PV modules modelling

André Mermoud
Institute of the Environmental Sciences
Group of energy - PVsyst
andre.mermoud@unige.ch

UNIVERSITÉ DE GENÈVE

Objectives

Establish a model for a general simulation program

- representing the I/V behaviour of PV modules of any technology
- in any Irradiance and Temperature conditions
- should be established with a minimum of parameters
  (manufacturer's parameters + few additional ones)

We start from the "Standard" one-diode model

We try to find corrections for representing measured data

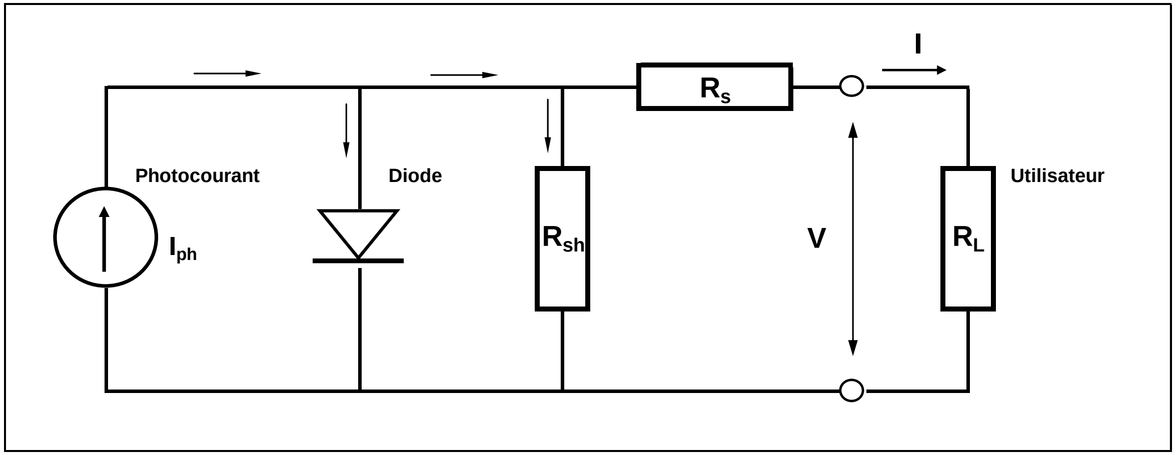
Methodology

Establishing a model and assessment with outdoor measured data

- Measurements of I/V characteristics every 10 minutes,
  - samples in any Irradiance and Temperature (G,T) conditions.
  - Pyranometer measurements of GlobPlane, GlobHor, DiffHor,
  - Cell reference measurements for stability assessment
  - Incidence irradiance on collector, corrected for incidence angle
- Choose one I/V characteristics in this sample (around 1000 W/m2)
  - Establish the parameters of the "One-diode" model [Townsend-Beckman]
  - Comparison (Measured - Modelled) values for all measurements
    - Analysis of the distributions of Pmax, Voc, Isc (not Vmpp, Impp)
    - Graphical distributions according to diverse variables (G, T, time)
    - Using MBD and RMSD as quantitative indicators
    - Adjustments of secondary parameters for optimizing MBD and RMSD

Standard "One diode model"

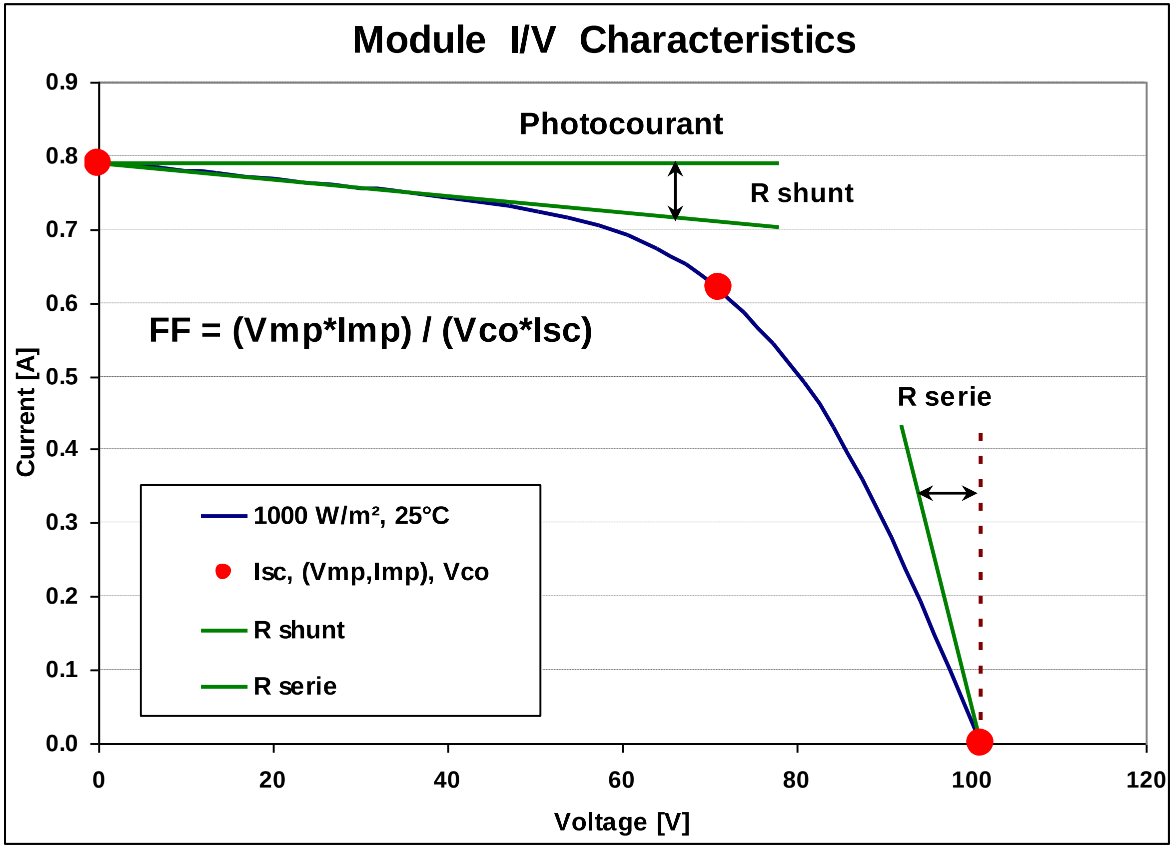
The PV cell may be represented by the following schema:



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

Photocurrent — Current in the diode — Current in Rsh

Standard model I/V characteristics



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

Parameters of the model

Variables

- I = Module current [A].
- V = Module voltage [V].

5 Parameters to be determined

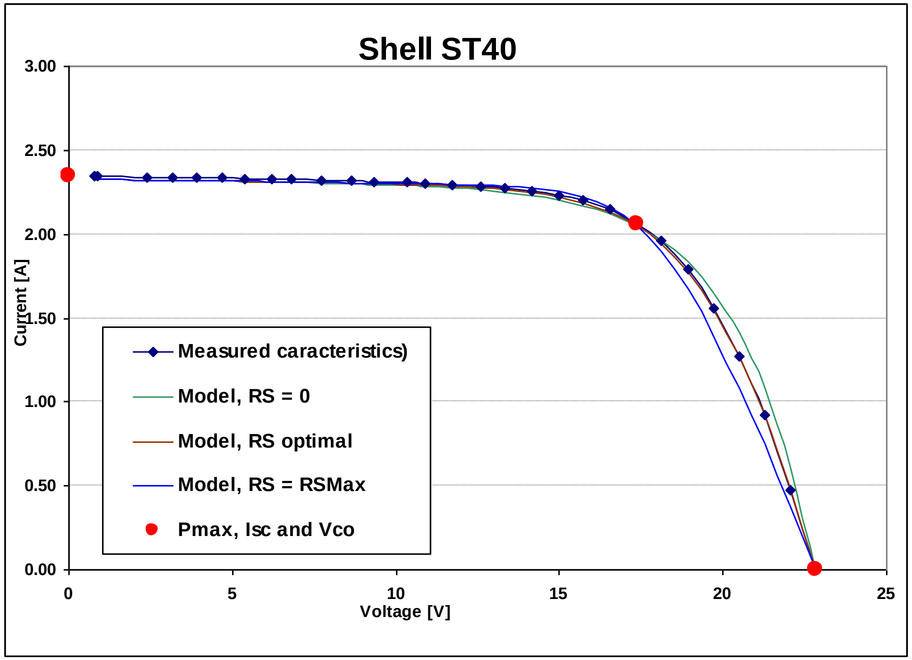
- Iph = Photocurrent [A], proportionnal to the irradiance Φ,
- Io = Diode saturation current, dep. on temperature
- Rs = Series Resistance [Ω].
- Rsh = Shunt Résistance [Ω].
- γ = Diode quality factor, normally between 1 and 2.

Constants

- q = Electron charge = $1.602 \cdot 10^{-19}$ Coulomb
- k = Bolzmann constant = $1.381 \cdot 10^{-23}$ J/K.
- Ncs = Number of cells in series.
- Tc = Effective cell temperature [Kelvin]
- q/kT = 26 mV at 300 K

Parameter determination

For determining the 5 parameters (Iph, Io, Rsh, Rs, γ)
The measurement of one I/V characteristics at (Gref, TRef) is sufficient !



Rsh is determined by the inverse of the slope around Isc = 0

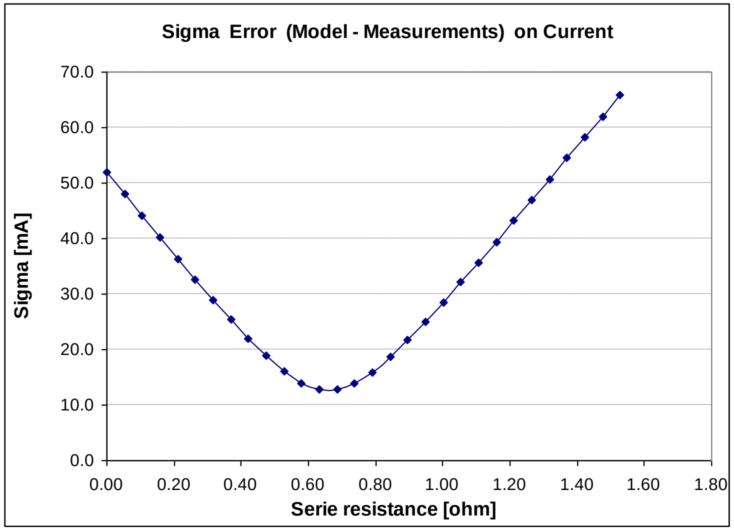
The equation written at the 3 usual points at STC (or any other (Gref, Tref) conditions) :

(0, ISC) (Vmp, Imp) (Vco,0)

gives 3 equations, leaving one free parameter.
We choose to fix Rserie.

=> For a given value of Rs, it is possible to establish Iph, Io and γ,
i.e. the full I/V model

Rseries determination



Using the **measured** reference I/V :

=> Détermination of Rs:
The value is easily obtained by minimizing the I (meas. - model) errors.

NB: The errors σ (Imodel – Imes) are usually lower than 0.4 % of Isc !

With **manufacturer's data** Isc, Vco, Imp, Vmp at STC :

- Rshunt estimated using (Isc - Imp) / Vmp slope
- Rserie defined using fixed γ = 1.3 or 1.35
  (corresponds to around half the RsMax)

Could be determined by specified apparent Rserie, not reliable.

Beckman: proposes using specified μVco, not reliable.

Conditions at different (G, T)

The model has been established for reference conditions (Gref, Tref)

The photocurrent is proportionnal to the irradiance
with slight temperature correction (μIsc in specifications)

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

The diode saturation current Io varies strongly with the temperature

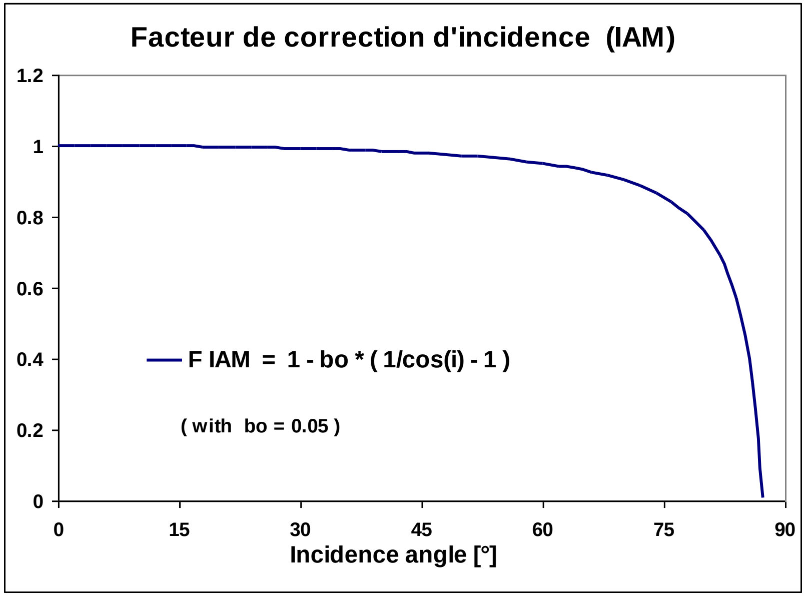
$$Io = Io\ ref\ (T_C / T_{C\ ref})^3 \cdot \exp\ [\, (q \cdot \varepsilon_G / \gamma \cdot k) \cdot (1/T_{C\ ref} - 1/T_C) \,]$$

(where ε_G = junction gap energy)

Incidence correction (IAM)

To be applied to incident irradiance, for all technologies.

Reflexions according to the Fresnel's laws.



Usual parametrisation proposed by "ASHRAE":

FIAM = 1 - bo · (1/cos i - 1)

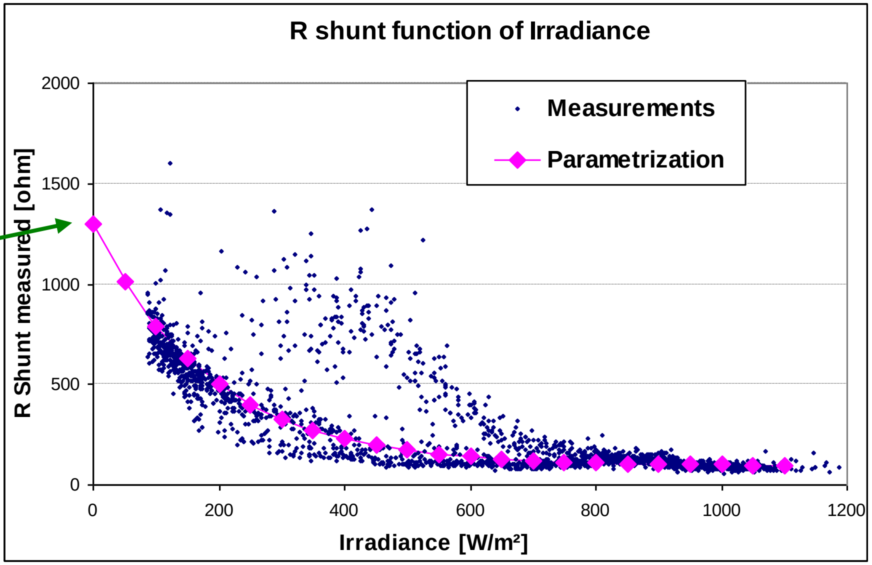
with i = incidence angle

bo = 0.05 for glass

Validation of the model

Model established on one measured characteristics (Vmp, Imp, Vco, Isc)
=> parameters IphRef, Io, γ, Rshunt, Rserie

\+ Exponential correction on Rsh
(acc. to measurements)
RshExp = 5.5 fixed for ~ all modules
=> Additional parameter Rsh(0)



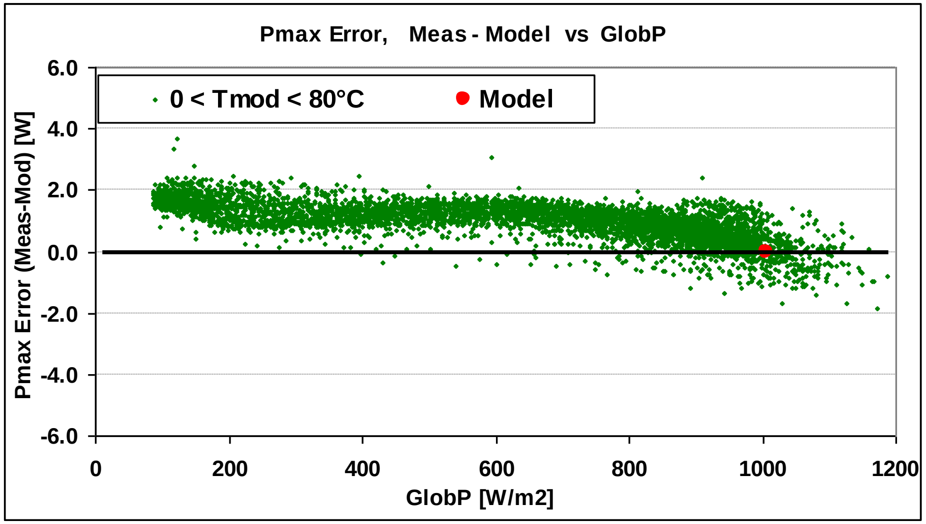
The model is applied on each I/V measured characteristics

The model quality is estimated by indicators on (Pmax, Voc, Isc)

$$\mu = MBD = \Sigma\ (Val._{meas} - Val._{model}) / N_{meas}$$

$$\sigma = RMSD = SQRT\ [\ \Sigma\ (Val._{meas} - Val._{model})^2 / N_{meas}\ ]$$

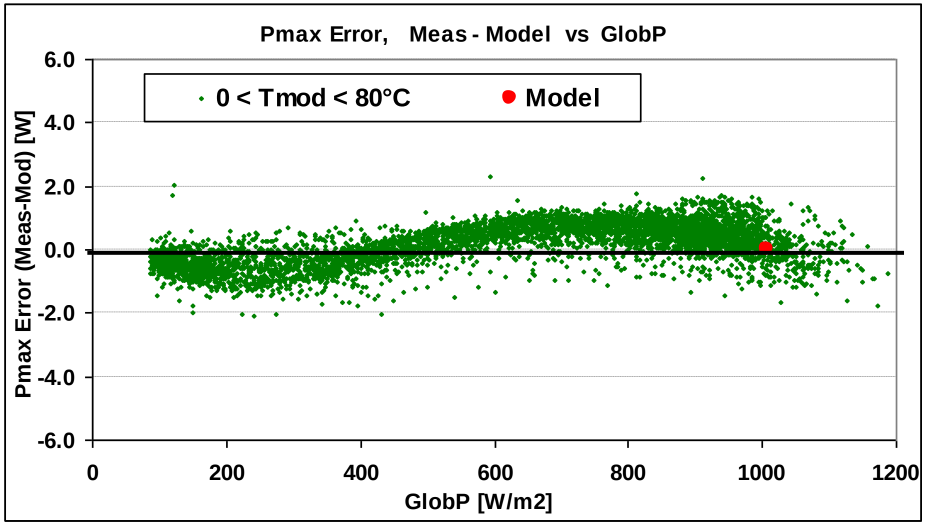
Results on a crystalline module



"Pure" standard model

on Pmax : μ = 1.8% σ = 1.1%

on Vco: μ = 1.0% σ = 0.9%

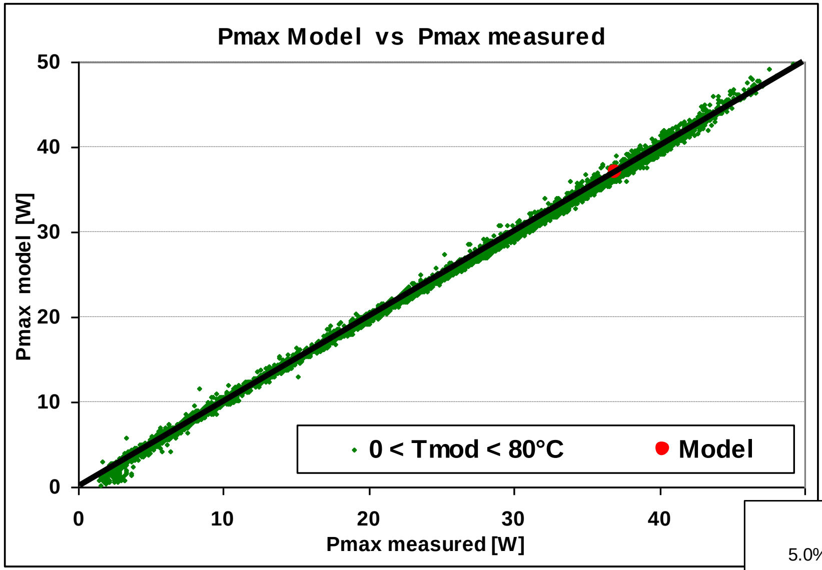


With Rshunt exp. correction

on Pmax : μ = 0.2% σ = 1.2%

on Vco: μ = 0.4% σ = 0.5%

Results on a CIS module (Shell ST40)



With Rshunt correction

Errors on 6 years of measurements

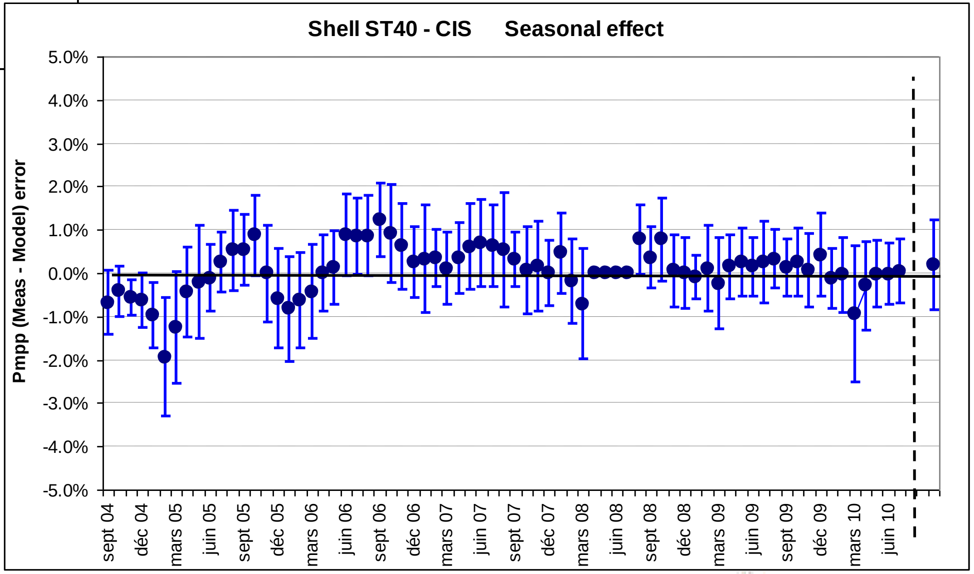
on Pmax : μ = 0.2% σ = 1.0%

on Vco: μ = 0.0% σ = 0.9%

on Isc: μ = 0.5% σ = 0.8%

This CIS module obeys quasi-perfectly the one-diode model !

Long-term results very stable.



Low-light performances

These validations against outdoor data indicate that low-light performances are well described (outdoor) by the "one diode" model.

In the model, the low-light behaviour is related to:

- The Series resistance : losses behave as $R * I^2$
  - ⇨ low light efficiency better with "bad" (high) Rserie
- The shunt resistance: exponential behaviour
  - ⇨ low light efficiency better with "bad" (low) Rshunt
    (with good Rshunt, nothing to gain when decreasing the irradiance)

The low-light efficiency of the model is very often in contradiction with the data produced by the manufacturers.

- How are they measured ? Indoor or outdoor ?
- Indoor: effect of the filters ? Spectral neutrality ?
- Outdoor: How are they renormalized to fixed T = 25°C ?
- Outdoor measurements with which irradiance sensors ?

This discrepancy has high implications, and should be understood.

Temperature behaviour

The temperature coefficient μPmax is a result of the model

We can adjust it to manufacturer's specifications
using a linear correction on the diode ideality factor :

$$\gamma = \gamma ref * \mu\gamma \; (Tc - Tcref)$$

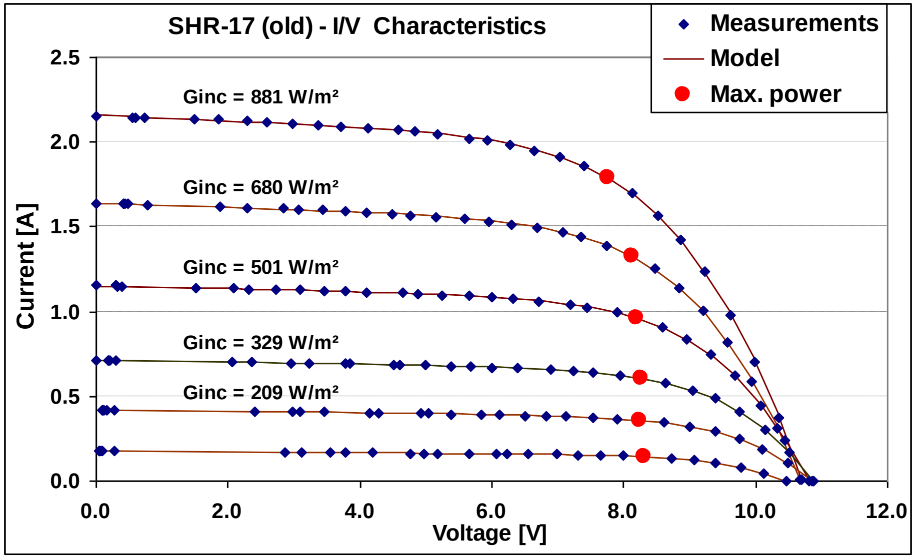
Usually $\mu\gamma$ is very small (< 0.2 %/°C)

μVco is also a result of the model
Depends on Rserie and also corrected by $\mu\gamma$
But cannot be adjusted simultaneously with μPmax

Amorphous modules

3 corrections to the standard model:

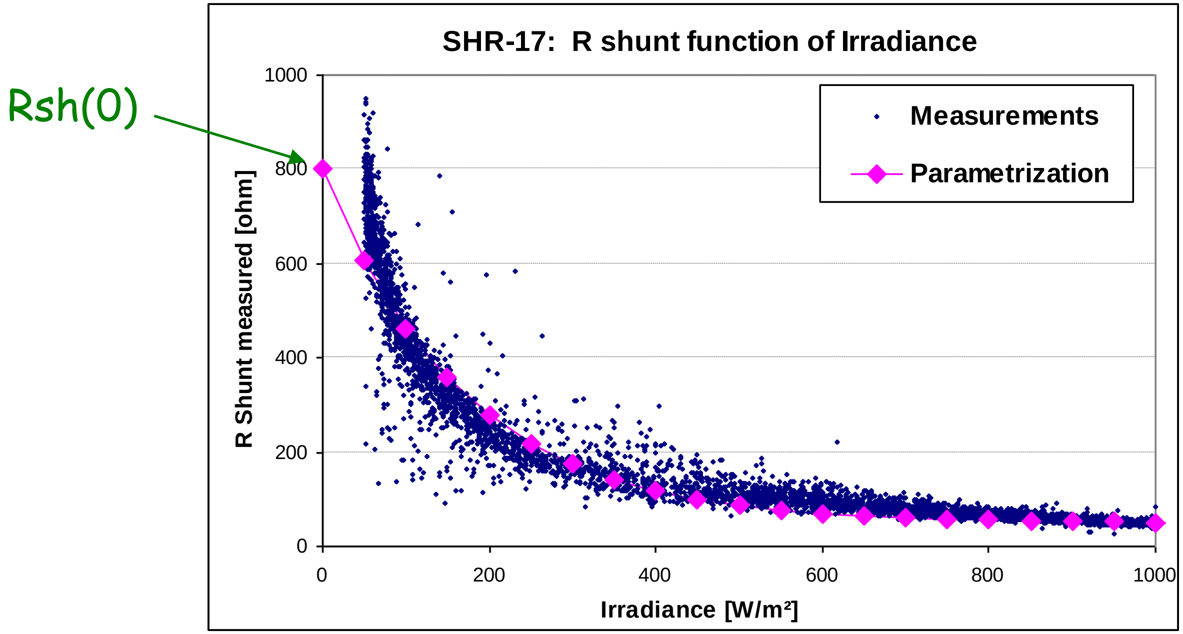
- Rshunt correction – more important weight, main contribution
- Recombination loss in the –i– layer
- Spectral correction



For a given I/V characteristics, it is always possible to find model parameters with good match:

errors $\sigma(I) < 0.4\%$ of Isc

Amorphous: Rshunt behaviour

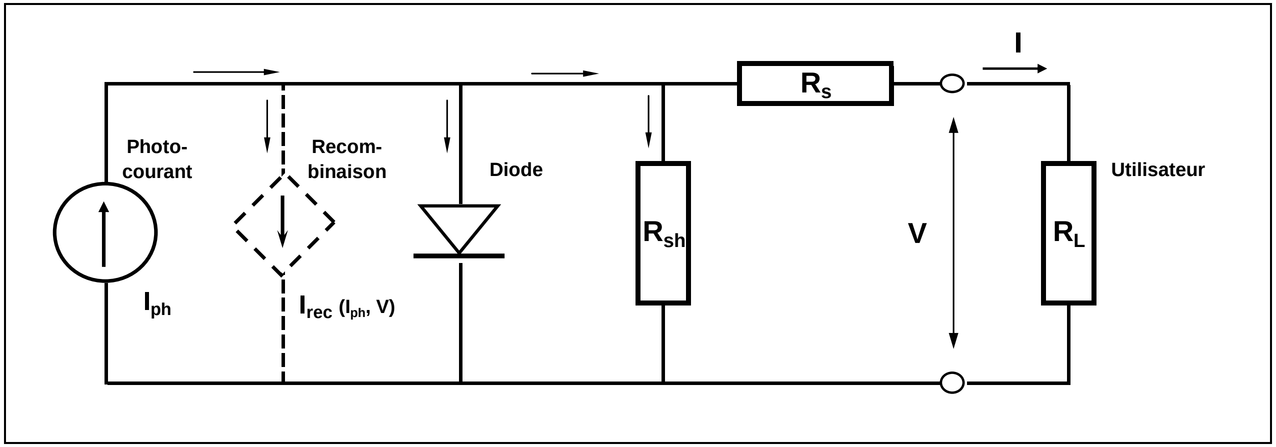


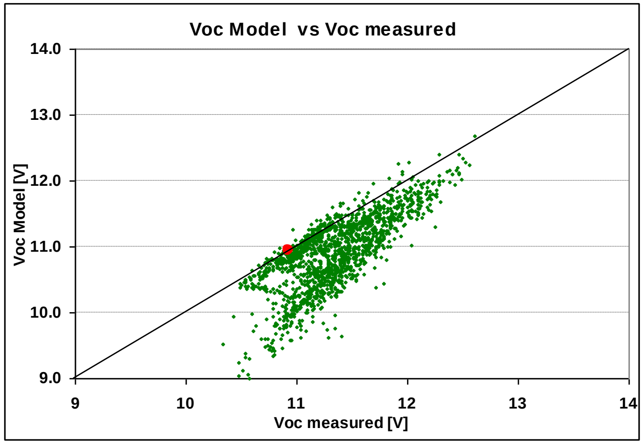
Shunt resistance at STC is far lower than for crystalline (higher slope)

But very high dynamics: Rsh(0) / Rsh(STC) ~ 12

Recombination correction

Add a term to the I/V equation [Mertens et al]





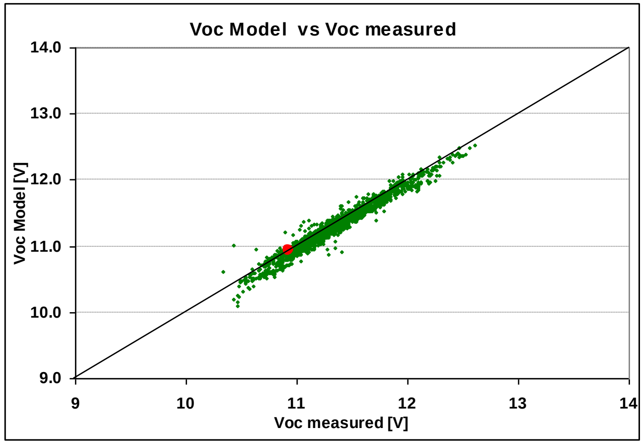
Parameter

$d^2\mu\tau$

Effect on Voc

without corr.

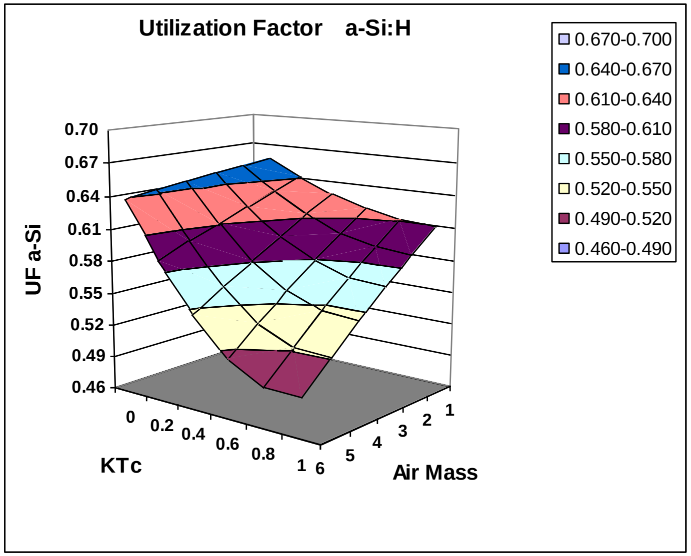
after corr.



Spectral correction

Correction proposed by CREST [Univ. of Loughborough, UK]

- Caracterisation of the energetic contents (APE – Average Photon Energy) according to air mass and clearness index
- UF = Utilisation factor: convolution with the spectral sensitivity of each technology (proposed for amorphous only)



This correction is based on :

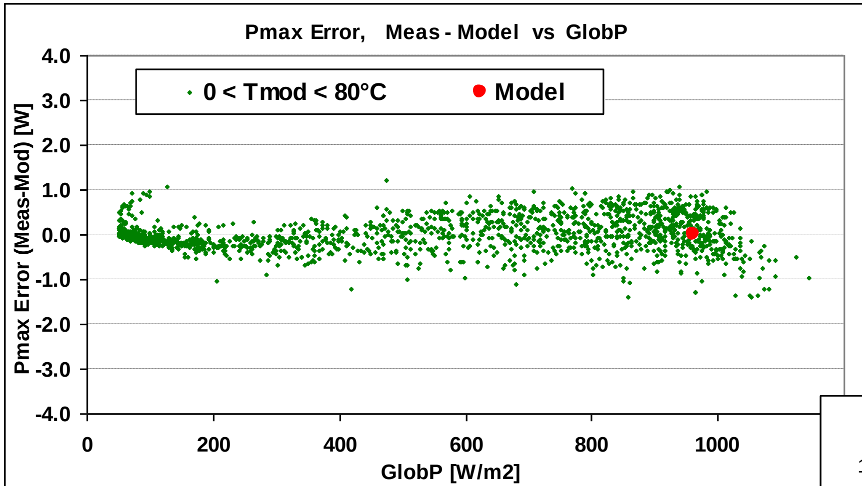
- the Loughborough climate
- computed for single amorphous only

Concerns photocurrent

Improves σ by some few %

May probably be improved for other technologies.

Results for SHR-17 (tripple Junction)

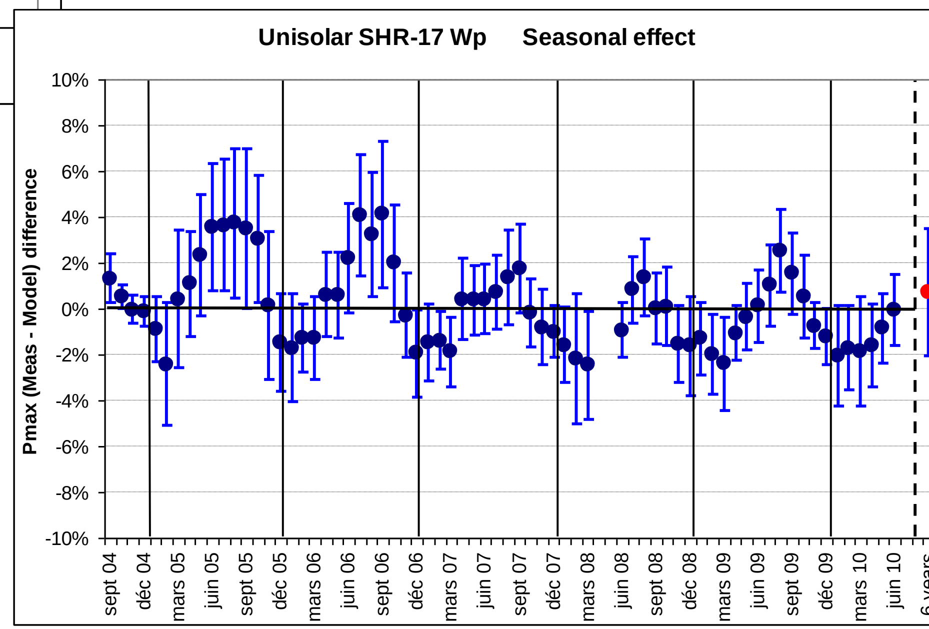


Over one year (2009-2010)

on Pmax : μ = 0.1% σ = 2.3%

on Vco: μ = 0.7% σ = 1.0%

on Isc: μ =-0.1% σ = 2.7%



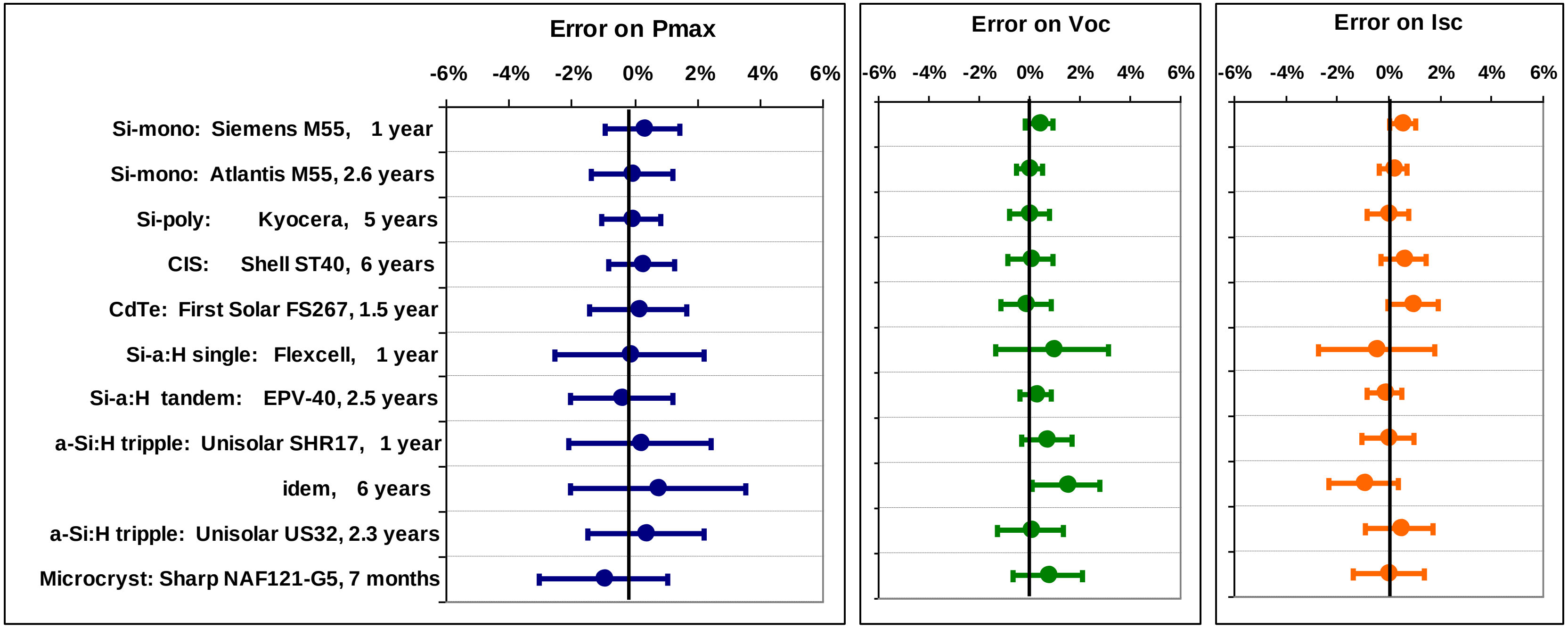
Over six years:

σ (month) ~ 1.2 %

The model should take seasonal annealing effect into account

(but how ? which parameters ?)

Modules of all technologies



Results of thin film modules (except CIS) affected by seasonal annealing effects which penalize the error on Pmax

Conclusions

- "Standard" one-diode model works well with Crystalline and CIS modules
  - One full I/V characteristics : completely defined
  - With manufacturer's data: hypothesis on 2 parameters Rshunt and Rserie
- Exponential Rshunt correction required by all technologies
  ⇨ additional parameter Rsh(0)
- Amorphous, μ-crystalline and CdTe require recombination correction
  ⇨ additional parameter $d^2\mu\tau$
- Spectral correction for Amorphous and μ-crystalline, not for CdTe
- Outdoor measurements reproduced with 1.0 to 1.6% RMSD for all technol.
  excluding annealing effects, not taken into account
- Low-light irradiance: discrepancies with indoor and manufacturer's measurements have still to be understood.
- Results on one measured module - not manufacturer's specifications

Dot not confuse "Model accuracy" and "Parameter accuracy" !!!