kWh/kWp:
Comparing modelling, claims and measurements
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www.steveransome.com
Introduction

• 19 years with BP Solar: indoor and outdoor measurements, modelling and simulation programs

• For the last two years as an independent PV consultant working with clients worldwide

• Studying kWh/kWp on many PV technologies since 1998
What are the main differences between kWh/kWp simulations and measurements?

- Some manufacturers have claimed up to 30% higher kWh/kWp than their competitors.
- Several recent independent tests show mostly < ±5% between different technologies and manufacturers – dominated by \( \frac{P_{\text{max \, actual}}}{P_{\text{max \, nominal}}} \)

- Simulation programs often predict > 5% kWh/kWp difference (usually suggesting better for thin film).
- I have investigated the assumptions made and algorithms used in some simulation programs.
Simulation program flow chart to calculate kWh/kWp

1a) Weather Generator: Irradiance, Tambient vs time
1b) Measured Weather: Irradiance, Tambient vs time

2) PV Database: modelled parameters
3) DC PV Performance: Pmax vs Irradiance, Tmodule etc.
4) DC losses: Dirt, Mismatch, Shading etc
5) AC Losses: Vmp tracking Inverter efficiency, clipping etc

User inputs e.g. dirt, Pmax/Pnominal

Insolation vs. irradiance (depends on frequency of measurement)

Model of Efficiency vs. irradiance and module temperature
How simulation programs usually calculate kWh/kWp (Matrix method)

\[ \text{kWh/kWp} \sim \sum \text{Insolation}^{(T_{\text{mod}}, \text{Irradiance})} \times \text{Efficiency}^{(T_{\text{mod}}, \text{Irradiance})} \]

10min data
Kassel

Module Temperature (°C)
A frequent statement:
“My simulation program gives approximate values of kWh/kWp therefore it is validated”

- kWh/kWp depends on the product of >4 items
  - Insolation (Gi, Tm)
  - PV Efficiency (Gi, Tm)
  - Inverter Efficiency (Gi, Tm)
  - Unknowns e.g. dirt, Pmax/Nominal

- Errors may self cancel (e.g. too high an insolation with too low a PV Efficiency)

- Exact fits to measured data can be found by “fixing” the unknowns – but these would then be technology or site dependent

- **Every stage must be checked to be correct to validate a simulation, not just the sum of kWh/kWp**
A 1 diode model (de Soto et al) is often used to fit an IV curve to 5 “knowns”

- Usually fitted to manufacturers’ data sheets or a tested module
- 1 diode model is not a perfect fit to c-Si or thin film
- Problems fitting c-Si with high Rsh
- Diode theory is used to predict temperature dependence (rather than use IEC 61215 / 61646 standard measurements)
- Equation also predicts low light level response (rather than EN 50380 measurements)
- This fits 1 module, what is the random variability in IV curves?
Minimum variation in data sheet module parameters from for typical c-Si and 1J - Thin Film

(2% bins) More improvements in Isc than Voc or FF

(3% bins) Most improvement in FF, Vmax (i.e. lower Rseries)

$$P_{\text{max}} = I_{\text{mpp}} \cdot V_{\text{mpp}} ; \quad P_{\text{max}} = I_{\text{sc}} \cdot V_{\text{oc}} \cdot FF$$
**kWh/kWp modelling error depends on all the uncertainties in measurements**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error Range</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrated reference module Pmax W</td>
<td>±2.5%</td>
<td>for c-Si, less accurate for thin films</td>
</tr>
<tr>
<td>Flash tester W</td>
<td>±x% (1%?)</td>
<td>Repeatability error</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Not perfect AM1.5 spectrum, capacitance/timing issues)</td>
</tr>
<tr>
<td>LID/Pmax degradation allowance %</td>
<td>-1 to -3%</td>
<td>B doped p type c-Si</td>
</tr>
<tr>
<td></td>
<td>-10 to -35%</td>
<td>greater for thin films</td>
</tr>
<tr>
<td>Pmax bin width W</td>
<td>±2.5%</td>
<td>e.g. 200&lt;Pmax&lt;210W or 100&lt;Pmax&lt;105W</td>
</tr>
<tr>
<td>Insolation kWh/m²</td>
<td>±2.3%</td>
<td>pyranometer reference cell</td>
</tr>
<tr>
<td></td>
<td>±1.7-7%</td>
<td>Satellite data, Tilted plane algorithm, site interpolation</td>
</tr>
<tr>
<td>Module temperature</td>
<td>3°C/sun</td>
<td>(T\text{JUNCTION} - T\text{BACK})</td>
</tr>
<tr>
<td></td>
<td>0.5 to 1.5%</td>
<td>% Pmax error (assuming gamma is -0.15 to -0.5%)</td>
</tr>
<tr>
<td>Yearly insolation</td>
<td>±4%/y</td>
<td>random variations, more effects such as el Niño etc.</td>
</tr>
<tr>
<td>Micro climate</td>
<td></td>
<td>Can’t linearly interpolate near coasts, mountains etc.</td>
</tr>
<tr>
<td>Shading loss</td>
<td></td>
<td>Varying tree cover, new buildings, self shading</td>
</tr>
<tr>
<td>Dirt loss</td>
<td></td>
<td>Site dependent daily rise, falls after clean or ~&gt;5mm rain</td>
</tr>
<tr>
<td>Snow cover</td>
<td></td>
<td>Winter when low daily insolation – small effect ?</td>
</tr>
<tr>
<td>Mounting C</td>
<td></td>
<td>High temperatures from close mounting, BIPV etc.</td>
</tr>
</tbody>
</table>

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Correlation of meteorological parameters

High Irradiance correlates with:
- High Temperatures
- Low Angle of incidence
- Low Air Mass
- Summer
- High Beam Fraction
Correlation of meteorological parameters

**High Irradiance vs. Low Irradiance**

**High Irradiance** correlates with:
- High Temperatures
- Low Angle of incidence
- Low Air Mass
- Summer
- High Beam Fraction

**Low Irradiance** correlates with the opposite values.
Correlation of meteorological parameters

Low Irradiance; **High** vs. **Low** Clearness

High Clearness
→ clear morning/evening
→ high angle of incidence, clear sky

Low Clearness
→ dull daytime
→ Lower angle of incidence and overcast sky

Measured outdoor low light level efficiency will be a site dependent mix of these two conditions
Low light value depends on sensor spectral response
Averaged low light value depends on overcast: clear ratio (site specific)

(dull daytime) Scatter and rise in efficiency at low light
(clear mornings/evenings) Fall in efficiency ~ high AOI, Air mass at low light

• Low light value depends on sensor spectral response
• Averaged low light value depends on overcast: clear ratio (site specific)
Calculating IEC standard values from PV efficiency/nominal vs. irradiance and module temperature:

![Graph showing Mod Eff/Nom vs. Irradiance Gi (W/m²)]

- Eff@200/Eff@1000
- Gamma (dP/dT)
- Eff@NOCT

Graph includes lines for different temperatures (10, 25, 40, 55) and various points indicating changes in efficiency with different irradiance levels.
Comparing power temperature coefficients
\[(\text{Gamma} = \frac{1}{P_{\text{max}} \cdot \frac{dP_{\text{max}}}{dT}})\]

Simulation programs

Disagreement between program version values
Comparing power temperature coefficients \( \Gamma = \frac{1}{P_{\text{max}} \cdot \frac{dP_{\text{max}}}{dT}} \)

Simulation programs vs. Manufacturer datasheet

Also disagreement with manufacturer datasheet
Comparing Low Light efficiency changes (LLEC = Eff@200/Eff@1000-1)

Simulation programs

Disagreement between program version values
Comparing Low Light efficiency changes
(LLEC = Eff@200/Eff@1000-1)
Simulation programs vs. Manufacturer datasheet

Also disagreement with manufacturer datasheet
Correcting simulation program efficiency to manufacturer’s datasheet: c-Si #3

Low light efficiency change
82% → 95%

Gamma (1/\(P_{\text{max}} \times dP_{\text{max}}/dT\))
-0.42%/K → -0.48%/K

High \(R_{\text{shunt}}\) gives high efficiency down to low light levels for c-Si
Correcting simulation program efficiency to manufacturer’s datasheet: Thin film #9

- Low light efficiency change
  94% → 102%

- High $R_{series}$ causes efficiency to fall at high light levels due to $I^2R$ loss

- Gamma ($dP_{max}/dT_{Temperature}$)
  -0.32%/$K$ → -0.25%/$K$
## Checking kWh/kWp simulation errors at 5 sites worldwide

<table>
<thead>
<tr>
<th>Site name, Country</th>
<th>Latitude °</th>
<th>POA Insolation kWh/m²</th>
<th>Weighted Tambient °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munich, DE</td>
<td>48°N</td>
<td>1345</td>
<td>*</td>
</tr>
<tr>
<td>→ Dull, cool</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albuquerque NM, USA</td>
<td>35°N</td>
<td>2336</td>
<td>***</td>
</tr>
<tr>
<td>→ Very bright, warm</td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>Mumbai, IN</td>
<td>19°N</td>
<td>1988</td>
<td>**</td>
</tr>
<tr>
<td>→ Bright, Hot</td>
<td></td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Seoul, KO</td>
<td>38°N</td>
<td>1299</td>
<td>*</td>
</tr>
<tr>
<td>→ Dull, cool</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney, AU</td>
<td>34°S</td>
<td>1797</td>
<td>**</td>
</tr>
<tr>
<td>→ Bright, warm</td>
<td></td>
<td></td>
<td>**</td>
</tr>
</tbody>
</table>
Modelled hourly insolation vs. irradiance and module temperature at 5 sites worldwide

(more frequent measurements prove more insolation at higher light levels)
Simulation program modelled kWh/kWp vs. power temperature coefficient error

- #9: Gamma -0.32% → -0.25%
- #3: Gamma -0.42% → -0.48%
- Larger correction has bigger error (%/C)
- Hottest site (Mumbai) has biggest difference
Simulation program modelled kWh/kWp vs. Low light efficiency change error

- Larger correction has bigger error up to 8%
- Sunniest site has smallest difference

#3: LLEC 82% → 95%
#9: LLEC 95% → 102%
Conclusions

Measured kWh/kWp < ~±5% from several independent studies, dominated by \[\text{Wp.actual/Wp.nominal}\], not technology dependent

Simulation program kWh/kWp predictions

• dominated by errors in database values for “Efficiency at low light” and “Pmax vs. temperature”
• Efficiency at low light is modelled worse than manufacturers’ claims for both c-Si and thin film
• Correcting low light efficiency - biggest gain in cloudy conditions
• Correcting Pmax temp. coefficient - biggest change in hot conditions
• Corrections values vary by manufacturer and technology
• c-Si has been modelled more pessimistically than thin film
• These corrections should bring modelled kWh/kWp closer together by technology to match real measurements better
Acknowledgements: Oerlikon, IWES for data

Next conference: www.pvsat.org.uk
“The British Staffelstein”
Southampton, UK
24-26 March 2010

Thank you for your attention!

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