The 'best' PV Model Depends on the Reason for Modelling

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Many reasons for modelling performance of PV modules/arrays

1) **Production process optimisation** (to minimise losses at Standard Test Conditions).
2) **Determination of coefficients** “$P_{\text{MAX}}$ vs. $T_{\text{MODULE}}$”, “Efficiency vs. Irradiance” etc.
3) Overall system **energy yield predictions** vs. simulated weather inputs
4) **Benchmarking** different PV technologies (vs. differing $P_{\text{MAX}}$, Low Light ... coefficients)
5) **Validation of instantaneous performance** (prove module/array is working)
6) **Fault finding** (if under performance) – which model parameters are responsible?
7) **System output validation** e.g. kWh/ year
8) **Degradation rate** vs. time, which parameters are degrading?
Which parameters limit $P_{\text{MAX}}$ at high and low light levels?

Typical clear morning CdTe at NREL:

- 06:15 | 0.07 kW/m² | T_Mod 17C
- 10:45 | 0.95 kW/m² | T_Mod 56C

Locus of $P_{\text{MAX}}$ at $V_{\text{MP}}$
Which parameters limit \( P_{\text{MAX}} \) at high and low light levels?

Typical clear morning CdTe at NREL:

- \( P_{\text{MAX}} = I_{\text{SC}} \times \text{FF} \times V_{\text{OC}} \)
- \( I_{\text{SC}} \sim G_i, \text{AOI}, \text{AM}, \text{soil}, \text{snow}, \ldots \)
- \( V_{\text{OC}} \sim T_{\text{MOD}}, \ln(G_i) \ldots \)
- FF “Fill factor vs. irradiance” depends on module technology

(1) “Resistance at \( I_{\text{SC}} \)”
\[
R_{\text{SC}} = \frac{-1}{(dI/dV)|_{V=0}}
\]

(2) “Resistance at \( V_{\text{OC}} \)”
\[
R_{\text{OC}} = \frac{-1}{(dI/dV)|_{V=V_{\text{OC}}}}
\]

(3) “\( P_{\text{MAX}} @ \text{high light} \)” limited by \( R_{\text{OC}} \)

(4) “\( P_{\text{MAX}} @ \text{low light} \)” limited by \( V_{\text{OC}}, R_{\text{SC}} \) vs. \( G_i \)
Example PV Models and their fit types to IV curves

- **Full Curve Fit**
  - Fits entire curve – answer depends on glitches, non optimum performance, point distribution and/or weighting e.g. more important nearest \( P_{\text{MAX}} \)

- **Points + Gradients**
  - Takes values at only certain places on the IV curve e.g. \( V=0, V=V_{\text{MP}}, I=0 \) ...

- **Matrix method, IEC 61853, PVUSA, Empirical fits**
  - ONLY knows \( P_{\text{MAX}}, I_{\text{SC}}, V_{\text{OC}} \) etc. unknown
  - May know \( V_{\text{DC}} \)

- **1-diode model 5-7 parameters**
  - used in most simulation programmes, extended from de Soto 2006
  - Fits entire curve – answer depends on glitches, non optimum performance, point distribution and/or weighting e.g. more important nearest \( P_{\text{MAX}} \)
From IV curves vs. $G_\text{I}$ and $T_{\text{MOD}}$ to the three model types

IV curves

Vs. Irradiance and $T_{\text{MOD}}$

Matrix - $P_{\text{MAX}}$ only

Avg Eff ($G_\text{I}$, $T_{\text{MOD}}$)

1 diode (Full curve)

$L_\text{PH}$ $R_{\text{SH}}$ $I_0$ $R_{\text{SE}}$ $n_f$

LFM (Points and gradients)

Described in next talk

From IV curves $vs. G_\text{I}$ and $T_{\text{MOD}}$ to the three model types
<table>
<thead>
<tr>
<th>1 diode</th>
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</tr>
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<tbody>
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</tbody>
</table>

Irradiance →

<table>
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<tr>
<th>good c-Si</th>
<th>Good $R_{sc} + R_{oc}$</th>
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<tr>
<td>good TF</td>
<td>Poorer $R_{oc}$</td>
</tr>
<tr>
<td>poor TF</td>
<td>Poor $R_{sc}$ and $R_{oc}$</td>
</tr>
</tbody>
</table>

How models differentiate PV Technologies
IV curves

1 diode
Full curve
Irradiance →

Matrix
Avg Eff
only
Irradiance → Tmod ↑

LFM
Points+
Gradients
Irradiance →

good c-Si  Good $R_{\text{sc}} + R_{\text{oc}}$

good TF  Poorer $R_{\text{oc}}$

poor TF  Poor $R_{\text{sc}}$ and $R_{\text{oc}}$
**KEY**

- **GOOD**
- **MEDIUM**
- **POOR**
- **DIRECTION**

### 1 diode

**Full curve**

Irradiance →

### Matrix

**Avg Eff**

Only Irradiance →

### LFM

**Points+ Gradients**

Irradiance →

### Good c-Si

**Good $R_{sc} + R_{oc}$**

- $V_{MP}$
- $FF$
- $V_{MP}$

### Good TF

**Poorer $R_{oc}$**

- $V_{MP}$
- $FF$
- $V_{MP}$

### Poor TF

**Poor $R_{sc}$ and $R_{oc}$**

- $V_{MP}$
- $FF$

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**Points**

- **nIMP**
- **nVMP**

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**Gradients**

- **nRSC**
- **nROC**

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**Eff@High Tmod**

- PR=100%
- Max Eff @ Low T, Low G

**Eff@LowLight**

- PR<100
- $P_{MAX} < P_{MAX.REF}$
- "flat" Eff Vs. T and G

**Eff@High Tmod**

- Max Eff @ Low T, High G
- "flat" Eff Vs. T and G

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**Optimum= 1**

- **nIMP**
- **nVMP**

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**Good c-Si**

- **Good $R_{sc} + R_{oc}$**

---

**Good TF**

- **Poorer $R_{oc}$**

---

**Poor TF**

- **Poor $R_{sc}$ and $R_{oc}$**

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**KEY**

- **GOOD**
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**NREL**

**Steve Ransome Consulting Limited**
Needs for optimum modelling:

1) **Differentiate** “offsets between technologies” from “product variability within a type”

2) **Recreate** these curves with simple models

3) **Quantify** performance loss or optimisation possible from sub standard modules

Need curves that are easy to fit
Comparing residual errors from 1-diode, SAPM and LFM

PVSEC Paris 2013 4CO-11.1

Cumulative distribution functions for residuals of 11 modules measured at Sandia.
Degradation : IV curve Analysis : Poor CIGS in Arizona

Clear day IV measurements at 12:00 each month
Corrected for Irradiance and Module temperature.

- IV curve Degradation/Failure Analysis
- $I_{SC}$ $R_{SC}$ $I_{MP}$ $V_{MP}$ $R_{OC}$ $V_{OC}$
- Needs irradiance and temperature corrections
- Either fit 1-diode coefficients or analyse changes in shape of the curves - can be hard
- Glitches/imperfect behaviour make fitting difficult
Degradation : Point/Gradient LFM Analysis : Poor CIGS in AZ
Clear day IV measurements at 12:00 each month Corrected for Irradiance and Module temperature

• Residuals (enLFM = “measured-predicted”) of degrading CIGS module, no temperature correction needed

• Grey bars show residual < ±1%.

• Any fall in residual curve shows degradation

• It’s easy to determine rate and cause (note changes from April to October)

• Note: $n_{lsc}$ has more scatter as it has AOI and spectral and snow effects
Using an Hourly energy simulation program vary losses and study performance change sensitivity at different climates

1. Sun tracking gain
2. Shading
3. Snow
4. Soil
5. AOI
6. Spectrum
7. Seasonal Annealing
8. Thermal loss *(Gamma, NOCT)*
9. DC constant loss
10. Efficiency vs. Irradiance *(LLEC, I^2.Rs)*
11. Mismatch
12. DC I^2R loss cabling
13. Inverter Wakeup
14. Mppt loss
15. Inverter Efficiency
16. AC Constant loss
17. Clipping
18. Transformer efficiency
19. Tare
20. AC I^2R loss cabling
Insolation distribution vs. Irradiance (kW/m²) and Tmodule (°C) for worldwide sites

Energy yield will be affected differently at sites worldwide.

For example high $R_{\text{SERIES}}$ causes loss at high light levels (right) which will lose more energy yield at high insolation sites (right).

**INSOLATION vs. IRRADIANCE, $T_{\text{MODULE}}$**

- **KEY:**
  - SITENAME
  - Site irradiance distribution
  - % Irradiance (contours) vs. Module temperature, Irradiance kW/m² at 30° tilt to equator
  - $T_{\text{MODULE}}$ calculated assuming NOCT=47°C

**Hotter/brighter sites** have maximum insolation at both high temperature ↑ and high irradiance ➔

**Cooler/duller sites** have insolation distributions over a wide range of irradiance and lower temperatures.

Most world wide sites are between red and blue lines.
Energy yield sensitivity worldwide to finite changes in

**Gamma, NOCT (left)**

**Low Light Efficiency, I²R_{SERIES} (right)**

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**GAMMA +0.1%/K ↑**

**NOCT -10°C ↑**

**Hot**

**Cool**

**DIAGRAM 2:**

**Thermal stage loss % ↓**

1000 1200 1400 1600 1800 2000 2200 2400

**POA INSOLATION kWh/m²/y**

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**LLEC +5% ↑**

**I²R_{SERIES} +5% ↑**

**Bright**

**Dull**

**DIAGRAM 5:**

**Irradiance stage loss % ↓**

1000 1200 1400 1600 1800 2000 2200 2400

**POA INSOLATION kWh/m²/y**

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Conclusions

Recommendations

• Normalise data to ensure easier understanding (e.g. $I_{SC.MEAS}/I_{SC.STC}/G_i$)
• Use physically significant coefficients (e.g. $nV_{OC}$)
• Ensure IV Scans are good quality, calibrated and believable with little scatter

• Simple kWh/kWp calculations, optimum sites
  Efficiency only model may be enough

• Fast inline check, degradation/ non-optimum
  “points+gradients” models better

• For the ultimate understanding
  the full weighted point IV curves should be studied
Acknowledgements

- Gantner Instruments staff
- Bill Marion of NREL for data Bill.Marion@nrel.gov
- This analysis and conclusions of NREL data based solely on available information

- Thank you for your attention!

For more information:

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www.steveransome.com
• Spare slides
Model #2) Simplified normalised Loss Factors Model (LFM)

26th EU PVSEC 2011 Hamburg 4AV.2.41

“6 physically significant normalised orthogonal parameters”

Easily Determine

- Temperature and Irradiance Coefficients
- Performance validation
- Process optimisation (minimise losses)
- Fault finding
- Degradation rate and cause

I and V curvature parameters can detect

- Cell mismatch/shading (I @ 0.5*V_{MP})
- Non Ohmic back contacts (V @ 0.5*I_{MP})

\[ \text{PR}_{\text{DC}} = \frac{\text{Eff}_{\text{MEASURED}}}{\text{Eff}_{\text{NOMINAL}}} = \frac{n_I_{\text{SC}} \times n_{R_{\text{SC}}} \times n_{I_{\text{MP}}} \times n_{V_{\text{MP}}} \times n_{R_{\text{OC}}} \times n_{V_{\text{OC}}}}{n_I_{\text{SC}} \times n_{R_{\text{SC}}} \times n_{I_{\text{MP}}} \times n_{V_{\text{MP}}} \times n_{R_{\text{OC}}} \times n_{V_{\text{OC}}}} \]