades the accuracy of the model (i.e. degrades the σ value). Therefore we try to avoid using this artificial correction when possible.

6. RESULTS ON ANY TECHNOLOGIES

Our test facility is now running since 6 years with 8 channels available. We could experiment our model with modules of all technologies available on the market.

Crystalline modules: we "calibrated" our methodology with 2 monocrystalline (Siemens M55 and Atlantis M55, and have now valuable data of a polycrystalline Kyocera module over 5 years, which does not show any degradation.

CIS: In order to check a possible generalisation of the very good results on our old module, we have now a new CIGS module, ready to be installed on our test facility.

Amorphous, single junction: a little "Flexcell" module on flexible substrate, of VHF technologies.

Amorphous, tandem: Solarex MST-43MV and Asiopack 30. A module EPV-40 was analysed as sample of one of our measured system.

Amorphous triple junction: besides the SHR-17, we have data of a more recent model US-32 of Unisolar.

Micro-crystalline/amorphous: we have two modules from Sharp in test since just one year, with only preliminary results (due to initial degradation). We have a module of another manufacturer to be measured soon.

CdTe: we have measured 2 modules of Firstsolar since now 2 years. They behave in the same way as the amorphous modules (with recombination correction and annealing effect), but the spectral correction is not suited.

HIT (of Sanyo): we have a module ready to be measured, but not yet installed. Results should be available quickly as there is no initial degradation.

Fig. 7 summarizes the results of the differences (measurement – model) on P_{MAX}, V_{OC} and I_{SC} from our long-term measurements of modules of any technologies.

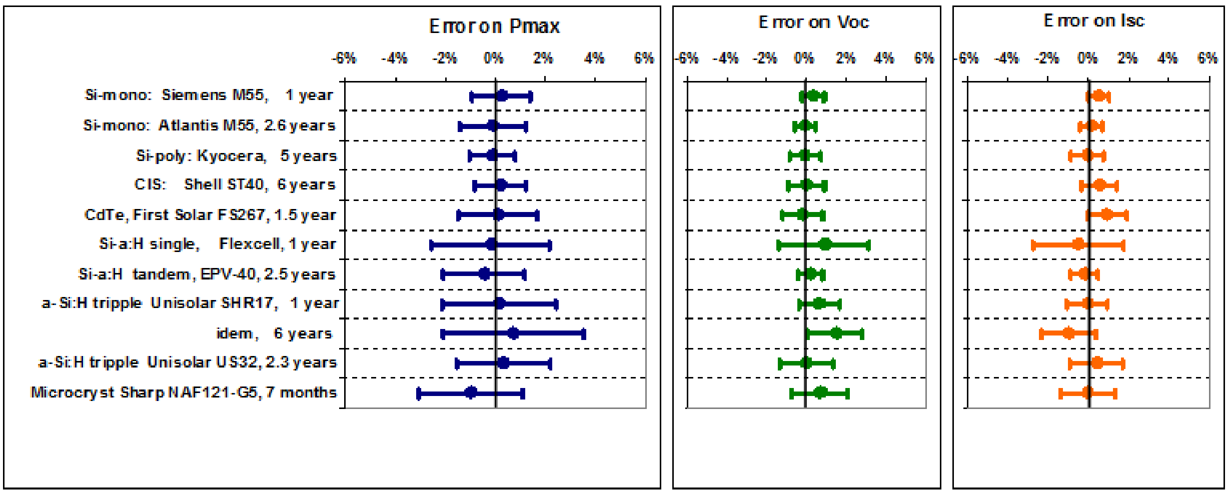


Figure 7. Long-term (Measurement-Model) results accuracy on modules of any technology (% of nominal values)

7. CONCLUSIONS

In this paper the accuracy of the "standard" one-diode model for crystalline and CIS modules was assessed.

With an exponential correction for the shunt resistance the accuracy of the RMSD between measured and modelled power values (σ) stays below 1.2% of the nominal power in any conditions over long periods (up to 6 years).

Trying to extend the "standard" model to amorphous technologies, we found that besides the exponential R_{Sh} (which is the main correction), the "standard" model requires two additional corrections: a "recombination" loss term proposed by Merten *et al.* [3], and a spectral correction computed by CREST (Betts *et al.* [1]). An additional correction on the γ value may be used when necessary for temperature behaviour matching.

With our triple-junction module, these corrections lead to an accuracy of σ = 2.3% over one year. But the seasonal annealing effect – which is not taken into account in our model – dominates the effect of these corrections. The monthly accuracies stay of the order of σ = 1.2%. All other amorphous modules lead to similar results.

The same model also applies to the CdTe technology modules, but the spectral correction proposed is not suited and is not used. The annealing effect is present but less pronounced, so that the 18-months accuracy is 1.4%.

The results on our micro-crystalline modules are slightly lower (σ = 2.1% over 6 months), but are still preliminary.

The corrections to the "standard" one-diode model proposed in this paper are implemented in the PVsyst simulation software (Mermoud [5]), developed by the Group of Energy at the University of Geneva since 1994.

8. REFERENCES

[1] T.R. Betts, R. Gottschalg, D.G. Infield. Spectral Irradiance Correction for PV system Yield Calculations, Proceedings of the 19th European Photovoltaic Solar Energy Conference, Paris, June 2004.

[2] J. A. Duffie, W. -A. Beckman, Solar Engineering of Thermal process, John Wiley and Sons, N-Y. 2^{nd} Ed., 1991.

[3] J. Merten, J. M. Asensi, C. Voz, A.V. Shah, R. Platz, J. Andreu, Improved Equivalent Circuit and Analytical Model for Amorphous Silicon Solar Cells and Modules. IEEE Transactions on Electron Devices, Vol. 45, No 2, Feb. 1998

[4] A. Mermoud, "Introduction des modules PV en couche mince dans le logiciel PVsyst", final report of SIG-NER project, ISE, University of Geneva, May 2005, www.unige.ch/cuepe/html/biblio/pdf/THF_RapportFinal.pdf

[5] A. Mermoud, "PVsyst: Software for the Study and Simulation of Photovoltaic Systems", ISE, University of Geneva, www.pvsyst.com.