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Understanding PV performance based on real world data

PV Systems Symposium,
Sandia National Labs, May 2nd, 2013

Juergen Sutterlueti, PV Systems Group
TEL Solar AG, Switzerland

TEL Solar

50 Years

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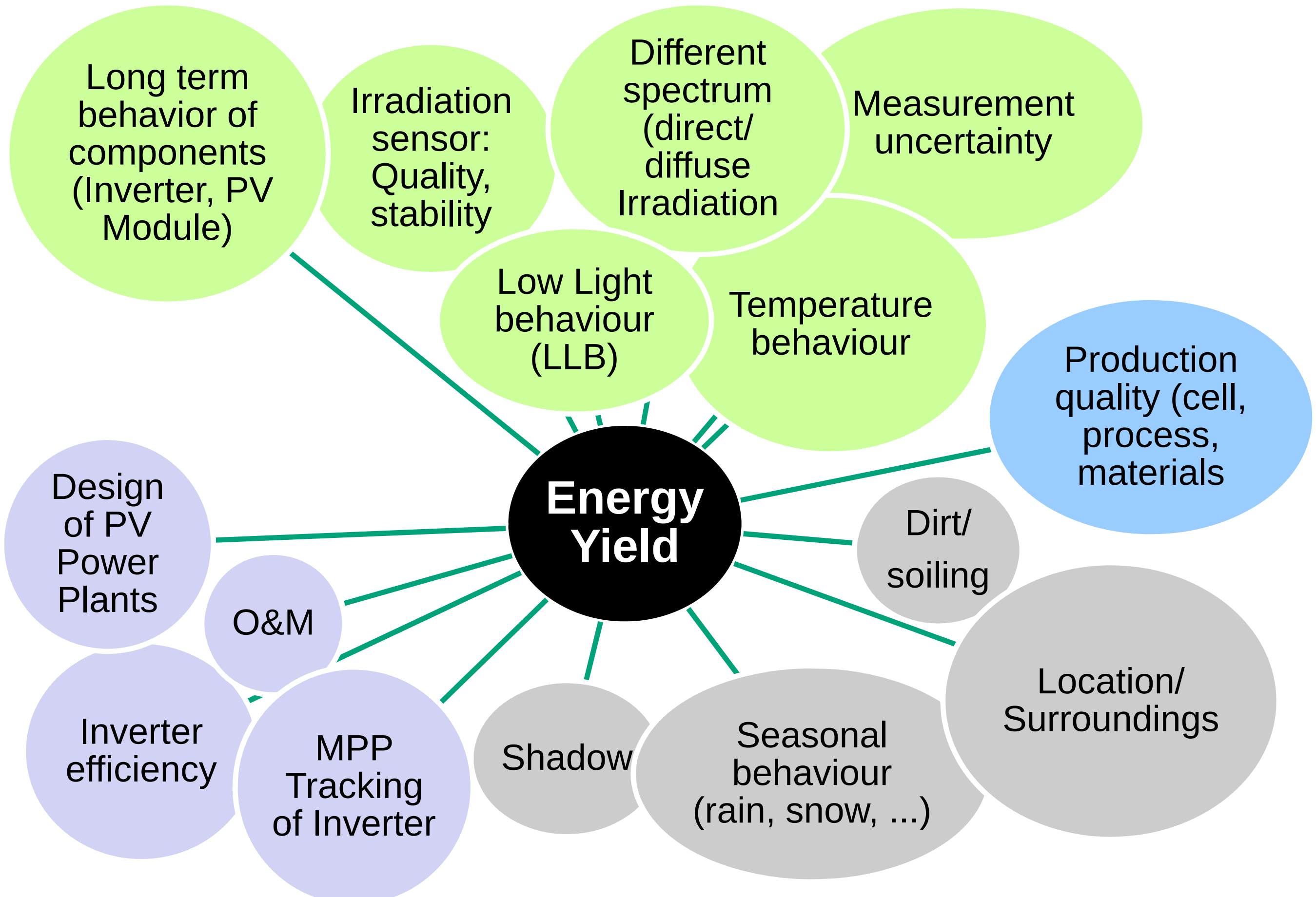
PV Performance

Which factors determine real world energy yield (kWh/kWp)?



How can we measure, analyze & predict these factors?

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Agenda

1	Data Collection efforts at TEL Solar
2	Quality of data, minimum input for proper characterization
3	Loss Factors Model (LFM)
4	How to improve existing PV Performance Models (Parameters)
5	Summary

TEL Solar AG Business concept

PV Systems Group

Focus
PV Systems Group

Capital Equipment | Turnkey Solutions | Module Manufacturer | BOS Suppliers | EPC Integrator | Wholesale Utilities

Feedback

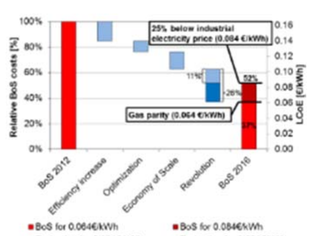
Outdoor Test Facilities

- 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

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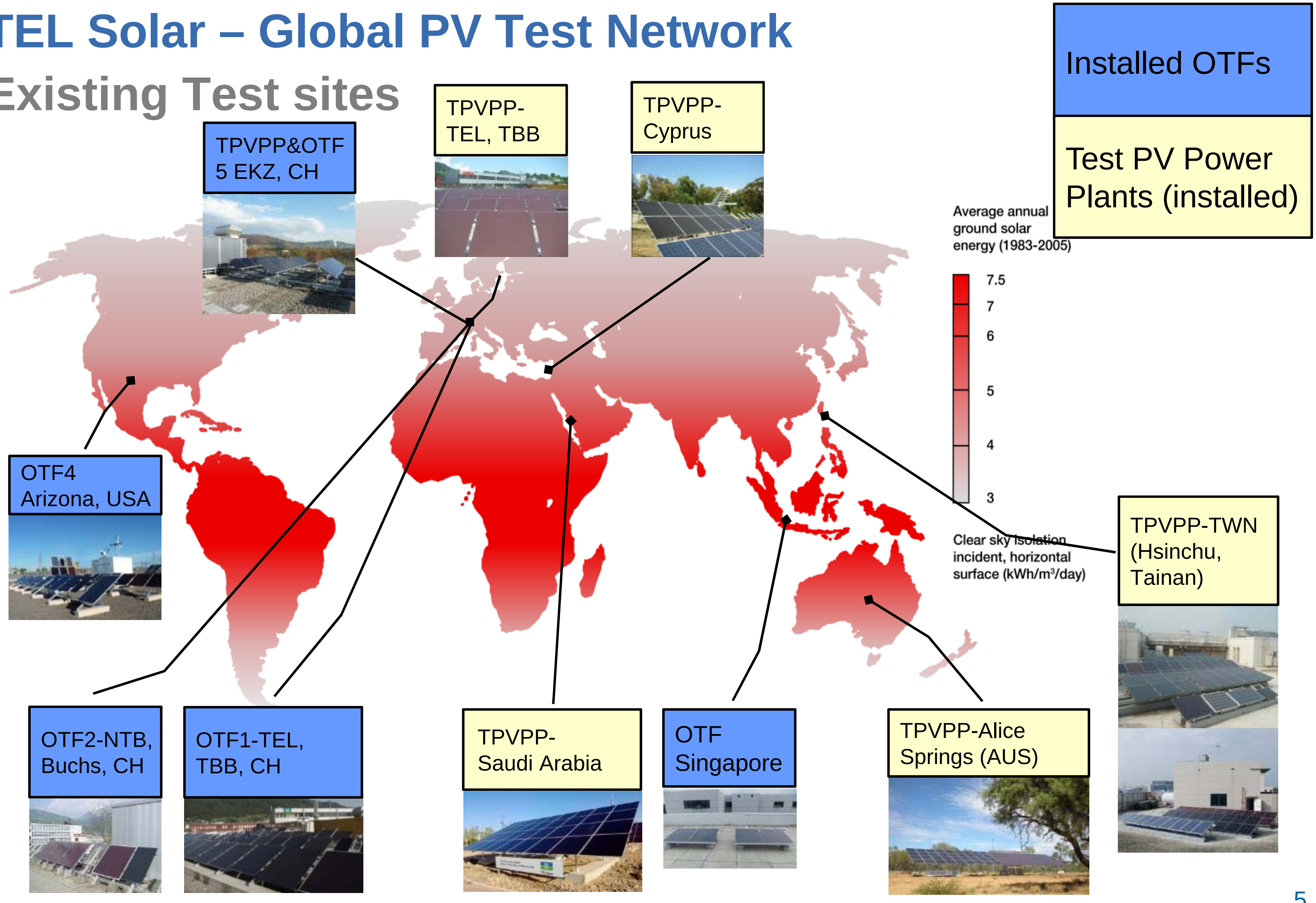
Rev. 130424

TEL Solar – Global PV Test Network

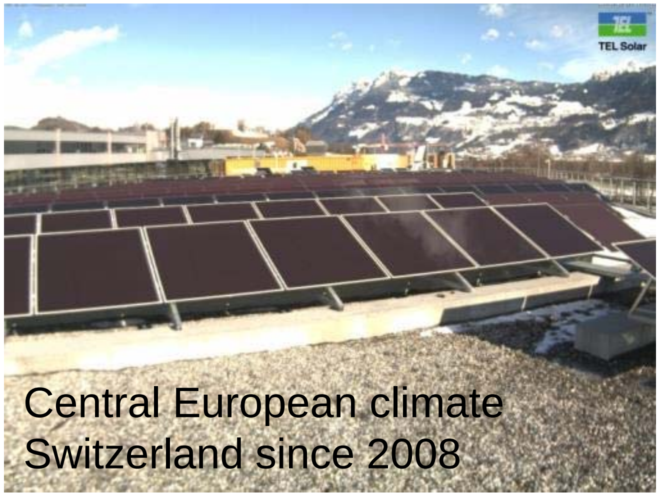
Existing Test sites



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

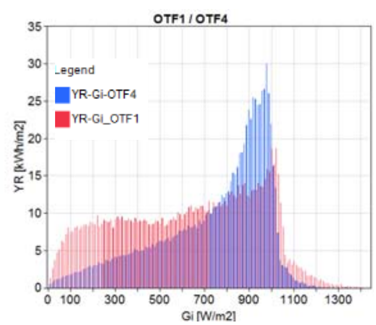
TEL Solar Outdoor Test Facilities (selected)



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

Snow in Switzerland

Dust storm in AZ, 2011

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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

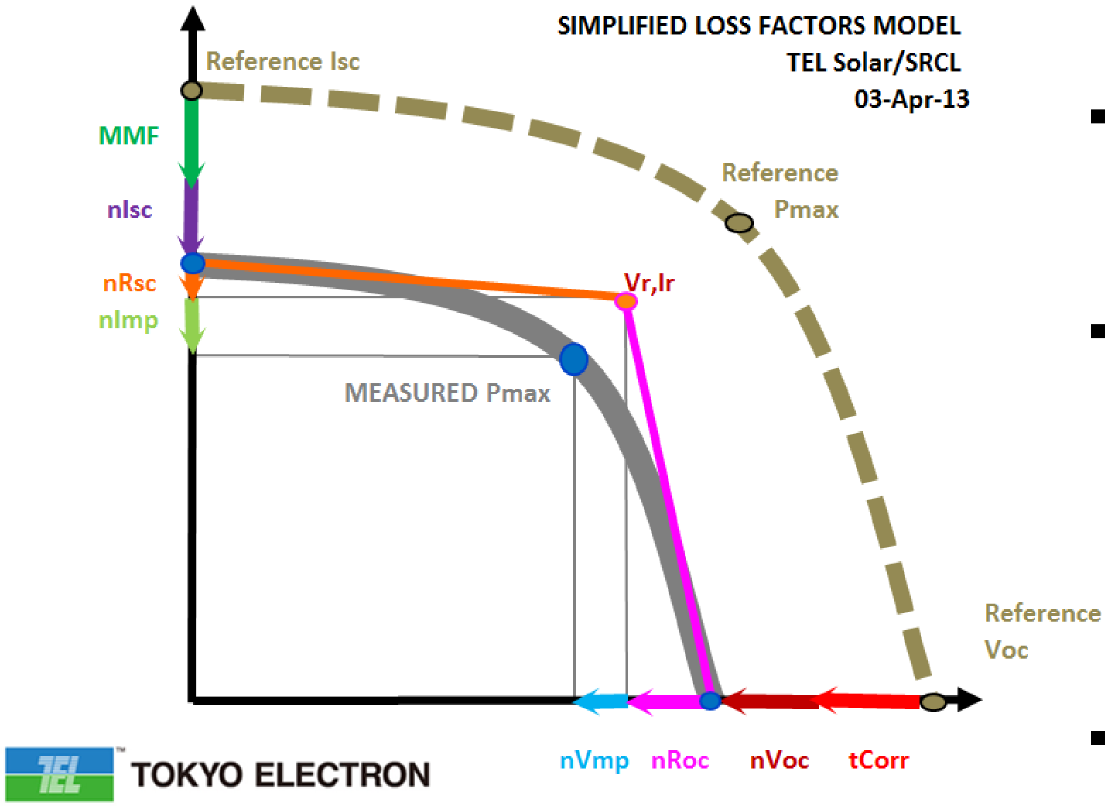
- AC / DC parameters, String level monitoring
- Weather conditions (irradiation sensors, humidity, rain, wind speed, temperature)
- Dust measurements (by TEL TWN team)

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



Efficiency ~ "product of 8 losses"
[MMF * nIsc * nRsc * nImp] * ← I
[nVmp * nRoc * nVoc * tCorr] ← V

- **8 physical, normalised, orthogonal losses <u>not just efficiency</u>**
- **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**
- **Simplified diagram shown**

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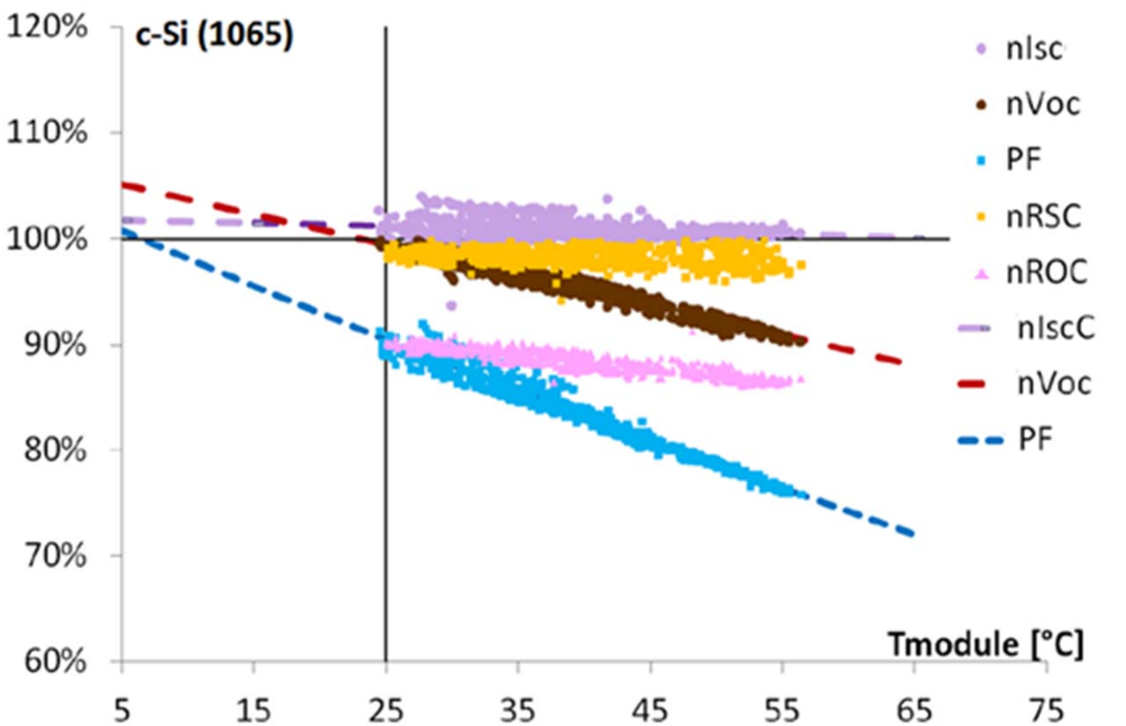
LFM Outdoor Temperature coefficients

- **Gradient at higher irradiances vs. module temperature gives thermal coefficients**
- **Not just Isc α, Voc β and Pmax γ but also d(Rsc)/dTmod & d(Roc)/dTmod**
- **Also possible at TPVPP arrays w/ DC side measurements**



Note: PF=PR_dc

50 Years

Typical plot of LFM coefficients vs. Irradiance

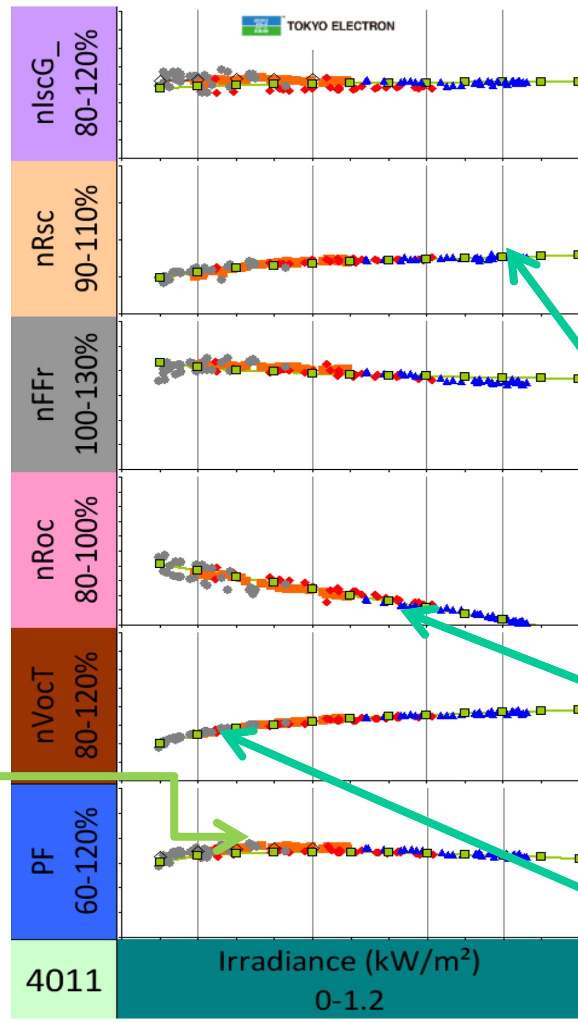
Thin Film Module in Arizona

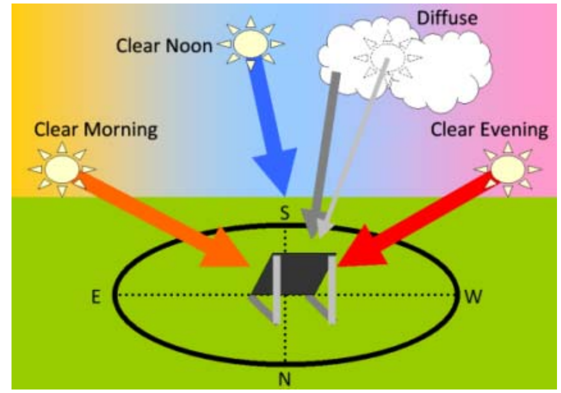
independent losses - **temperature** and **spectrum** corrected

→ Now only depends on irradiance

Fit e.g. 200 + 800W/m²

Calculated vs. measured Performance





WEATHER TYPES
Clear Morning
Clear Noon
Diffuse
Clear Evening

Loss due to **shunt resistances** gets better at high light levels Loss ~I/Rshunt

Loss due to **series resistances** gets worse at high light levels Loss ~I².Rseries

Loss due to **Voc** gets worse at low light levels due to Voc ~ln(I)

Note: LFM-A concept based on 5 parameters

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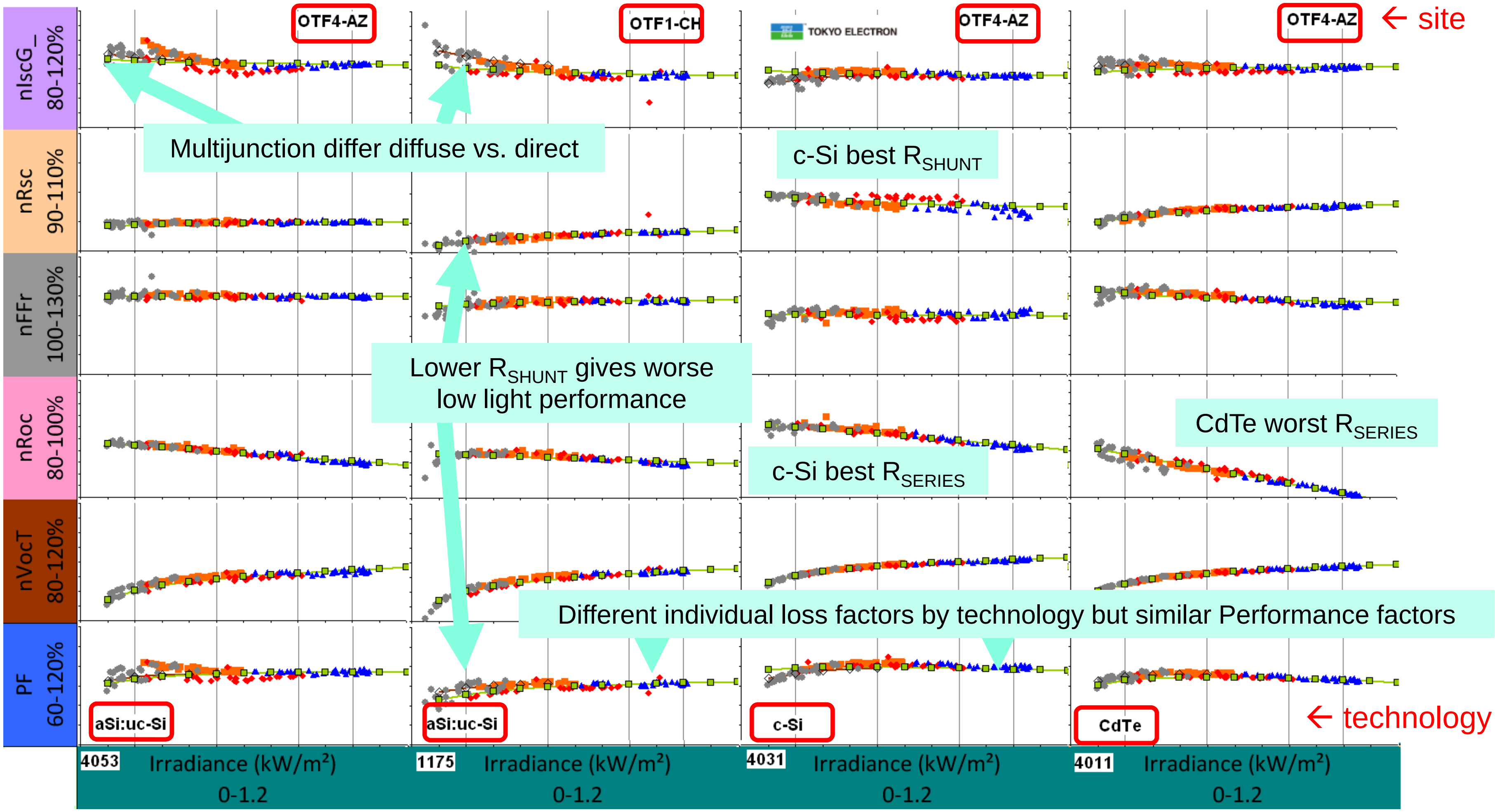
LFM – comparing different technologies and sites

AZ=Arizona, CH=Switzerland



AZ:Arizona, CH: Switzerland

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!

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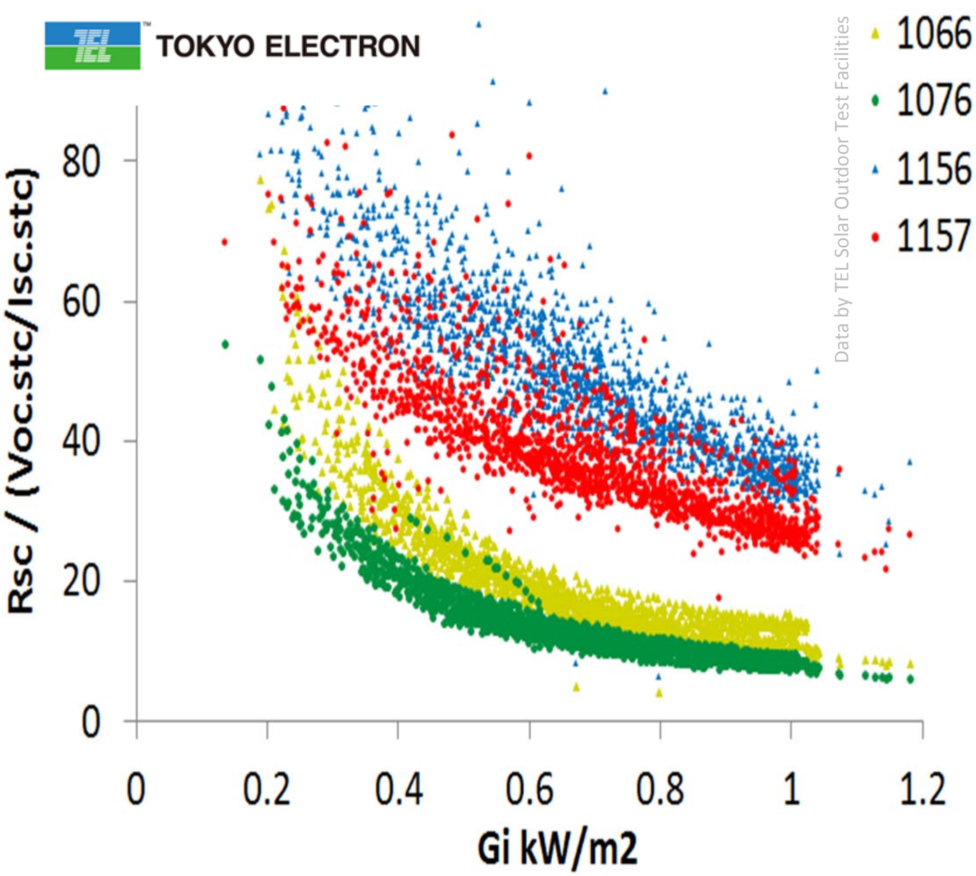
How Rsc varies with irradiance

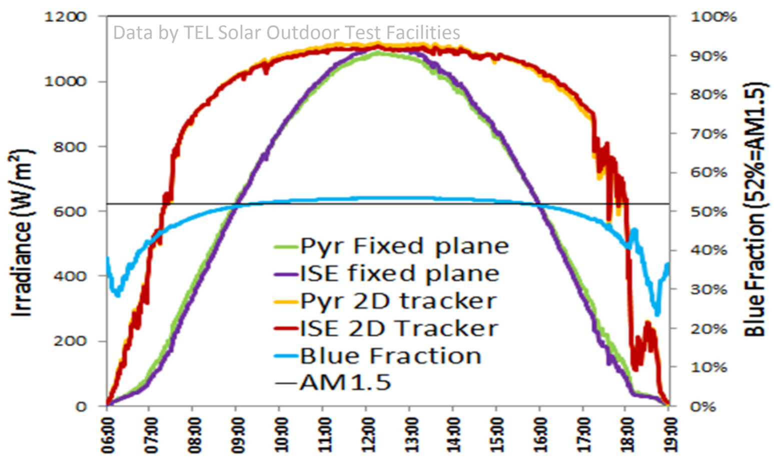
→ determines the low light performance

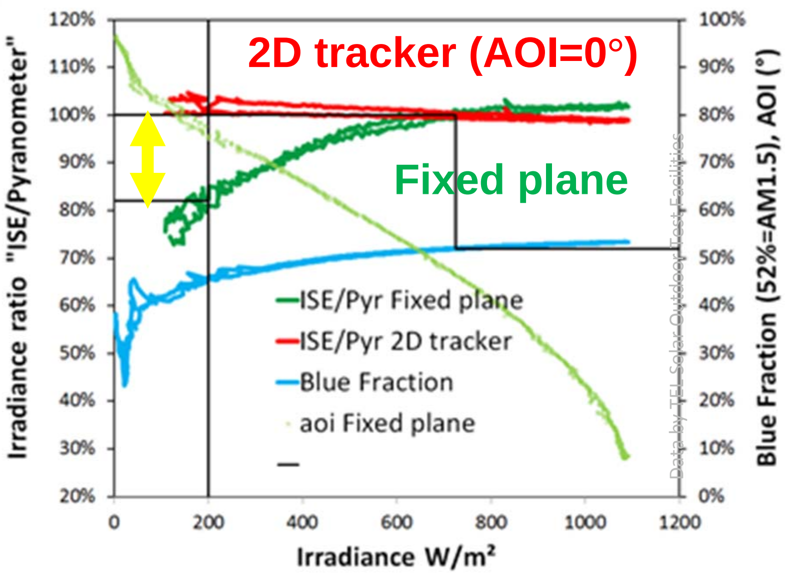


- **TEL Solar measured Rsc for 3rd party thin film modules Switzerland, a similar effect in Arizona ("normalised" to Rsc*Voc/Isc)**
- **Rsc rises exponentially with falling irradiance**
- **c-Si also follows same shape but scatter is worse as Rsc much higher (not shown)**

Data from OTF1, CH

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°

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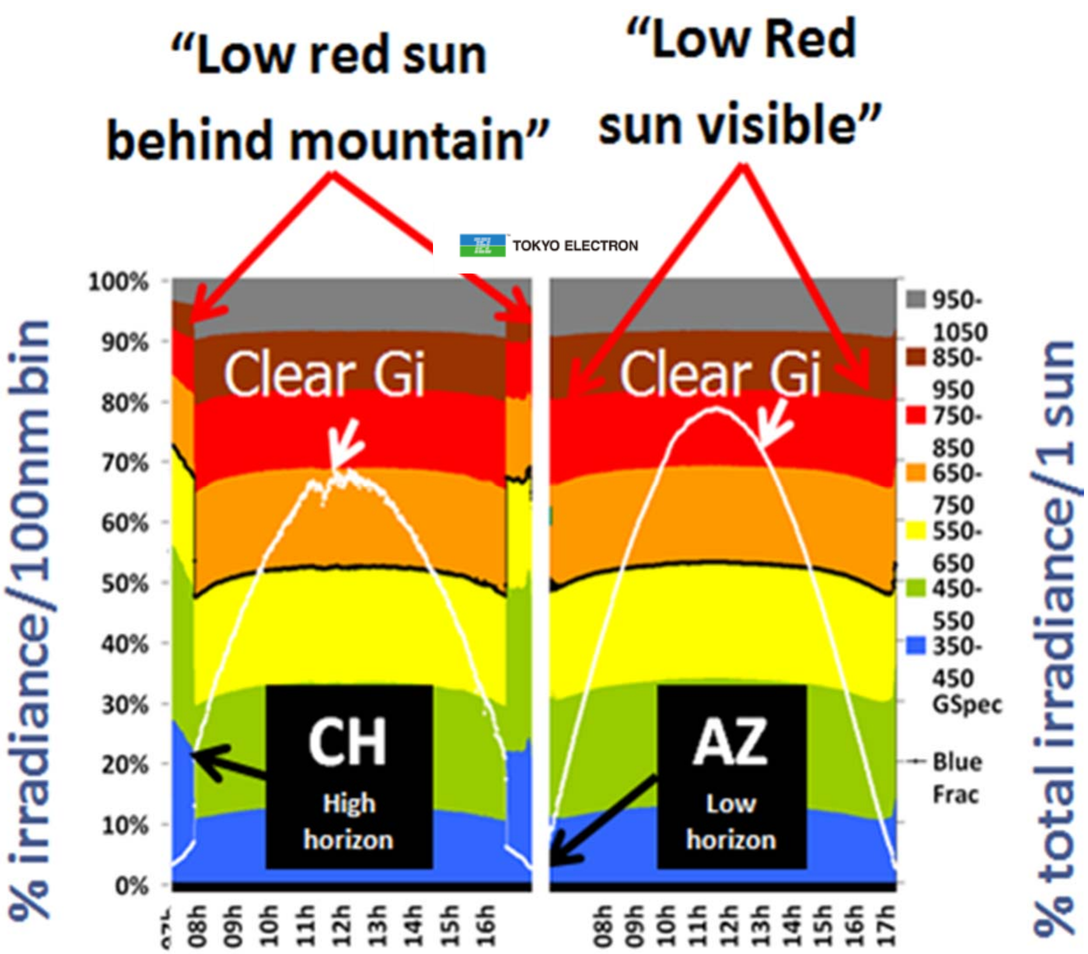
Clear day spectrum

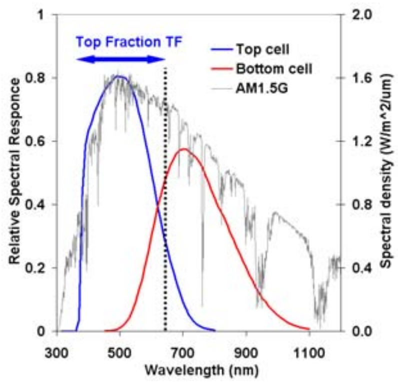
High(left) vs. Low (right) horizon



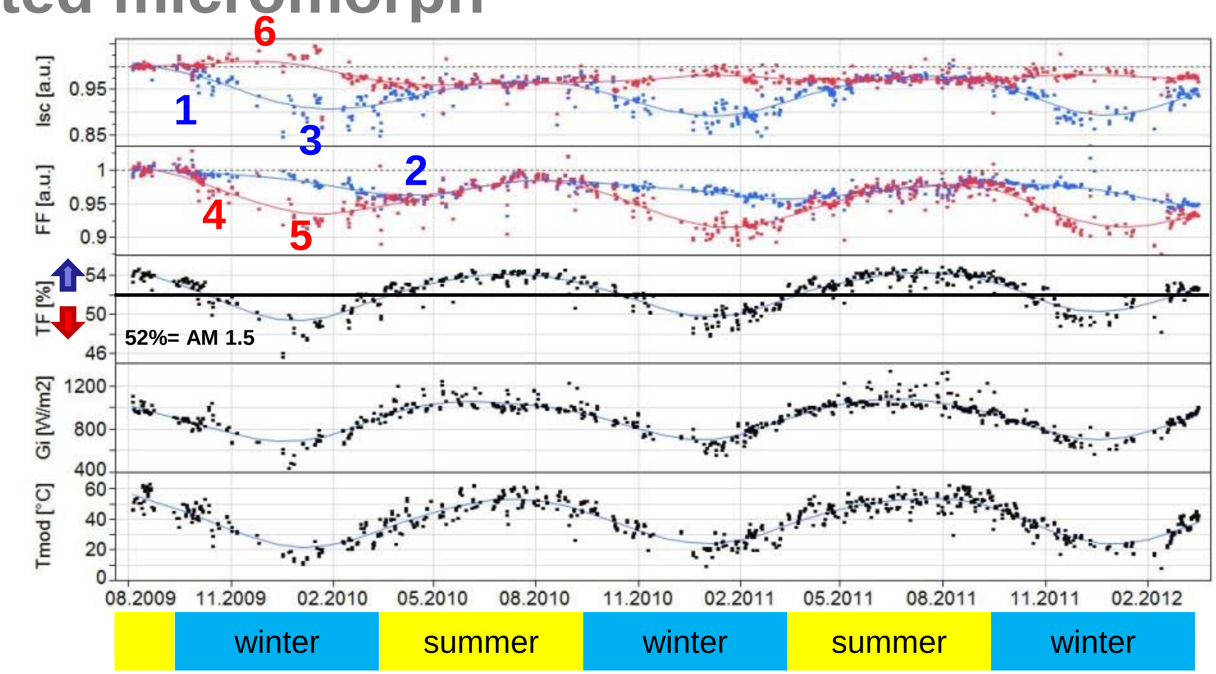
- Clear skies at equinox for a high horizon site (CH, left) and low horizon (AZ, right)
- High horizon sites lose red rich light by shading – giving more apparent kWh/kWp to blue sensitive technologies
- Same "glitch" to blue rich spectra from high horizons and tilted modules

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

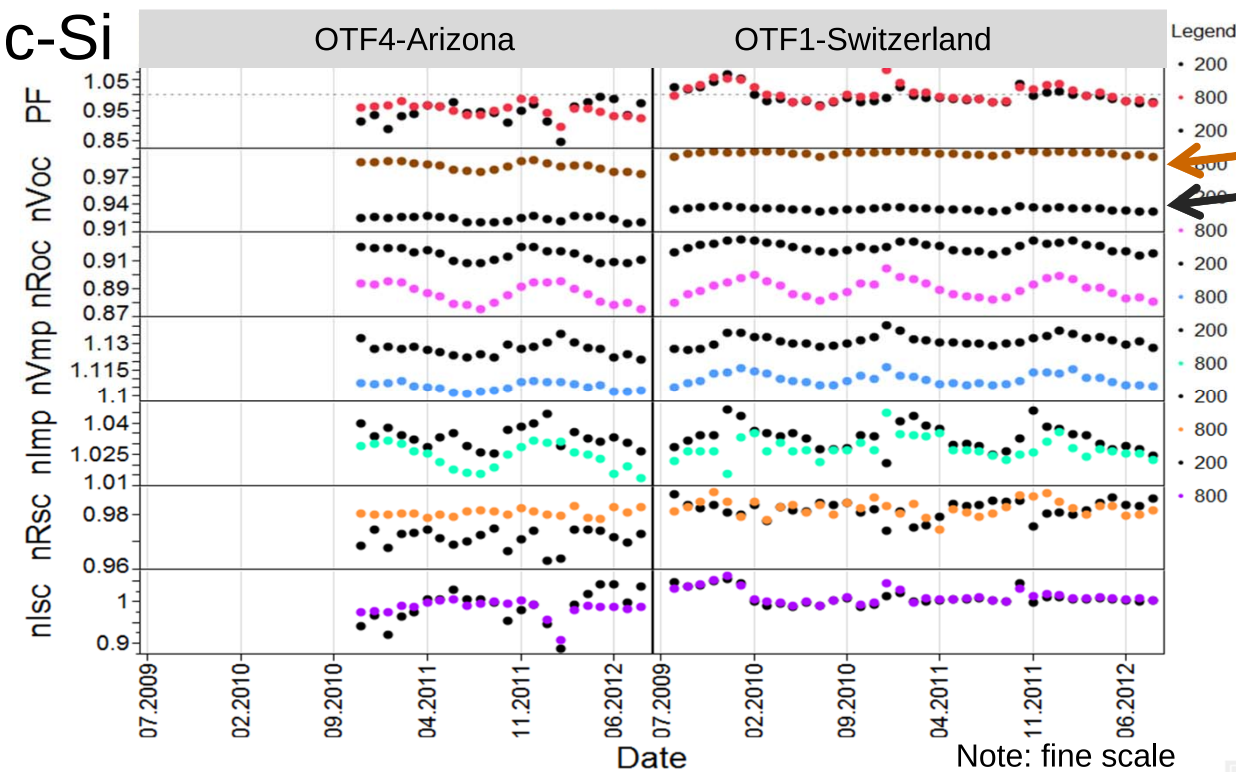
5 Minimum in FF, maximum in current at January → closest point to matching

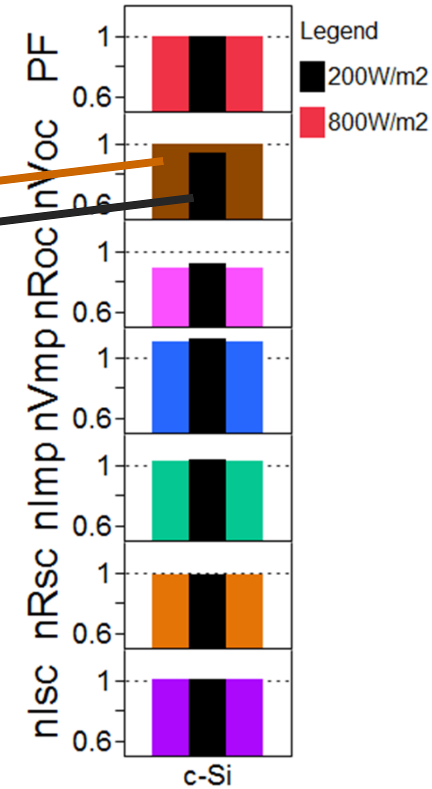
6 Current increases in winter due to advantageous spectral conditions for the bottom cell

Data around noon, Gi>200W/m^2, no Temperature correction

Long term variation / seasonal annealing

Real world variation of IV parameters, per month



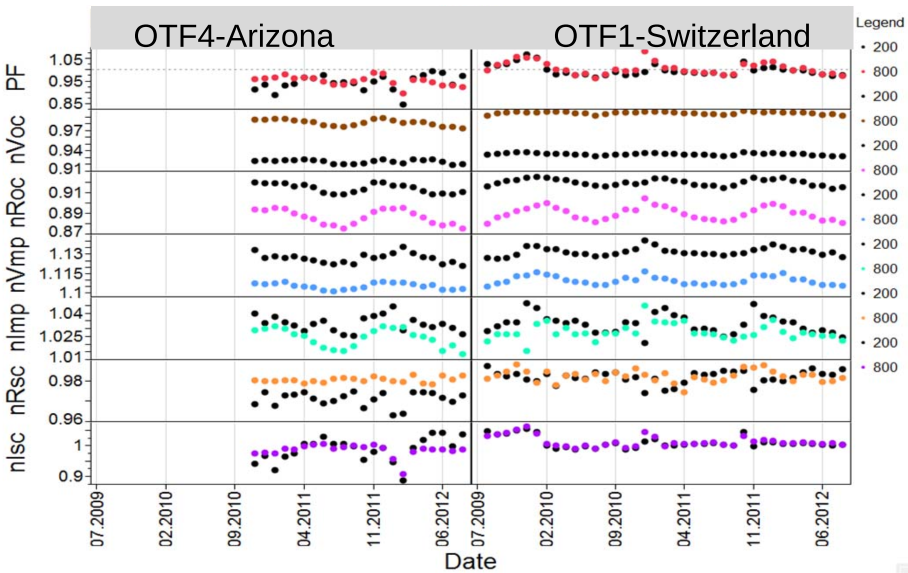


- The LFM model gives values of the 6 coefficients at low light (black) and high light (colored)
- Comparable performance at different sites, Dust should only affect nIsc and nPF
- Some Thin Film modules reversibly anneal after cooler & warmer periods, being better in autumn vs. spring.

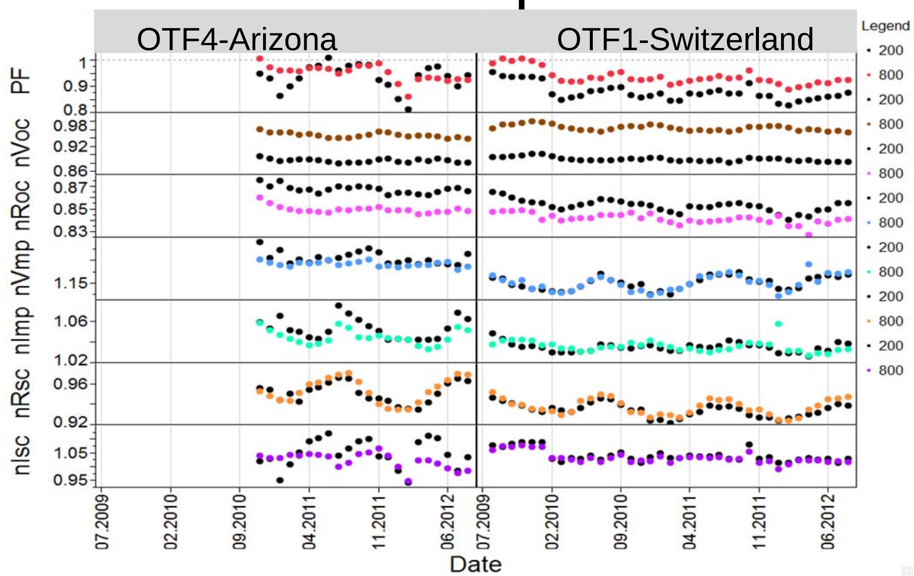
Long term variation / seasonal annealing II

Real world variation of IV parameters, per month

c-Si



a-Si/µc-Si



Note: fine scale

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- Comparable performance at different sites, Dust should only affect nIsc and nPF
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Real world PV PP data: MPP tracking -
Single Module vs. Array- 5 different inverter types

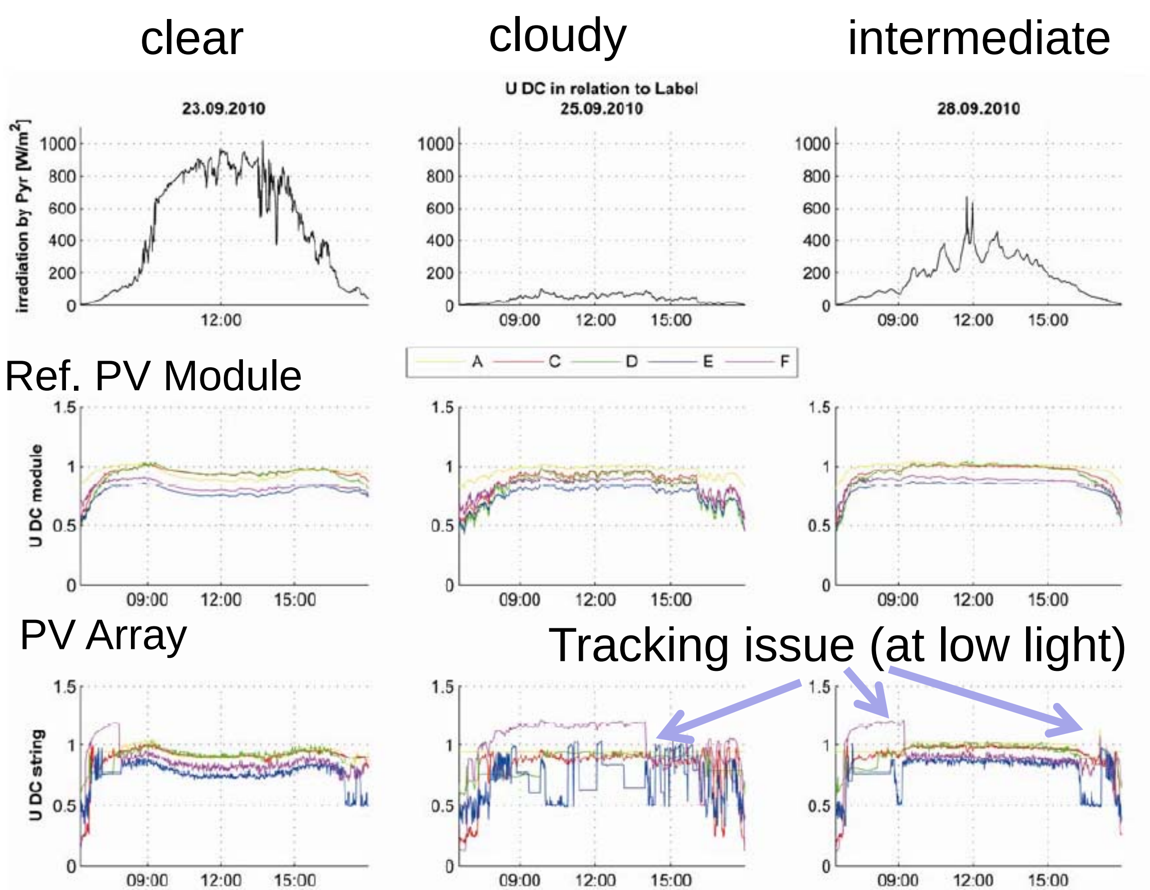
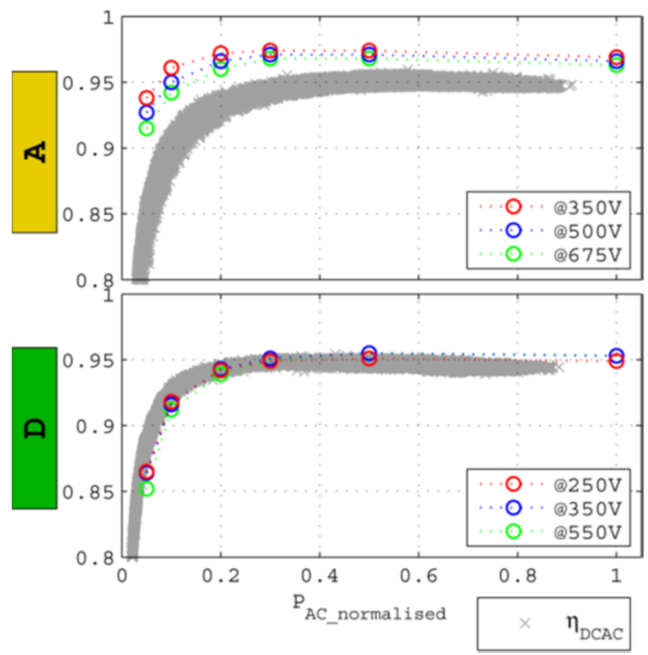


Fig. 10: MPP tracking of Udc based on 5 different Inverter types at 3 selected days in **September** 2010. Umpp tracking from the reference modules as comparison.

Inverter conversion efficiency:
performance vs. datasheet



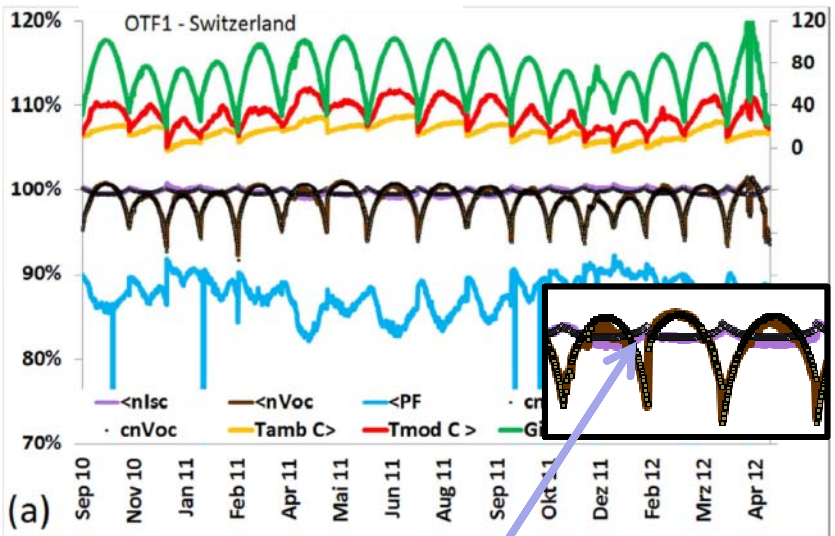
Have you checked the actual inverter efficiency at your system ?

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

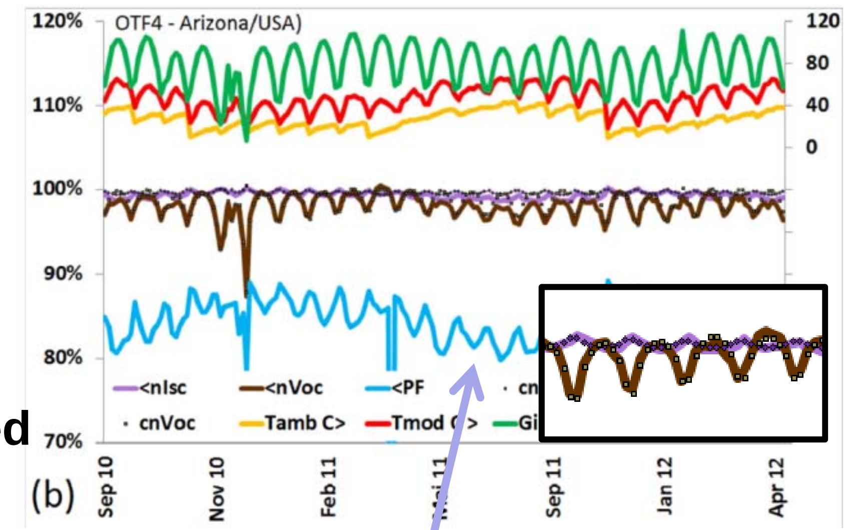
Variation of LFM , 16 clear days, 1/month, 2 sites, e.g. c-Si poly

Switzerland



Gi
Tmod
Tamb
nIsc
nVoc
PF
black: pred'ed

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_{DC})
- Possible for AC arrays!

Data from 09/2012 – 04/2012

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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

Test PV Power Plant Alice Springs, Australia

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
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- Jürgen Sutterlüti et al.; "Characterising PV modules under outdoor conditions: What's most important for energy yield"; Proceedings 26th EUPVSEC, (2011), pp.3608-3614.
- S. Sellner et al.; "Advanced PV module performance characterization and validation using the novel Loss Factors Model"; Proceedings 38th IEEE Photovoltaic Specialists Conference, (2012).
- 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
- J. Sutterlueti et al.; "Energy Yield Optimization and Seasonal Behaviour of Micromorph Thin Film Modules", 25th EUPVSEC, Valencia, 2010

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

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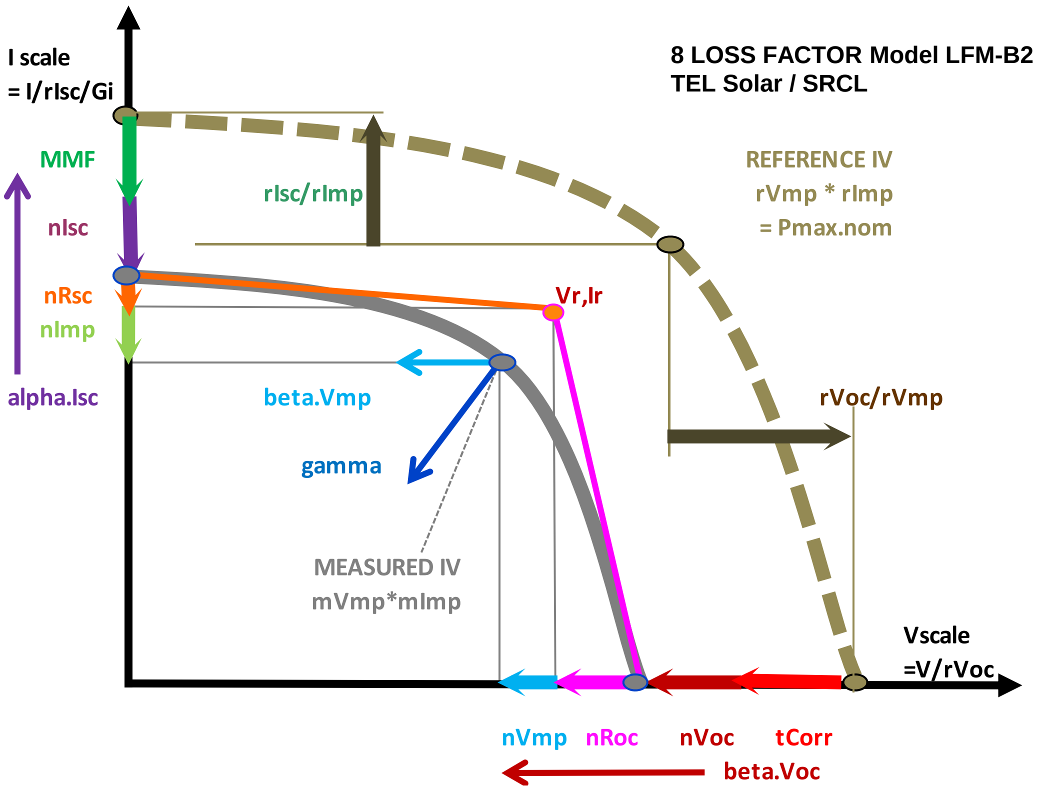
Loss Factors Model (LFM)



MMF	Spectral mismatch factor
nIsc	mIsc/rIsc/Gi
nRsc	%Pmax loss due to Rsc
nImp	mImpp/Ir*rIsc/rImp
TC.Isc	1+alpha*(25-Tmod)
nVmp	mVmpp/Vr*rVoc/rVmp
nRoc	%Pmax loss due to Roc
nVoc	mVoc/rVoc
TC.Voc	1+beta*(25-Tmod)

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

$$\mathrm{PF} = [MMF * (nIsc * TC.Isc) * nRsc * nImp] * [nVmp * nRoc * (nVoc * TC.Voc)]$$

Note: PF=PR_dc