PV module one-diode model - Parameter determination

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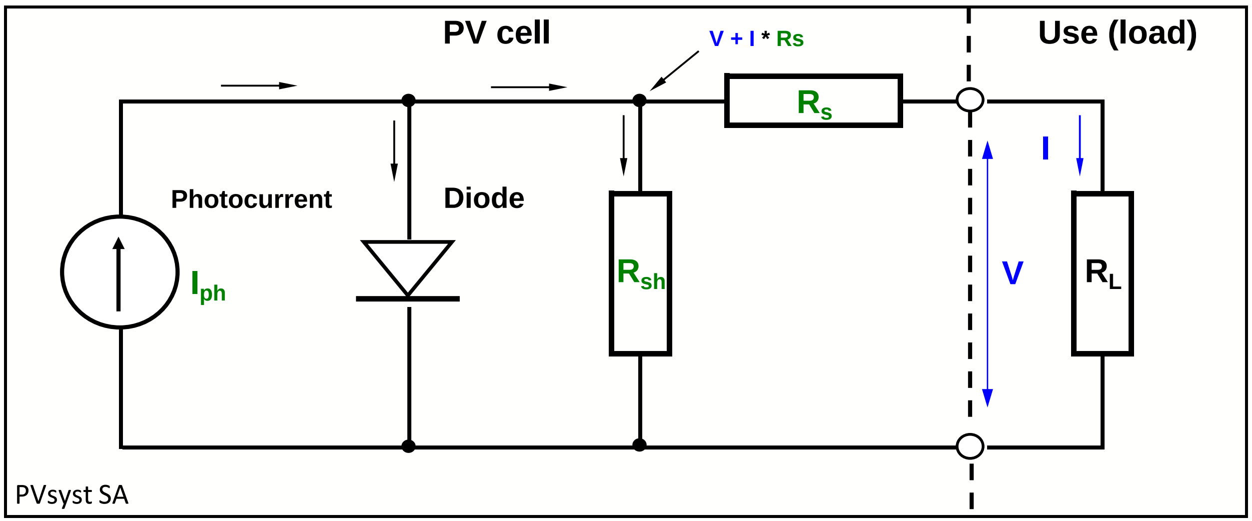
"Standard" 1-diode model

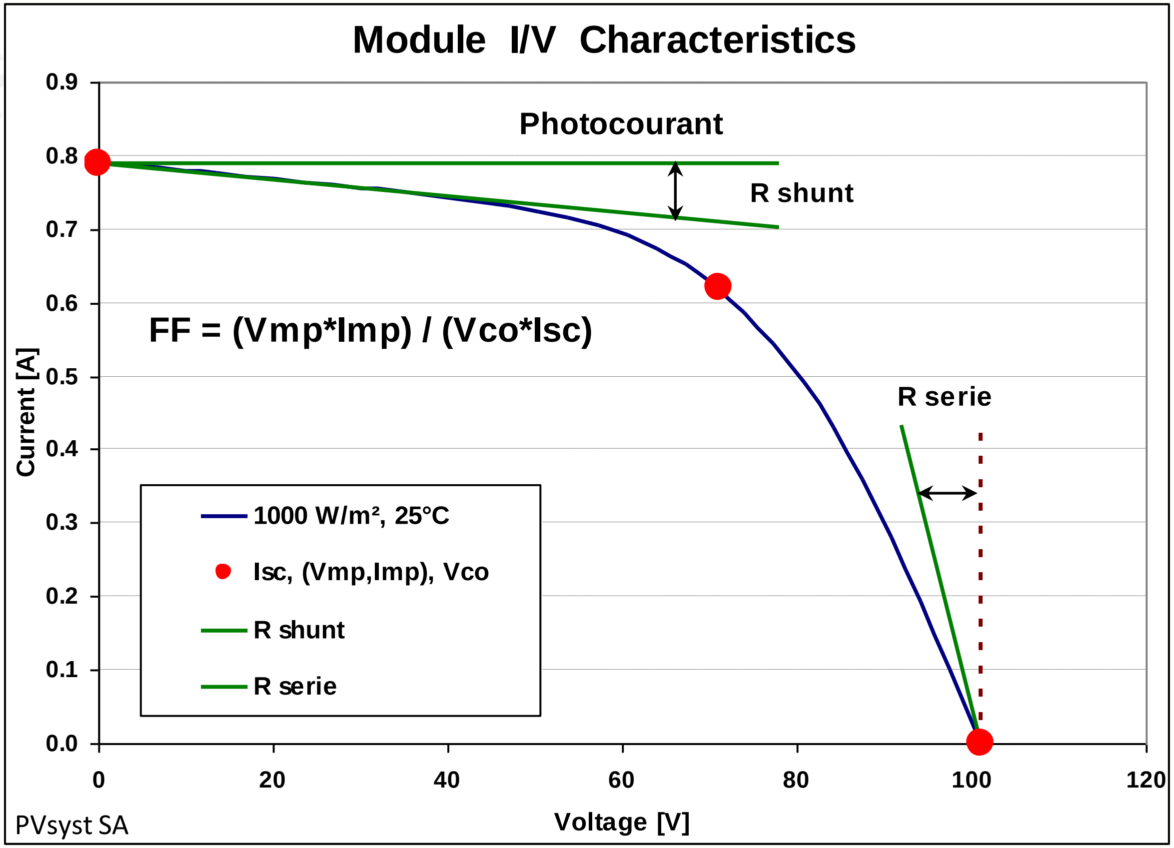
The PV cell may be represented by the equivalent electrical shema:



$$I = I_{ph} - I_o \left[\exp\left(q \cdot (V + I \cdot R_s) / (N_{cs} \cdot \gamma \cdot k \cdot T_c) \right) - 1 \right] - (V + I \cdot R_s) / R_{sh}$$

Photocurrent — Current in the diode — Current in Rsh

Interpretation of the 1-diode model



The Rserie
is not
the dV/dI
around Voc

$$I = Iph - Io\,[\exp(q \cdot (V + I \cdot Rs) / (N_{cs} \cdot \gamma \cdot k \cdot Tc)) - 1] - (V + I \cdot Rs) / Rsh$$

Different (G, T) conditions

The model has been established for reference conditions:

- G_{ref} = Irradiance when performing the measurement
- T_{cref} = Cell temperature during measurement

The photocurrent Iph is proportional to the irradiance :

$$Iph = (G / G_{ref}) \cdot [\, Iph_{ref} + \mu ISC \cdot (T_C - T_{C\,ref}) \,]$$

(small temperature dependence: $\mu ISC \cong 0.05\% \cdot ISC$ / °C)

The diode reverse saturation current Io varies with temperature :

$$Io = Io_{ref} \cdot (T_C / T_{C\,ref})^3 \cdot \exp\,[\,(q \cdot \varepsilon_G / \gamma \cdot k) \cdot (1/T_{C\,ref} - 1/T_C)\,]$$

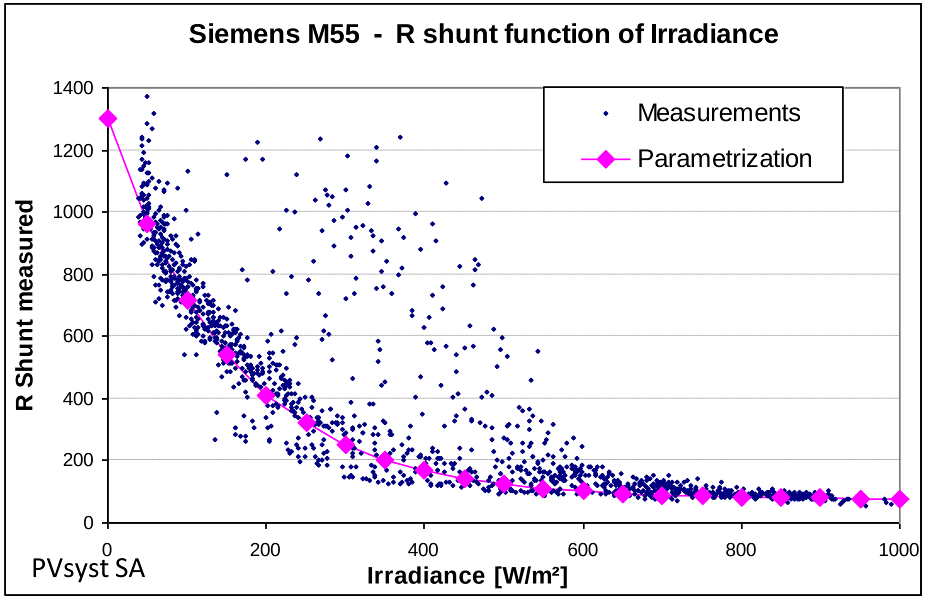
For matching the specified μPmpp, PVsyst includes a linear dependence on γ :

$$\gamma(T) = \gamma_{ref} \cdot (1 + \mu\gamma \cdot (T_C - T_{C\,ref}))$$

(μ denotes "Temperature coefficient", $\mu\gamma$ coeff. near 0, of the order of +/- 0.0003 / °C)

Rshunt Correction

The "standard" model supposes a constant Rsh.
Then we measure an exponential-like distribution:



$$R_{sh} = R_{sh\ base} + [\ R_{sh}(0) - R_{sh\ base}\ ] \ast \exp(-R_{sh\ exp} \cdot (G / Gref))$$

where: R_{shExp} fixed at 5.5 for almost all modules

$$R_{sh\ base} = (\ R_{sh}(Ref) - Rsh(0) \ast Exp(-R_{shExp})\ )\ /\ (1 - Exp(-R_{shExp}))$$

Parameters to be specified

- Iph_{Ref}, Io_{Ref}, γ_{Ref} : fixed by the the 3 ref. points (0, Isc), (Vmp, Imp), (Vco, 0) at STC

The Rshunt value may be measured on each I/V charactersitics ⇨ exp. with 3 parameters:

- Rsh_{Ref} : Measured at 1000 W/m²
  Default: taken as a fraction of the conductance (Isc-Imp)/Vmp
- Rsh_{exp} : Fixed to 5.5 - May be modified if direct measurements available
- Rsh(0) : Evaluated from the measured distribution of Rsh at different Irradiances
  Default: taken as 4 x Rsh(ref) - Should be increased to 10-12 x ?

- Rserie : Should be chosen for matching Low light efficiency
  Default : for getting specified γ value (diode ideality factor)

- $\mu\gamma$: Adjusted for matching the specified μPmpp temp. coefficient
  (the specified μVco cannot be reproduced accurately by the model)

- Rserie and $\mu\gamma$: check with Sandia model database

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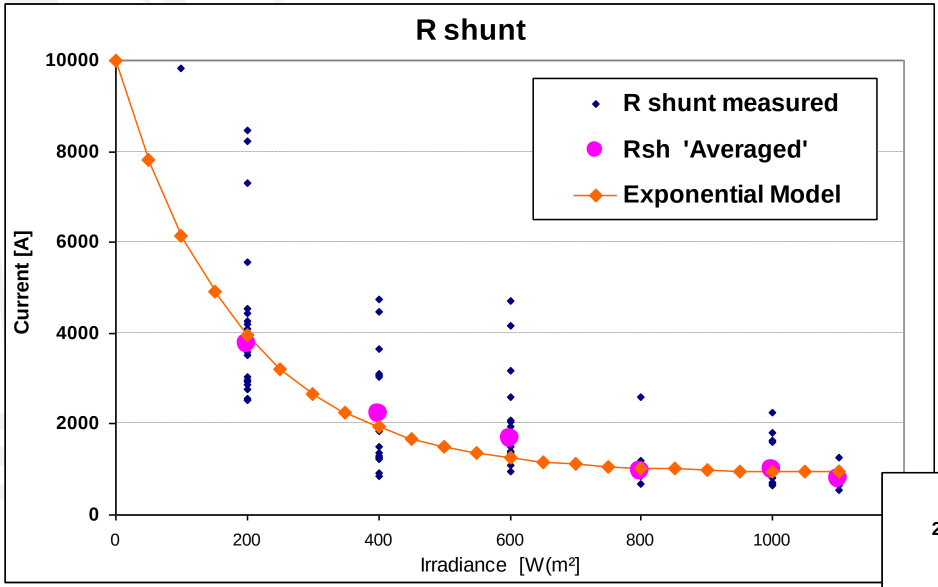
Sandia test modules : exponential Rshunt



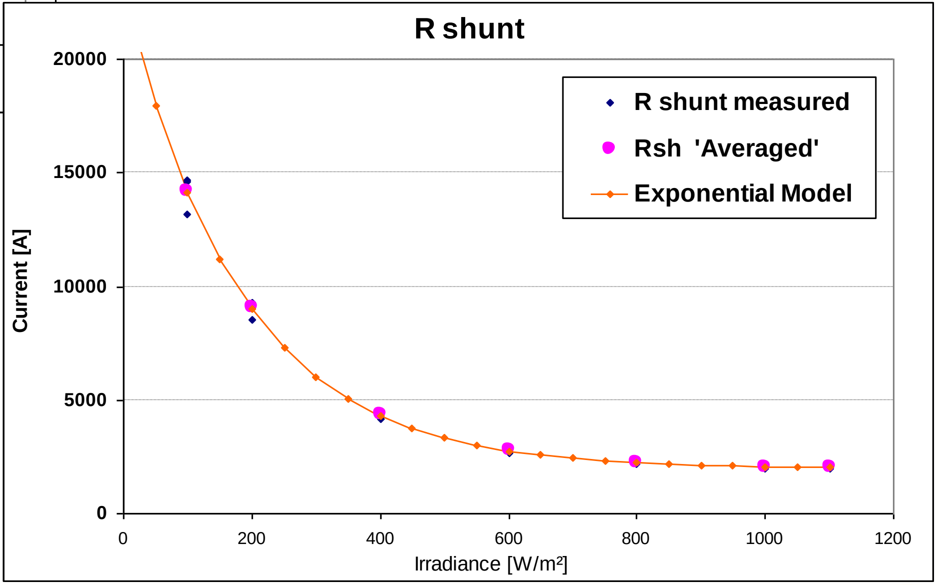
Module A :

102 I/V curves at any temper./irradiances

Rsh = -1/slope on each I/V curve ⇨ Vmp/2

Rsh (Gref) = 960 Ω

Rsh(0) = 10'000 Ω (x 10.4)



Module B :

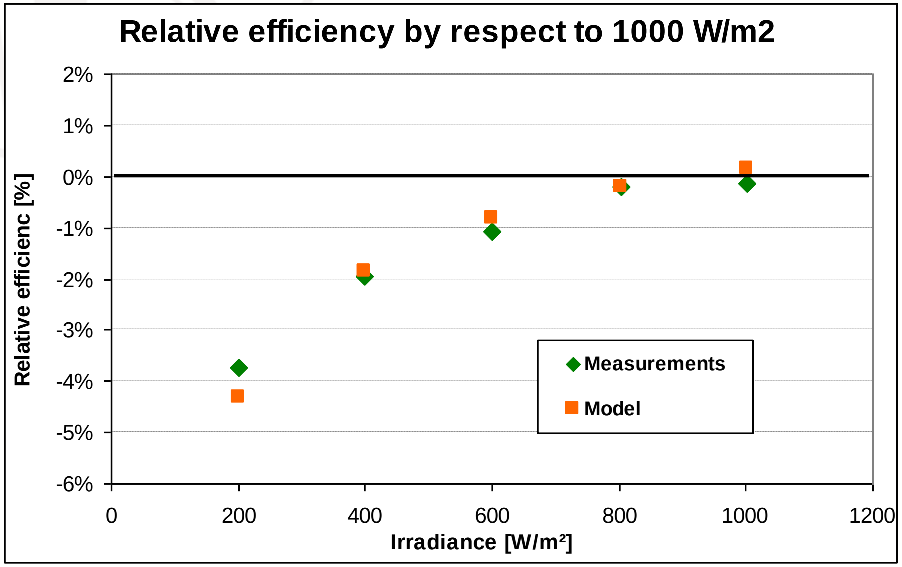
Measured points are "behind" the average points !

Rsh (Gref) = 2'065 Ω

Rsh(0) = 23'000 Ω (x 11.1)

Points perfectly aligned acc. to Rsh_{exp} = 5.5 !

Sandia test modules : Rserie f(Low-light eff.)

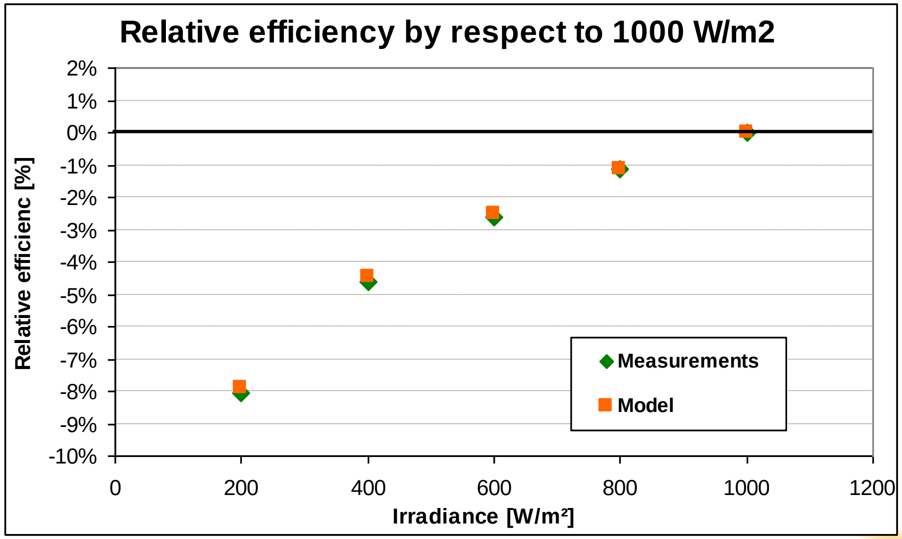


Module A :

Adjust Rserie for better match "by eye"

Rserie = 0.44 Ω (/ Rsmax = 0.61 Ω)

⇨ γ = 1.09



Module B :

Rserie = 0.03 Ω (/ Rsmax = 0.24 Ω)

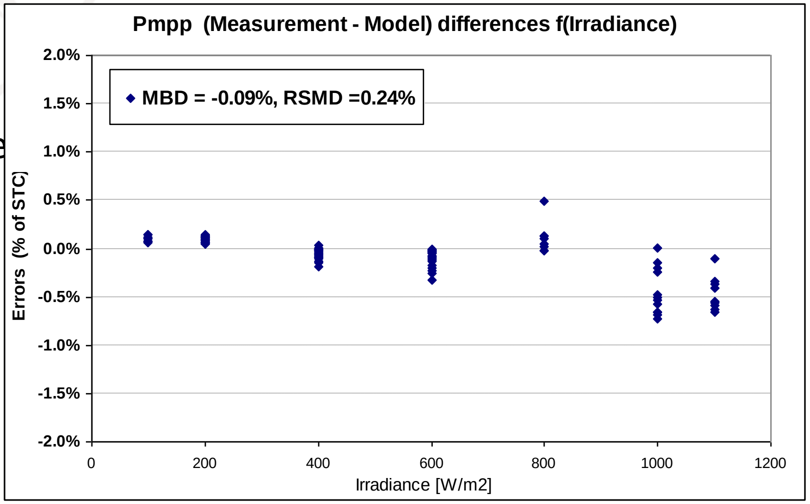
⇨ γ = 1.13

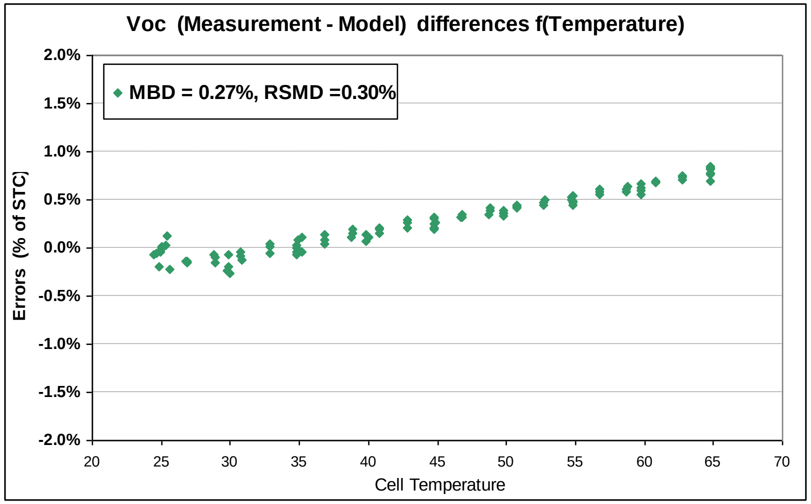
Very low efficiency - Very low Rserie !

Sandia test modules : Final results

Module A

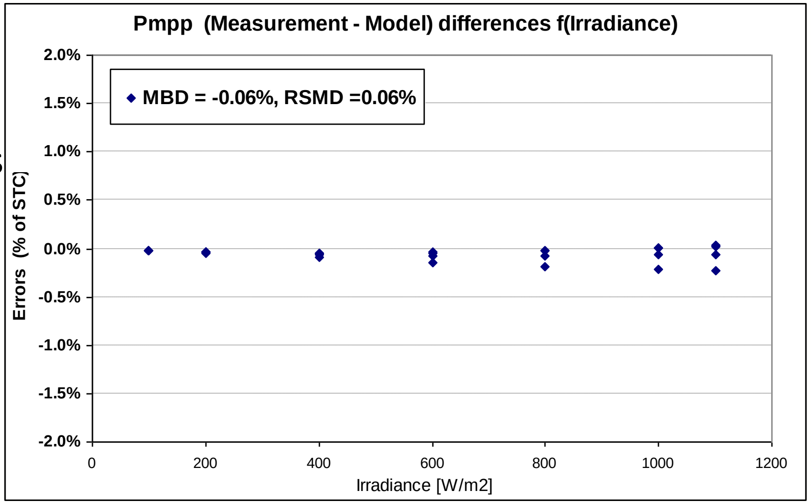
102 I/V curves
$\mu\gamma$ = - 0.0004

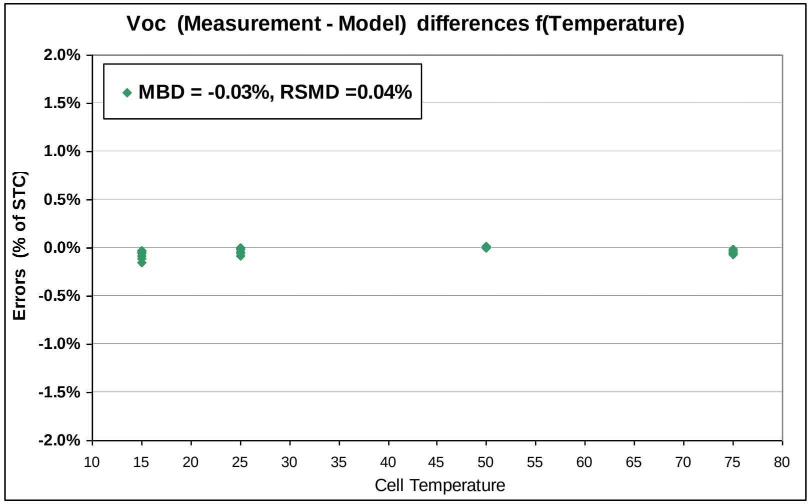




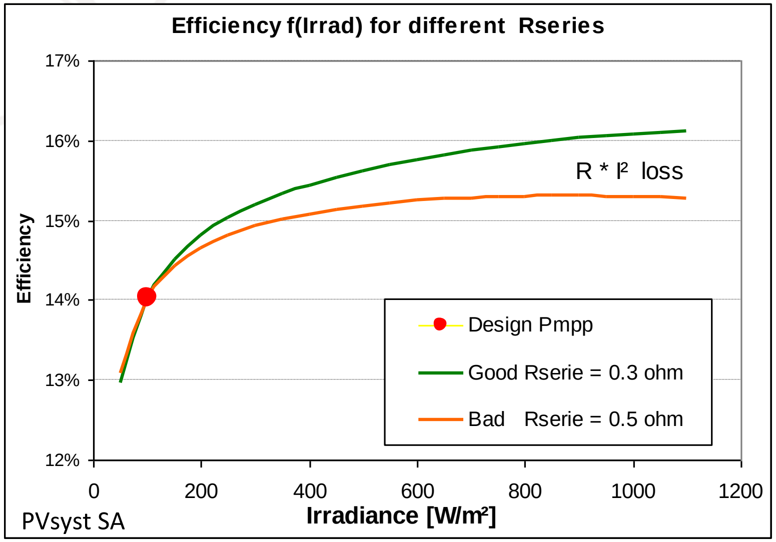
Module B

28 I/V curves
$\mu\gamma$ = + 0.0003





Effect of Rseries on low-light efficiency



Consider a module designed at low irradiance.

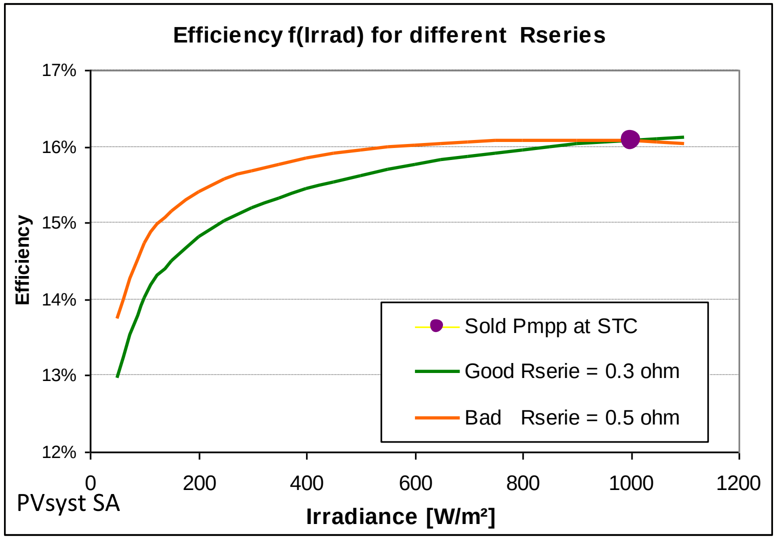
Resistive Loss goes with

$Rs * I^2$ or $Rs * Irrad^2$

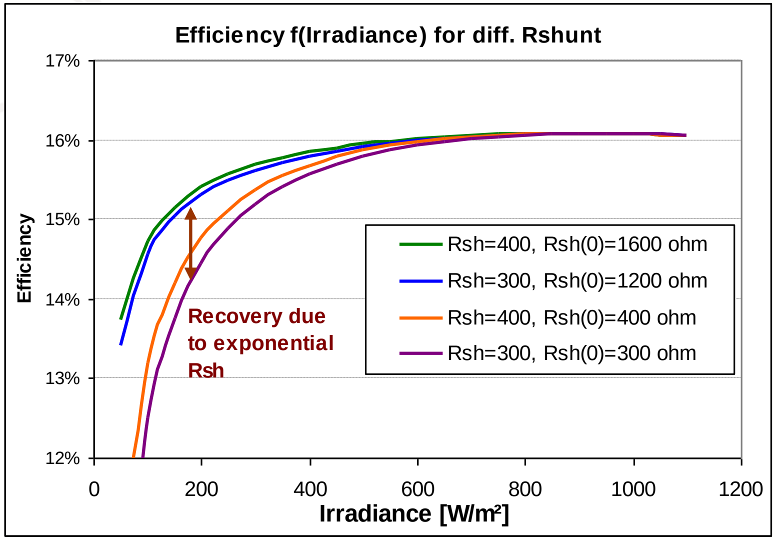
A module with good Rs will have higher STC performances

But you buy the STC performances:
For identical STC with bad Rs you should construct a much better module !

Therefore the module with good Rs has a worse low-light performance !



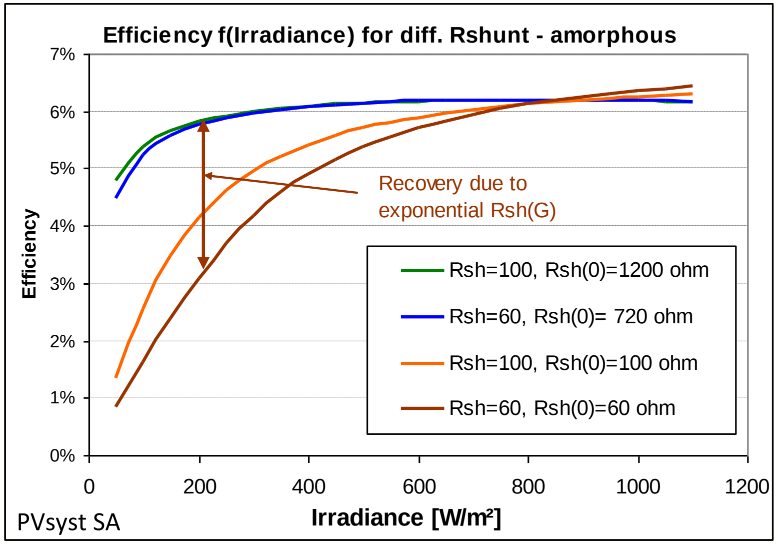
Effect of Rshunt on low-light efficiency



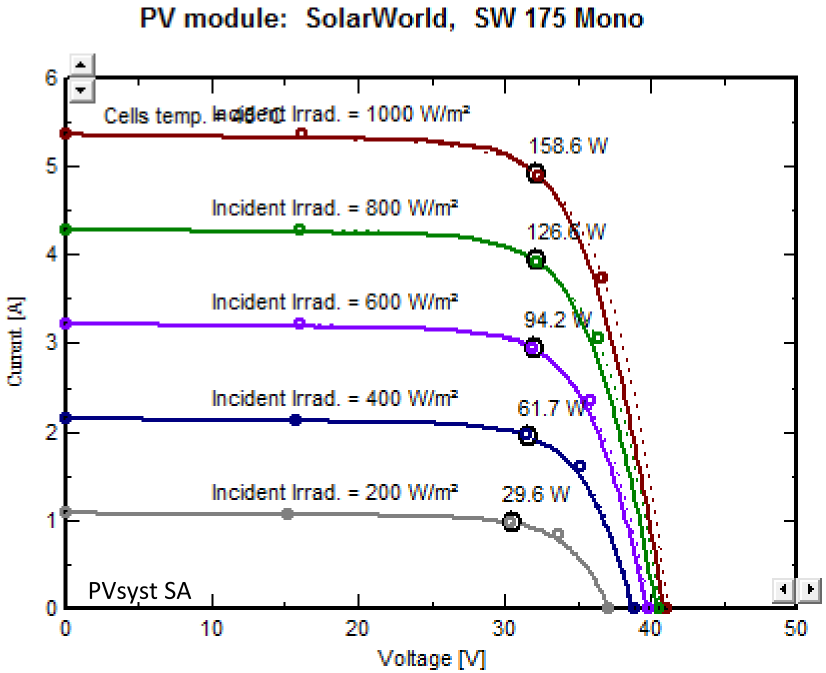
Crystalline modules:
The shunt resistance has very low effects

But the exponential Rshunt behaviour enhances the low-light performance

Amorphous modules:
the recovery of exponential is still more important !



Comparison with the Sandia Model



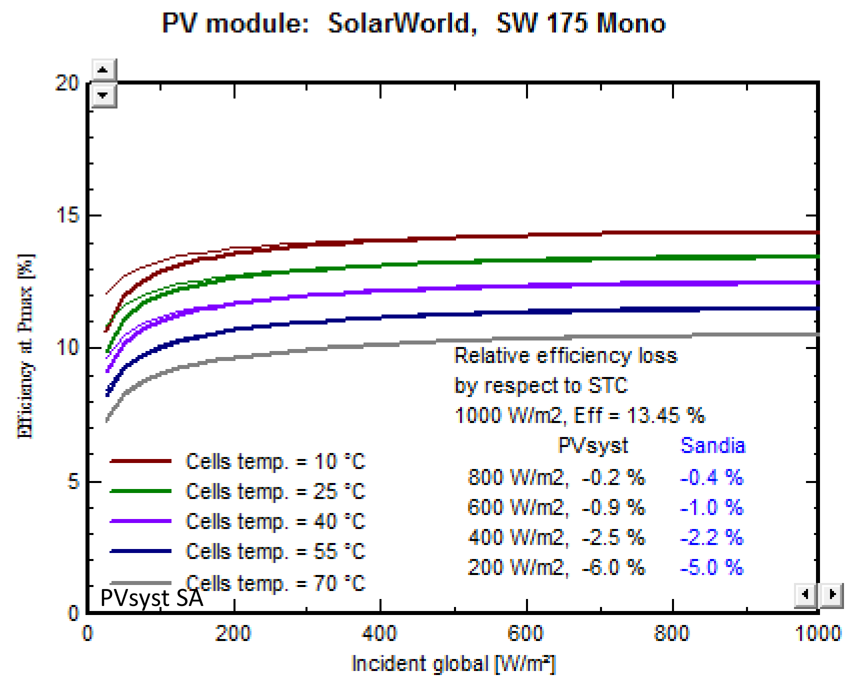
Sandia model :

- established Outdoor (Albuquerque, NM)
  (some few days, tracking, sunny climate)
- defines evolution of 5 points only
- PVsyst extends I/V curve by the one-diode model on each set of points

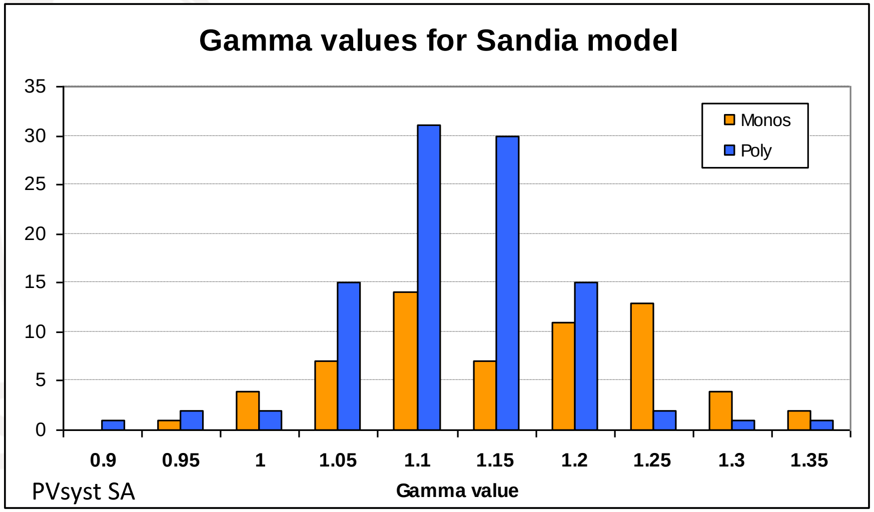
PVsyst model adjustment:

Rserie = 0.531 Ω

γ = 1.16



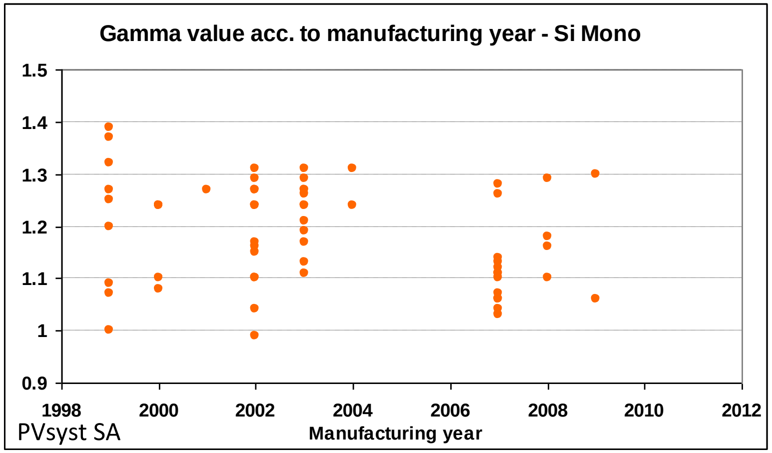
Sandia Model : γ values distribution

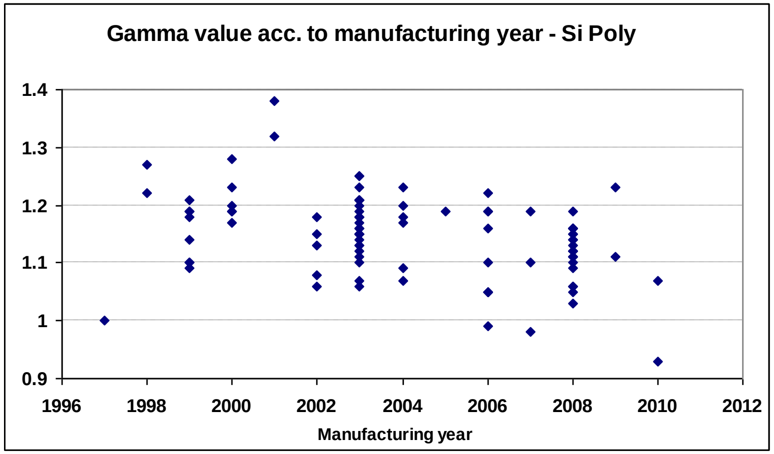


γ values of the one-diode model adjusted with the Sandia data (rather old modules)

Between 1.1 and 1.2 for Si-poly
More spread for Si-Mono

No very significant evolution along years
Poly: some few modules below $\gamma = 1$
What about very recent industry ?





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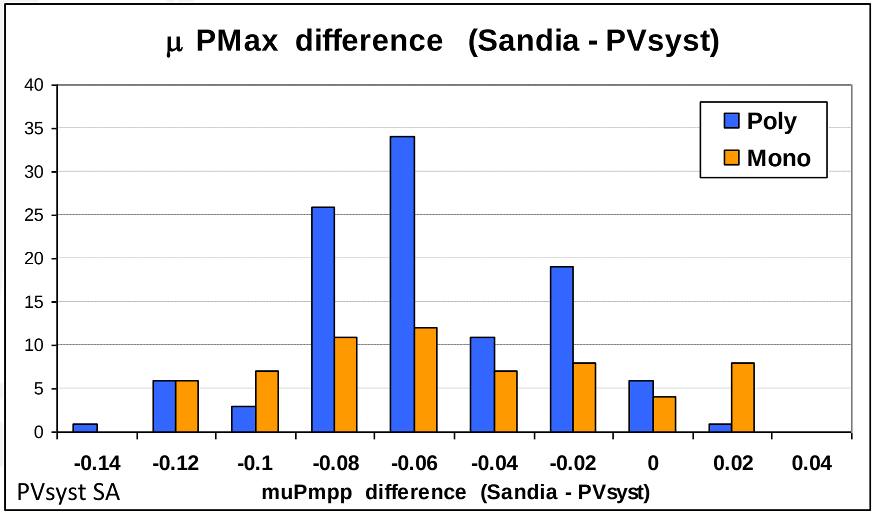
Sandia Model : μPmpp distribution



μPmpp Sandia : measurements

μPmpp PVsyst : mostly det. by the model

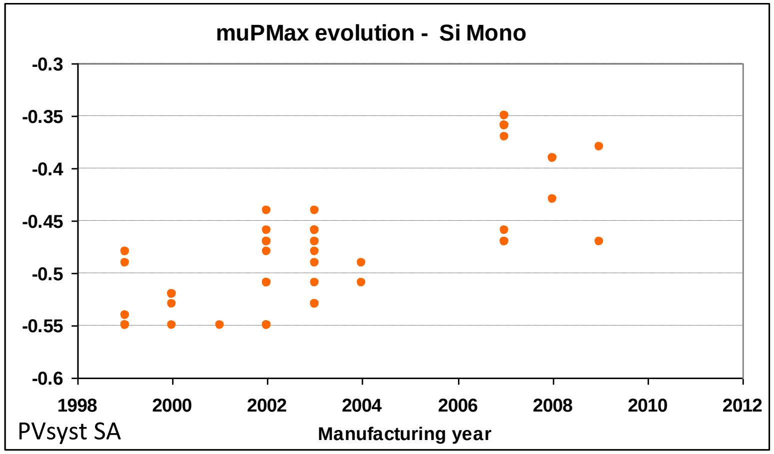
(the PVsyst DB doesn't have specified μPmpp for most of these old modules)

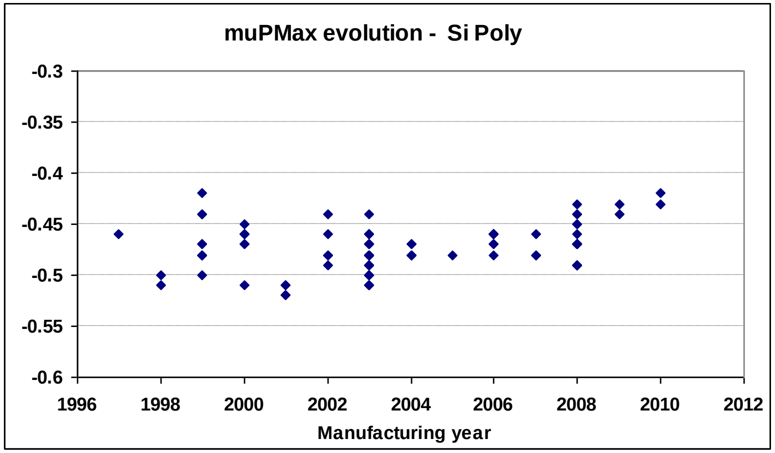
⇨ One-diode model without μγ correction underestimates the temperature losses

μPmpp is slightly improving along the years

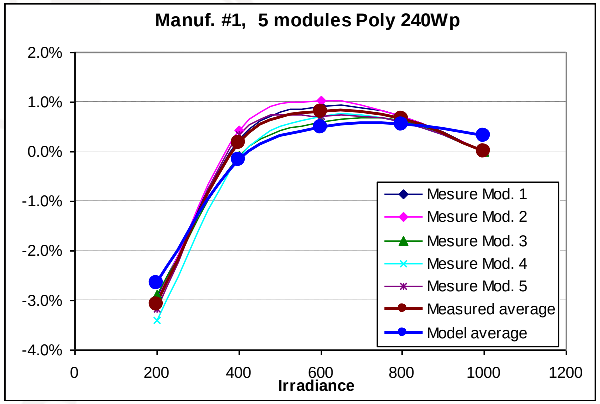
Special technologies attain - 0.36%/°C

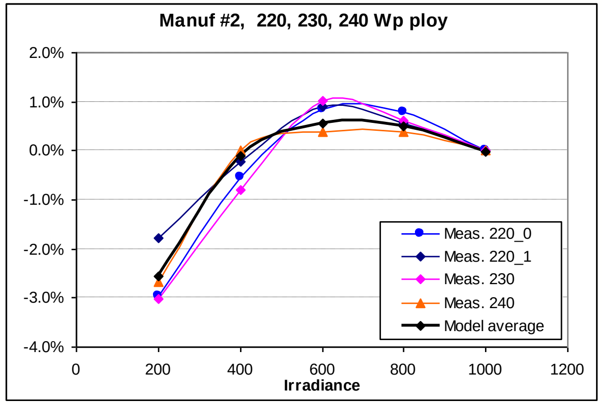
Is the manuf. specification reliable ?

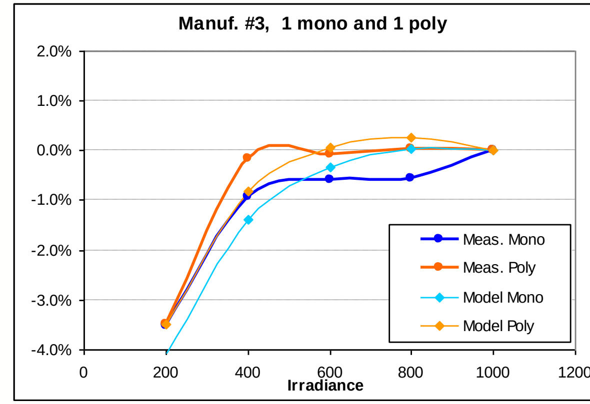


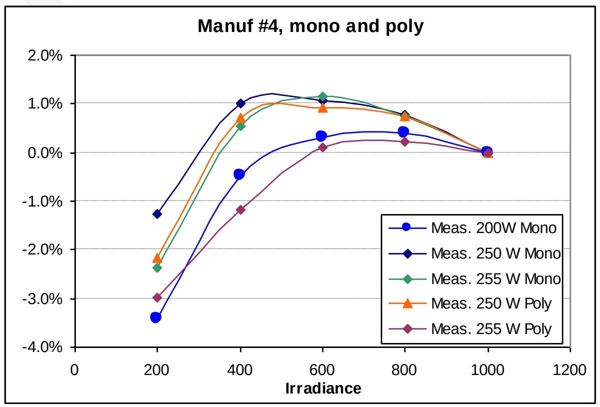


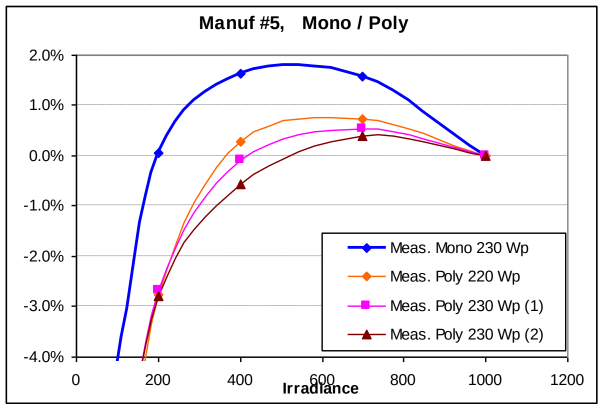
Low-light efficiency indoor measurements

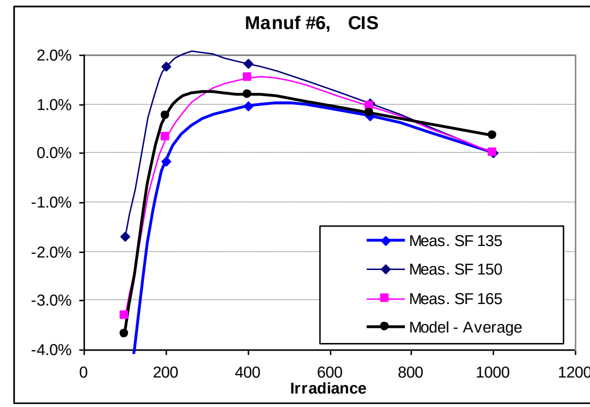












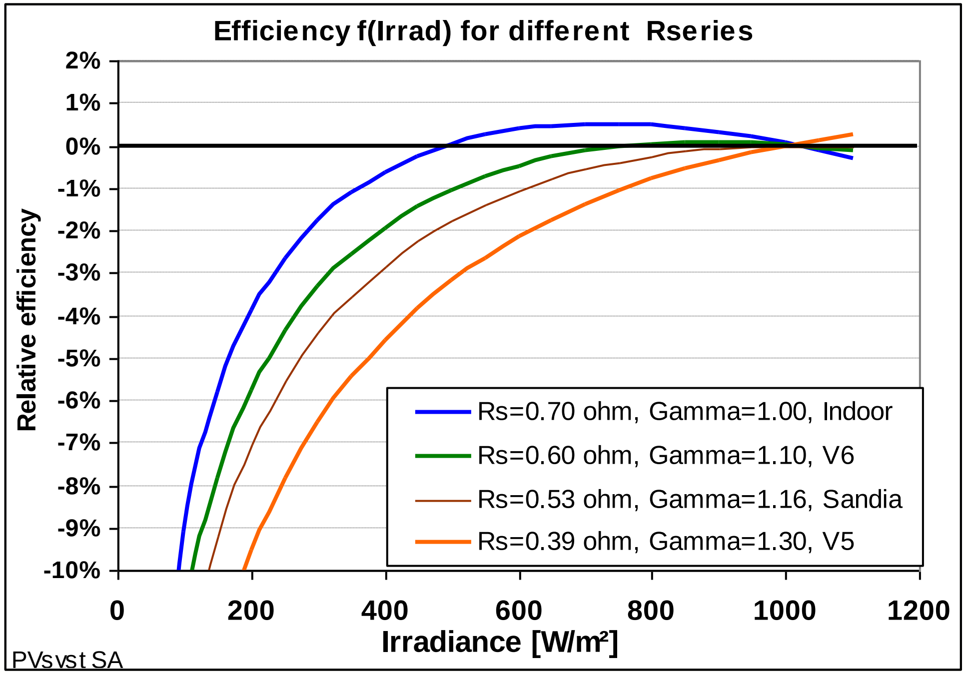
Indoor measurements by independent institutes:
- no evidence of diff. between Mono and Poly
- weak indication as function of power

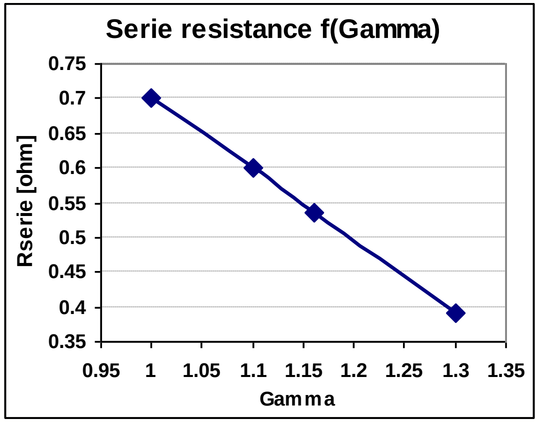
600-800 W/m²: values 0.5 to 1%
400 W/m²: values -1 to 0%
200 W/m²: -3 to -4%

Rserie effect on Low-light efficiency

Ex: Module SW 175 Mono

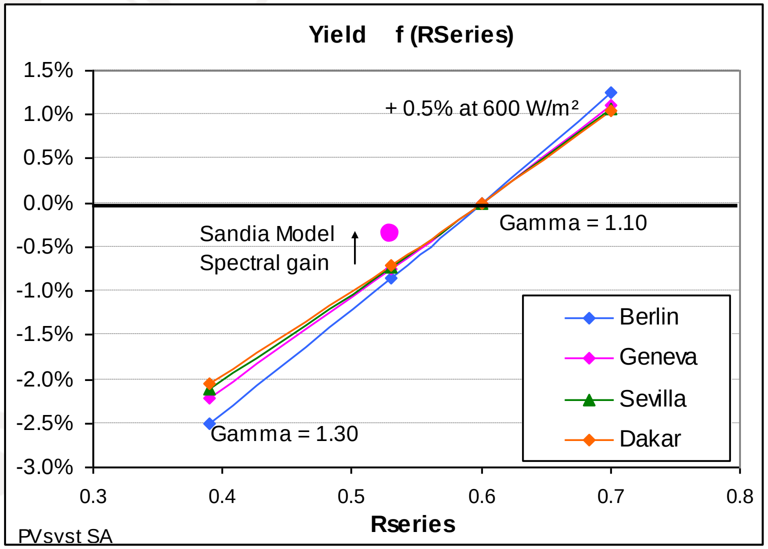
PVsyst V5: very underestimated
Sandia: outdoor measured values (with spectral correction)
PVsyst V6: default acc. to Sandia (slightly higher due to spectral corr) ?
Indoor meas: Much higher efficiencies !





⇨ PVsyst not able to give definitive parameters for comparing any module: the comparison between modules of the database is hazardous !

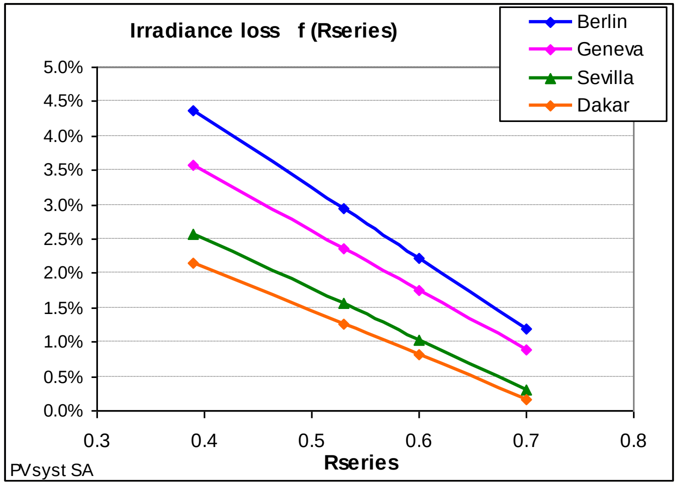
Effect on the simulation results



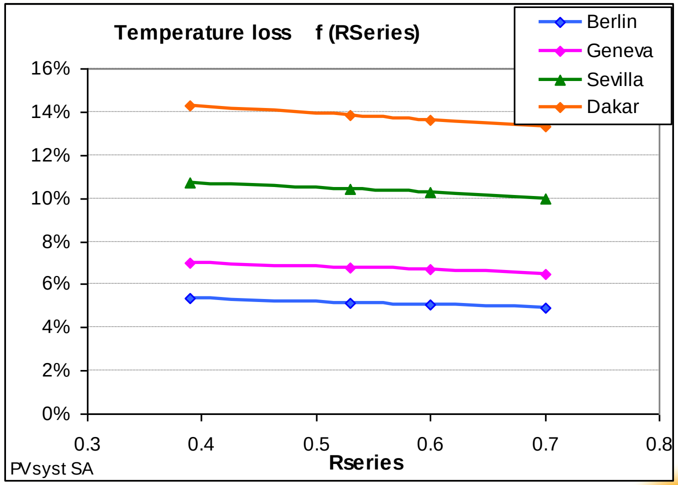
Effect on yield:

- comparable in magnitude to the low-light variations around 600 W/m²
- doesn't depend much on the climate

- PVsyst doesn't take spectral effects into account for crystalline modules
- Sandia model: spectral correction acc. to Air Mass ⇨ apply to beam only ?



Rseries:
Slight effect acc. to temperature



Conclusions – Doubts of PVsyst model

- The One-diode model is able to reproduce measured data very well
- The problem is the determination of the parameters:
- The accuracy of Rshunt has low effects for crystalline modules but exponential behaviour enhances the low-light performance
- The Rseries has high impact on the low-light performances
  established by default according to fixed Gamma value
  established on the basis of outdoor measurements (Sandia Model)
  discrepancies with Indoor low-light measurements, to be explained
- PVsyst database uses :
  Rserie default in absence of additional information
  Low-light performances when available
  ⇨ difficulties for the comparison between modules !!!
- Significant effect on final yield, low dependence on climate
  previous Rs default in V5 ⇨ very low performances (about -2%)