Understanding PV performance based on real world data

PV Systems Symposium,
Sandia National Labs, May 2\textsuperscript{nd}, 2013

Juergen Sutterlueti, PV Systems Group
TEL Solar AG, Switzerland
PV Performance
Which factors determine real world energy yield (kWh/kWp)?

Energy Yield

- Long term behavior of components (Inverter, PV Module)
- Irradiation sensor: Quality, stability
- Different spectrum (direct/diffuse Irradiation)
- Measurement uncertainty
- Low Light behaviour (LLB)
- Temperature behaviour
- Production quality (cell, process, materials)
- Dirt/soiling
- Location/Surroundings
- Seasonal behaviour (rain, snow, ...)
- Shadow
- MPP Tracking of Inverter
- O&M
- Inverter efficiency
- Design of PV Power Plants

How can we measure, analyze & predict these factors?
# Agenda

<table>
<thead>
<tr>
<th></th>
<th>Data Collection efforts at TEL Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Quality of data, minimum input for proper characterization</td>
</tr>
<tr>
<td>3</td>
<td>Loss Factors Model (LFM)</td>
</tr>
<tr>
<td>4</td>
<td>How to improve existing PV Performance Models (Parameters)</td>
</tr>
<tr>
<td>5</td>
<td>Summary</td>
</tr>
</tbody>
</table>
TEL Solar AG Business concept
PV Systems Group

Focus
PV Systems Group

Feedback

Outdoor Test Facilities
- Worldwide network
- Performance analysis
- New characterization models / methods (e.g. Loss Factors Model LFM)

PV Power Plants
- Test power plants
- Reference power plants
- Performance analysis
- LCoE optimization

BoS costs
- Analysis (Trends, innovations, cost drivers)
- Tracking and benchmarking
- Technology comparisons
- Optimization
TEL Solar – Global PV Test Network

Existing Test sites

TPVPP&OTF 5 EKZ, CH
TPVPP-TEL, TBB
TPVPP-Cyprus

TPVPP: Test PV Power Plant (AC&DC DAQ); OTF: Outdoor Test Facility (single module testing, DC), both including all relevant environmental parameters
TEL Solar – Global PV Test Network II

TEL Solar Outdoor Test Facilities (selected)

- Central European climate Switzerland since 2008
- Hot & dry climate Arizona since 2010

- Same system setup/DAQ at all sites
- >24 channels fixed orientation south + 2D Tracker
- IV scans each minute
- Same technology set ("twins") of PV Modules per location

- High precision measurement equipment for environmental data & e.g. component cells

- Dust storm in AZ, 2011
- Snow in Switzerland
TEL Solar – Global PV Test Network III

Test PV Power Plants

TPVPP Specs

- Standardized, grid connected Test PV Power Plant
- Different technologies (a-Si, a-Si/μc-Si)
- High quality measurement & data acquisition system w/ direct data access
- Easy installation around the world: prefabricated cabinet incl. own data acquisition concept
- Advanced Inverter concept, 3phase
- Low cost BoS (-24% cost reduction due to MMI)

Measurements

- AC / DC parameters, String level monitoring
- Weather conditions (irradiation sensors, humidity, rain, wind speed, temperature)
- Dust measurements (by TEL TWN team)

Experiments

Technology behavior under local climate conditions (temperature, spectrum & seasonal variation), dust studies

Other TPVPP in Cyprus, 2x Switzerland etc
Loss factors model (LFM) - IV curve fit

- 8 physical, normalised, orthogonal losses not just efficiency
- Works with
  - all PV technologies tested (a-Si, a-Si:uc-Si, CdTe, CIGS, c-Si, HIT ...)
  - Different sites (Switzerland, Arizona, ...)
  - All weather (Clear noon, morning, evening or cloudy)
  - Pyranometer and/or c-Si reference cell
  - Fixed plane or 2D tracker
- Can validate performance and predict energy yield

Efficiency ~ “product of 8 losses”

\[
\text{Efficiency} \sim \left[ \frac{\text{MMF} \cdot \text{nIsc} \cdot \text{nRsc} \cdot \text{nImp}}{\text{Meas. Pmax}} \right] \cdot \left[ \frac{\text{nVmp} \cdot \text{nRoc} \cdot \text{nVoc} \cdot \text{tCorr}}{\text{V}} \right]
\]
LFM Outdoor Temperature coefficients

- Gradient at higher irradiances vs. module temperature gives thermal coefficients
- Not just Isc $\alpha$, Voc $\beta$ and Pmax $\gamma$ but also $d(R_{sc})/dT_{mod}$ and $d(R_{oc})/dT_{mod}$
- Also possible at TPVPP arrays w/ DC side measurements

Note: PF=PR_dc
Typical plot of LFM coefficients vs. Irradiance
Thin Film Module in Arizona

Independent losses - temperature and spectrum corrected

→ Now only depends on irradiance

Fit e.g. 200 + 800W/m²

Calculated vs. measured Performance

Note: LFM-A concept based on 5 parameters
LFM – comparing different technologies and sites
AZ=Arizona, CH=Switzerland

- c-Si best \( R_{\text{SHUNT}} \)
- CdTe worst \( R_{\text{SERIES}} \)
- Multijunctions differ diffuse vs. direct
- Lower \( R_{\text{SHUNT}} \) gives worse low light performance
- Different individual loss factors by technology but similar Performance factors
Energy yield determining effects - which can be included / improved for better PV modelling

- Rsc vs. Irradiance
- Angle of Incidence (AOI) differences between module and sensor
- Fixed plane vs. 2D tracking
- Spectral response
- Low vs. high horizon
- Current matching (multi junction devices)
- Seasonal annealing
- (Light induced) Degradation
- Soiling & cleaning impact (see Dust Detection System by TEL TWN team)
- Production quality distribution
- ...

All required for improved kWh/kWp or ct/kWh analysis!
How Rsc varies with irradiance
→ determines the low light performance

- TEL Solar measured Rsc for 3rd party thin film modules Switzerland, a similar effect in Arizona ("normalised" to Rsc*Voc/Isc)

- Rsc rises exponentially with falling irradiance

- c-Si also follows same shape but scatter is worse as Rsc much higher (not shown)
Measured “low light efficiency” is determined by the AOI dependence of the Irradiance sensor type.

- Clear day in April, Arizona
- Pyranometer vs. c-Si ISE reference
- Fixed plane (33° tilt) vs. 2D tracker
- Calibrated at AM1.5 on 2D tracker

The calculated low light efficiency of any module will appear worse when using a pyranometer rather than a c-Si reference cell due to AOI effects. Shown example: 18% at AOI=75°
Clear day spectrum
High(left) vs. Low (right) horizon

- Clear skies at equinox for a high horizon site (CH, left) and low horizon (AZ, right)
- High horizon sites lose red rich light by shading – giving more apparent kWh/kWp to blue sensitive technologies
- Same ”glitch” to blue rich spectra from high horizons and tilted modules
Matching of Multi-junction cells
Top & Bottom limited micromorph

- Multi junctions (e.g. Micromorph) are series connected blue & red cells (same current)
- Matched at one spectrum
- Current limitation based on spectrum (e.g. red junction in blue rich light and vice versa)
- Can optimize matching based on local conditions (e.g. bluer than AM1.5)

Module A
1. Decreases in current with constant FF until November → top limited
2. Minimum in FF in May, constant current → matched status.
3. Strongest current mismatch (top limited) observed in January

Module B
4. Decrease in FF, constant current until January → bottom limited
5. Minimum in FF, maximum in current at January → closest point to matching
6. Current increases in winter due to advantageous spectral conditions for the bottom cell

Data around noon, Gi>200W/m², no Temperature correction
Long term variation / seasonal annealing
Real world variation of IV parameters, per month

- The LFM model gives values of the 6 coefficients at low light (black) and high light (colored).
- Comparable performance at different sites, Dust should only affect nIsc and nPF.
- Some Thin Film modules reversibly anneal after cooler & warmer periods, being better in autumn vs. spring.
Long term variation / seasonal annealing II
Real world variation of IV parameters, per month

- The LFM model gives values of the 6 coefficients at low light (black) and high light (colored).
- Comparable performance at different sites; Dust should only affect nIsc and nPF.
- Some Thin Film modules reversibly anneal after cooler & warmer periods, being better in autumn vs. spring.
Real world PV PP data: MPP tracking -
Single Module vs. Array - 5 different inverter types

Inverter conversion efficiency:
performance vs. datasheet

Ref. PV Module

PV Array

Tracking issue (at low light)

Have you checked the actual inverter efficiency at your system?

Fig. 10: MPP tracking of Udc based on 5 different Inverter types at 3 selected days in September 2010. Unmpp tracking from the reference modules as comparison.

Date: September from 2010, OTF5;
Inverter plot: steady conditions - filtered data from the entire year 2011, OTF5; 3rd party product, conditions: max. spread: Gi: +/-0.5%, Tmodule: +/- 1K, Gi>10W/m²
LFM - Checking performance and stability over time

Variation of LFM, 16 clear days, 1/month, 2 sites, e.g. c-Si poly

Switzerland

Arizona

nIsc and nVoc should be near 1 and consistent for a well calibrated, stable PV module

Performance factor should be high and consistent for a stable PV module

- Seasonal variation and losses
- Generally good agreement between prediction & measured LFM parameters
- Prediction of Energy Yield only with uncorrected PF (PR\textsubscript{DC})
- Possible for AC arrays!

Data from 09/2012 – 04/2012
Summary

- **TEL Solar’s Global PV Test Network:**
  - generate track record under different (extreme) environmental conditions for bankability, reliability & modeling
  - Validation for BoS cost reduction initiatives (electrical, mechanical, inverters, ..)
  - With accurate data and the option of Loss Factor Model (LFM):
    - can validate and predict performance and responsible parameters for changes (incl. Dust)

- **Loss Factors Model (LFM):**
  - Monitors relative changes in efficiency and finds responsible IV parameter
  - LFM: works for different technologies and site, different weather and applications (fix vs. tracked), normalized parameters
  - Distinction between Seasonal Changes (i.e. annealing) and Degradation.
  - Allows prediction of Energy Yield from uncorrected PR_{DC} incl. dust check (TEL TWN)

- **Combination of single PV Module and Test PV Power Plants**
  enables specific electrical BoS optimization & design (e.g. Inverter)

- Modelling efficiency vs. irradiance and temperature is not reflecting real world behavior
  - Adapt models to R_{SHUNT}, spectral and seasonal variation per technology and location

Measure accurate & long term with regular O&M – and your PV model can be better validated for realistic performance predictions!
Thank you very much for your attention!

Acknowledgment: Teams at TEL Solar, TEL PVE, TEL TWN, SRCL
Additional Information/ References:

- Y. Ueda et al.; “Comparison between the I-V measurement and the system performance in various kinds of PV technologies”; 25th EU PVSEC, Valencia 2010
- J. Sutterlueti et al.; “Detailed Outdoor Performance Analysis of Thin Film and Cristalline Silicon Based Reference PV Power Plants in Switzerland”; 3rd Int. Conference of Thin-Film Photovoltaics, Munich 2011
- J. Sutterlueti et al.; “Outdoor characterisation and modeling of thin-film modules and technology benchmarking”; 24th EU PVSEC, Hamburg 2009
- Sellner et al.; "Understanding Module Performance further: validation of the novel loss factors model and its extension to ac arrays”; 27th PVSEC Frankfurt 2012
- S. Ringbeck, J. Sutterlueti; “BoS costs: Status and optimization to reach industrial grid parity”; 27th EUPVSEC Frankfurt 2012
- S. Ransome, J. Sutterlueti; “The sensitivity of LCOE to PV technology including degradation, seasonal annealing, spectral and other effects”; 27th EUPVSEC Frankfurt 2012
- S. Ransome et al.; “PV technology differences and discrepancies in modelling between simulation programs and measurements", 38th PVSC, Austin 2012

Key words: real world data, PV Systems, sensitivity, prediction, Global test PV Power Plant network, weather types, Loss Factor Model, extension to AC arrays.
Loss Factors Model (LFM)

- Based on measured outdoor and reference IV parameters
- 6 normalized and independent parameters plus corrections for spectrum and temperature.
- Performance Factor,

\[
PF = [MMF \times (nIsc \times TC.Isc) \times nRsc \times nImp] \\
\times [nVmp \times nRoc \times (nVoc \times TC.Voc)]
\]

Note: PF=PR_{dc}