Optimised fitting of indoor (e.g. IEC 61853 matrix) and outdoor PV measurements for diagnostics and energy yield predictions

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Present status of this study …

- A comparison of 12 existing Empirical models showed a limitation in their accuracies fitting measured data (i.e. with scatter) due to some coefficients being unphysical [1,2,3]

- Therefore an optimised Mechanistic Performance Model (MPM) was proposed with only physical coefficients

- This study looks at yearly energy yield prediction uncertainties due to fitting data vs. added random noise

How some models predict PV performance from $G_I$ and $T_{MOD}$

(DC Performance Ratio $\text{PR}_{\text{DC}} = \frac{\text{Eff}_{\text{DC.MEAS}}}{\text{Eff}_{\text{STC}}}$ or MPR)

**Measurements**
- **WEATHER:** Irradiance $G_I$, $T_{\text{MODULE}}$, WindSpeed
- **ELECTRICAL:** $\text{PR}_{\text{DC.MEAS}}$

**Empirical or Mechanistic Model:**

$$\text{PR}_{\text{DC.PREDICT}} = \sum_N C_N \ast \text{func}_N (G_I, T_{\text{MOD}}...)$$

**Predicted Performance:**

- Measurements
- Optimise fit coefficients $C_N$ to minimise rms error using e.g. Python, Excel
- Fit indoor $\text{IEC-61853-1}$ matrix data (NIST/CFV)
- Fit outdoor data vs. time

**3-7 Fit Coefficients $C_N$**

**Weather functions**

**Gantner**
How does PV performance depend on weather inputs?

Model only expected behaviour

1. $I_{\text{MAX}} \propto G_i$
2. $P_{\text{MAX}} \propto (1+\gamma*(T_{\text{MOD}}-25))$ ...
3. $V_{\text{MAX}} \propto \log(G_i)$
4. $\Delta P_{\text{MAX}} \propto I_{\text{MAX}}^2 * R_{\text{SERIES}}$
5. $T_{\text{MOD}} \sim T_{\text{AMB}} - \text{fn}(\text{Windspeed})$
6. $R_{\text{SHUNT}} \propto 1/\exp(G_i)$

Module STC rating actual/nominal

Power temperature coefficient “$\gamma$”

From diode equation

$I^2.R_s$ loss

NMOT Thermal rise

(dependant on PV technology)

$$\begin{align*}
\text{PR}_{\text{DC}} &= C_1 + C_2 \times (T_{\text{MOD}} - 25) + C_3 \times \log_{10}(G_i) + C_4 \times G_i + C_5 \times WS + (C_6/G_i) <\text{MPM}> \\
\text{PMAX.ACTUAL} & \text{ Temperature} \quad \text{Voc} \quad \text{RSERIES} \quad \text{NOCT} \quad \text{<<RSHUNT>>}
\end{align*}$$

MPM model has only “Meaningful, Orthogonal, Robust, Normalised” coefficients
How does PV performance depend on weather inputs?

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$PR_{DC} =$

\[ P_{MAX\,ACTUAL} = C_1 + C_2*(T_{MOD} - 25) + C_3*\log_{10}(G_i) + C_4*G_i + C_5*WS + \left(C_6/G_i\right) <\text{MPM}> \]

MPM model has only “Meaningful, Orthogonal, Robust, Normalised” coefficients
Comparing Empirical and Mechanistic models (61853-1 matrix)

(PR_{DC} vs. Irradiance and T_{MODULE} coloured lines)

Compare fits to raw model data vs. 2% rms added noise to mimic measured data

Empirical Model A

Empirical Model D

Mechanistic model

Raw data from model: add 2% rms noise seed 0 add 2% rms noise seed 1
Comparing Empirical and Mechanistic models (61853-1 matrix)

(PR<sub>DC</sub> vs. Irradiance and T<sub>MODULE</sub> coloured lines)

**All fit “Perfect” data**

**Empirical Models don’t fit “imperfect or noisy data” well**

- [1] [2] Poor extrapolation and interpolation
- [4] [5] Variable temperature coefficient vs. irradiance

[Check marks and crosses indicating fit or no fit with different datasets and models.]

Raw data from model

add 2% rms noise seed 0 add 2% rms noise seed 1

13-Nov-17

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Comparing Empirical and Mechanistic models (61853-1 matrix)
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- [1] [2]
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- [4] [5]
  Variable temperature coefficient vs. irradiance

**Mechanistic model always fits well**, even to noisy data

All fit “Perfect” data

Raw data from model

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**add 2% rms noise seed 1**
Comparing Empirical and Mechanistic models (61853-1 matrix) (PR$\text{DC}_{\text{1}}$ vs. Irradiance $\equiv$ and T$\text{MODULE}$ coloured lines)

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Raw data from model  add 2% rms noise seed 0  add 2% rms noise seed 1
Comparing model coefficients vs. technology cSi aSi CdTe

**Empirical model**

No pattern to coefficients even though fits are reasonable and c-Si measurements were quite similar

**MPM Mechanistic model**

Sensible values of all coefficients = more robust

P<sub>MAX</sub> tolerance  ➔ Realistic P<sub>MAX</sub> Temperature coefficient etc.
Comparing model coefficients vs. technology  cSi  aSi  CdTe

[SUPSI data]

<table>
<thead>
<tr>
<th>Technology</th>
<th>ID</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
<th>C₅</th>
<th>rms</th>
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</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>60</td>
<td>-42.3</td>
<td>53.9</td>
<td>-10.7</td>
<td>-32.9</td>
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<tr>
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<td>-127.2</td>
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<td>-31.7</td>
<td>-97.8</td>
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<td>0.22</td>
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<td>c-Si</td>
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<td>90.5</td>
<td>-18.0</td>
<td>-55.3</td>
<td>13.5</td>
<td>0.09</td>
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<td>-127.6</td>
<td>-22.4</td>
<td>-72.0</td>
<td>-17.6</td>
<td>1.84</td>
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<td>c-Si</td>
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<td>3.02</td>
<td>123.8</td>
<td>24.6</td>
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<td>0.24</td>
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<td>-13.1</td>
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<td>131.4</td>
<td>-98.7</td>
<td>21.9</td>
<td>23.5</td>
<td>0.10</td>
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<td>c-Si</td>
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<td>-6.8</td>
<td>1.4</td>
<td>4.1</td>
<td>-1.0</td>
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<tr>
<td>c-Si</td>
<td>72</td>
<td>10.7</td>
<td>-132.5</td>
<td>16.7</td>
<td>10.1</td>
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<td>0.59</td>
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<tr>
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<td>16.3</td>
<td>88.4</td>
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<tr>
<td>TF a-Si</td>
<td>65</td>
<td>-0.2</td>
<td>1.1</td>
<td>-0.3</td>
<td>-0.5</td>
<td>0.1</td>
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<td>TF a-Si</td>
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<tr>
<td>TF CdTe</td>
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<td>2.2</td>
<td>-0.6</td>
<td>-1.2</td>
<td>-0.3</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Empirical model

No pattern to coefficients even though fits are reasonable and c-Si measurements were quite similar

MPM Mechanistic model

Sensible values of all coefficients = more robust

$P_{\text{MAX}}$ tolerance  $\Leftarrow$  Realistic $P_{\text{MAX}}$ Temperature coefficient etc.
How well can MPM fit IEC 61853-1 data?

Typical c-Si data from NIST/CFV has an rms error of 0.12%
MPM can easily fit 3rd party indoor, outdoor and models.

Data From Gantner, SUPSI, NIST, ASU, ESTI, TUV Rheinland, CFV, SAPM and PVSYST.
Are all the model coefficients independent?

$$C_1 + C_2 \cdot dT_{MOD} + C_3 \cdot \log(G_I) + C_4 \cdot G_I + (C_5 \cdot WS + (C_6 / G_I))$$

- $P_{MAX.ACCUAL}$
- $\gamma$
- $Voc$
- $R_{SERIES}$
- $NOCT$
- $\langle R_{SHUNT} \rangle$

If we alter each coefficient individually - all traces should change differently.

These graphs do that so the MPM has unique fits and is robust.
Investigating energy yield

• How does the robustness and variability of a model fit affect its energy yield predictions?

• Consider fit variability at low and high light levels and temperatures with sites that are dull, bright, cold or hot.
How do the model fits vary vs. $T_{\text{MOD}}$ and irradiance bins?

**Empirical A**
1. Decline in accuracy as irradiance falls

**Empirical D**
2. Variable at low light
3. Poor at Cold+Mid light levels

**MPM**
4. Good almost everywhere
5. Only slightly worse at lowest light or
6. cold+mid light levels
Insolation fraction vs. Irradiance and Module Temperature varies for sites worldwide – Koeppen colours.

The diagram shows a comparison of annual POA insolation in kilowatt-hours per square meter per year (kWh/m²/y) against TmodG weighted in Celsius. The sites are color-coded according to Koeppen climate types.
Insolation fraction vs. Irradiance and Module Temperature varies for sites worldwide – Koeppen colours

- **TROPICAL**: Most insolation at high light, high temperature
- **ARID**: Most insolation at very high light, very high temperature
- **POLAR, COLD CONTINENTAL**: Most insolation at low light, low temperature
- **TEMPERATE**: Most insolation from cool+dull to warm+bright

Weighted module temperature (°C)
Energy Yield predicted variability by site

- Polar to Arid

- Each site has rms error for
  1) Summer month (Jul or Jan)
  2) Winter month (Jan or Jul)
  3) Yearly Average (All 12 months)

- The most robust model should have lowest rms error everywhere

<table>
<thead>
<tr>
<th>Site name, Koeppen climate designation</th>
<th>Summer AD</th>
<th>Winter AD</th>
<th>Year AD</th>
<th>Summer DMP</th>
<th>Winter DMP</th>
<th>Year DMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARENTSBERG, Polar Tundra Eternal winter (ice cap)</td>
<td>1.09%</td>
<td>0.77%</td>
<td>0.40%</td>
<td>1.21%</td>
<td>0.72%</td>
<td>0.36%</td>
</tr>
<tr>
<td>ANCHORAGE, Cold (continental) Without dry season Cold summer Dfc</td>
<td>0.50%</td>
<td>0.30%</td>
<td>0.25%</td>
<td>1.14%</td>
<td>0.96%</td>
<td>0.44%</td>
</tr>
<tr>
<td>HAMBURG, Temperate Without dry season Warm summer Cfb</td>
<td>0.40%</td>
<td>0.33%</td>
<td>0.23%</td>
<td>1.89%</td>
<td>0.82%</td>
<td>0.41%</td>
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<td>TOKYO, Temperate Without dry season Hot summer Cfa</td>
<td>0.43%</td>
<td>0.37%</td>
<td>0.28%</td>
<td>0.31%</td>
<td>0.28%</td>
<td>0.30%</td>
</tr>
<tr>
<td>SYDNEY, Temperate Without dry season Hot summer Cfa</td>
<td>0.23%</td>
<td>0.33%</td>
<td>0.23%</td>
<td>0.34%</td>
<td>0.28%</td>
<td>0.27%</td>
</tr>
<tr>
<td>LA PAZ, Temperate Dry winter Warm summer Cwb</td>
<td>0.30%</td>
<td>0.26%</td>
<td>0.22%</td>
<td>0.18%</td>
<td>0.23%</td>
<td>0.17%</td>
</tr>
<tr>
<td>MUMBAI, Tropical Savanna, Wet Aw</td>
<td>0.44%</td>
<td>0.39%</td>
<td>0.29%</td>
<td>0.22%</td>
<td>0.24%</td>
<td>0.19%</td>
</tr>
<tr>
<td>RIYADH, Arid Desert Hot Bwh</td>
<td>0.24%</td>
<td>0.36%</td>
<td>0.36%</td>
<td>0.21%</td>
<td>0.29%</td>
<td>0.21%</td>
</tr>
<tr>
<td><strong>AVERAGE 22 SITES</strong></td>
<td><strong>0.33%</strong></td>
<td><strong>0.36%</strong></td>
<td><strong>0.27%</strong></td>
<td><strong>0.56%</strong></td>
<td><strong>0.42%</strong></td>
<td><strong>0.29%</strong></td>
</tr>
</tbody>
</table>
Conclusions

Existing empirical models

❌ Can’t repeatably fit imperfect data. They have unphysical coefficients.

Mechanistic Performance Model (MPM)

✅ Much more robust and useful than empirical fit models
✅ Added to Gantner Instruments’ [www.gantner-webportal.com](http://www.gantner-webportal.com) SaaS platform

Energy yield predictions

✅ Much less variability in EY from fitting errors for MPM
  MPM 0.25-0.29% vs. Empirical 0.33-0.56%

\[
PR_{DC} = C_1 + C_2 \cdot (T_{MOD} - 25) + C_3 \cdot \log_{10}(G_I) + C_4 \cdot G_I + C_5 \cdot WS + \frac{C_6}{G_I}
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\(\text{P}_{\text{MAX.ACTUAL}}\), \(\text{Temperature}\), \(\text{Voc}\), \(\text{R}_{\text{SERIES}}\), \(\text{NOCT}\), «\(R_{\text{SHUNT}}\)>>
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See Poster 7TuPo.225
Quantifying and analysing the variability of PV module resistances $R_{SC}$ and $R_{OC}$ to understand and optimise kWh/kWp modelling

Thank you for your attention!

• Please contact me to share your data steve@steveransome.com