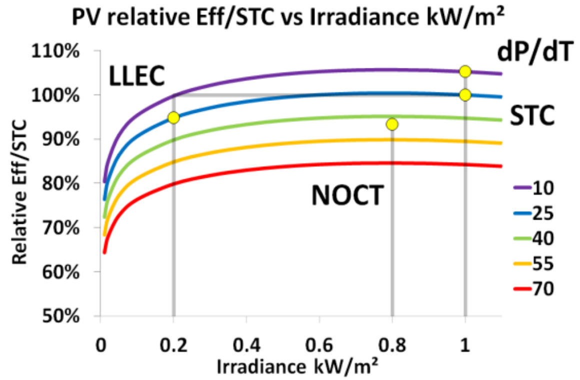
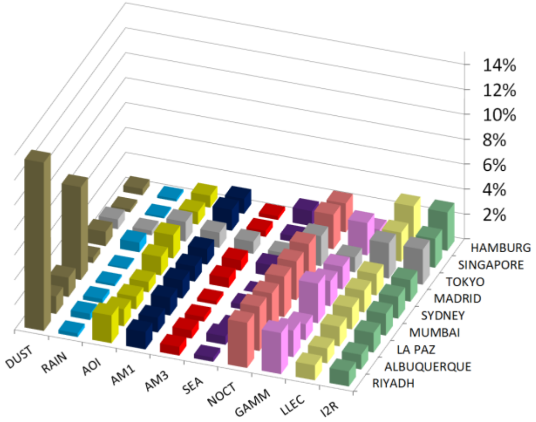



# The sensitivity and limitations of present and alternative PV models

**Steve Ransome - Independent PV Consultant, SRCL, UK**

**Juergen Sutterlueti – TEL Solar, Switzerland**

**Sandia PV Modelling Workshop; Santa Clara, USA**

**1st May 2013**



TOKYO ELECTRON

SRCL

# The present status in kWh/kWp measurements and modelling

- **Many recent independent outdoor studies find <±5% kWh/kWp**
  (with different rankings between technologies)
  there's less kWh/kWp variation expected with process optimisation
- **Measured kWh/kWp is often dominated by $P_{MAX.ACTUAL}/P_{MAX.NOMINAL}$**
  tolerance (e.g. "-0%/+3%") ; flash test calibration ; process variability within bins (e.g. 210-220 Wp) ; seasonal annealing (particularly thin film) ; soiling ; LID and long term degradation etc.
- **Many simulation procedures give "acceptable predictions" kWh/kWp**
  even if they don't model all energy yield affecting parameters correctly

# What other approaches to PV modelling are there ?

**(as far as is known from user documentation – source code/algorithms are commercially sensitive and are hidden)**

| Model | Summary | "Advantages" | "Disadvantages" | Comments ? |
|---|---|---|---|---|
| **Estimate Losses/stage** e.g. PV Watts | Series of independent losses for each stage | Simple to understand | Correct kWh/kWp may have cancelling input errors | Good initial estimate |
| **1-2 Diode/"n parameter"** (fit IV curves to datasheet values) | Lumped element model, 5-7 coefficients | Easy to understand, some physical significance e.g. Rs, Rshunt … | Iterative IV equations, unknown Rshunt vs. Gi | Might not model :<br><br>Module variability<br>Spectral Response<br>Angle of Incidence<br>Direct:Diffuse<br>Seasonal Annealing |
| **Matrix method** (IEC 61853) | Efficiency vs. Irradiance and Tmodule | Easy indoor test, can be interpolated outdoor | Still need to correct for AOI, Beam Fraction and Air Mass | |
| **Empirical fits** (e.g. PVUSA) | ~5 coefficients model P *Gi, *Gi^2, *Gi*Tmod, *Gi*WS … +Constant | Extrapolate to STC, Better if normalised to confirm performance | Not all coefficients are physically significant | |
| **Simulation programs** (mostly 1 diode PV model.) | Enhanced 1 diode model with Rsh vs. Gi | Powerful and mature code, some validation | Hidden algorithms; can't validate all stages | |
| **Sophisticated Verification** (SV) | Sequential losses – unsure efficiency model | Determines many losses, in line check | Might not model all effects | |
| **Sandia Model** (King) | 29 parameter - fixed tilt and 2D track | Fits almost all PV parameters such as Vmp, Isc … | Needs full IV curve, Not all coefficients independent or physical (e.g. $AM^4$) | Good fit to one module may lead to lack of applicability to others |
| **Loss Factors Model** (TEL) | 8 normalised orthogonal coefficients | Finds independent behaviour of I, V, R, P, α,β,γ vs. Irradiance, time … | Needs full IV curve not just Imp, Vmp | **See talk Juergen Sutterlueti tomorrow for more details** |

# Some limitations in present models and suggestions for improvements

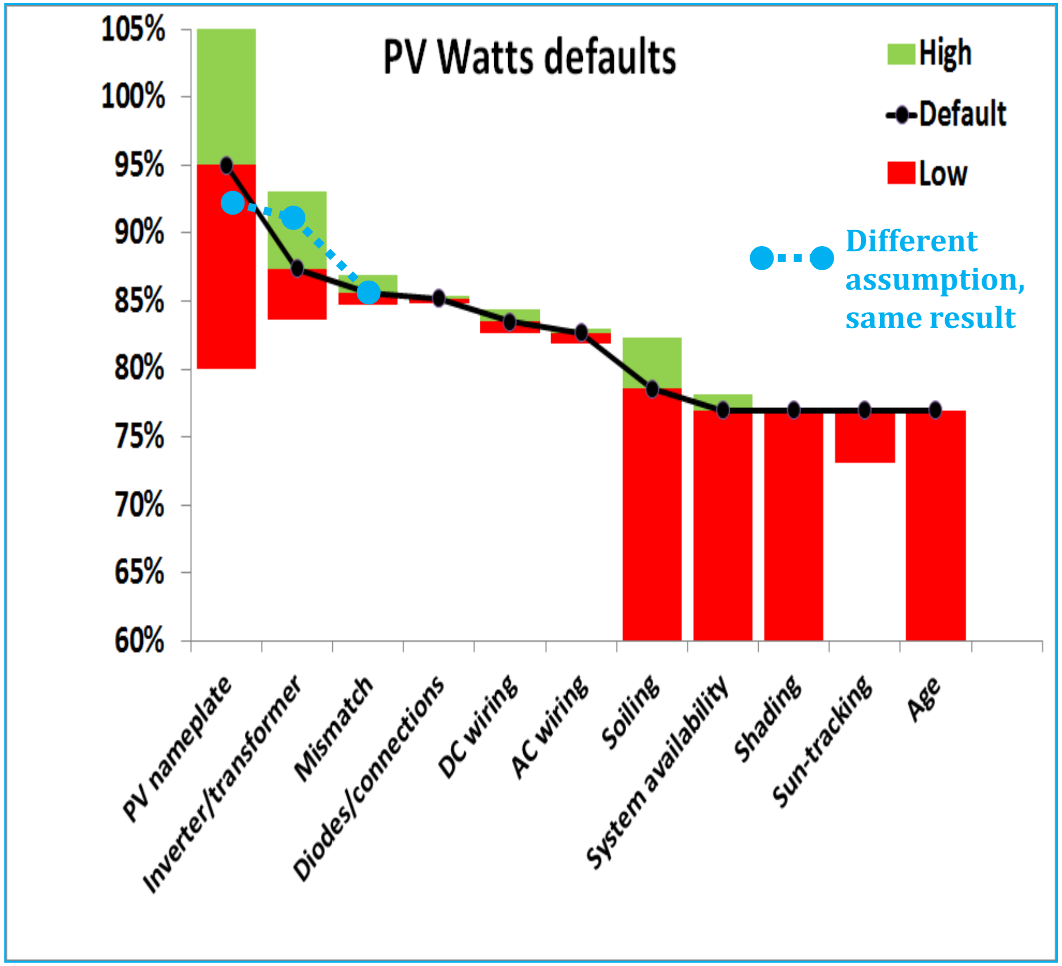
| Limitations | Status in present models | Improvements to future models – particularly for thin film, multi junction etc. |
|---|---|---|
| 1) Too many unknowns | Potential for self cancelling errors e.g. "better Pactual/Pnominal * worse dirt loss";<br>Checking only at one site,<br>fixed plane only | **Measure and model at more loss stages dc, ac –**<br>dc IV, ac Yield, cleaning, 2D vs. fixed …<br>Check more sites with different climates, fixed vs. 2D track (to distinguish aoi vs. spectrum) |
| 2) IV curve fitting errors | Thermal coefficients , low light performance not as datasheet due to unknown Rshunt vs. irradiance | **Check model vs. IEC standards** ;<br>Model Rshunt vs. irradiance properly |
| 3) Module performance variability | Databases of PV fits are usually to only one module measurement or datasheet values | **We need to understand module variability**;<br>PV coefficients need uncertainties and ranges e.g. Isc.mean, ± Isc.stdev … |
| 4) Only PV efficiency is usually modelled | Most modelling only covers efficiency vs. irradiance/temperature (plus simple Vmp for MPP tracking) | **Model Rshunt , Rseries and other parameters** which may vary with irradiance and time (seasonal changes, degradation) and differentiate technologies |
| 5) Distribution of irradiance vs. measurement frequency | Insolation vs. Irradiance ($kWh/m^2$ vs. $kW/m^2$) varies with measurement frequency<br>– hourly averages have more low light insolation | **Use minutely or faster model or measurements** as it has a more realistic behaviour (more high irradiance peaks) – less important at highest insolation sites.<br>Compare measured vs. modelled data |
| 6) Weather parameters are all correlated | Most models based on independent indoor coefficients Irradiance, Temperature, Spectrum , Angle of incidence etc. | **Correlated weather (no "double counting")**<br>High Irradiance ~ High Temperature ~ Low AOI ~ Bluer Skies ~ High Beam fraction ~ low shading etc. |
| 7) Energy yield determining effects not usually modelled | | **Need to understand and model more effects**<br>Seasonal anneal, Spectral response – particularly TF/Direct Diffuse -<br>Particularly important for thin film, multi junctions etc. |

# 1) Too many unknowns – non unique solutions "Estimate losses per stage"

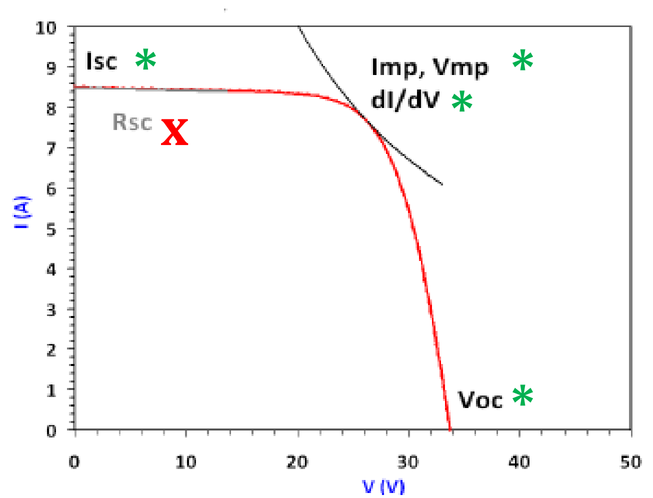
**[PVWatts] 2012**

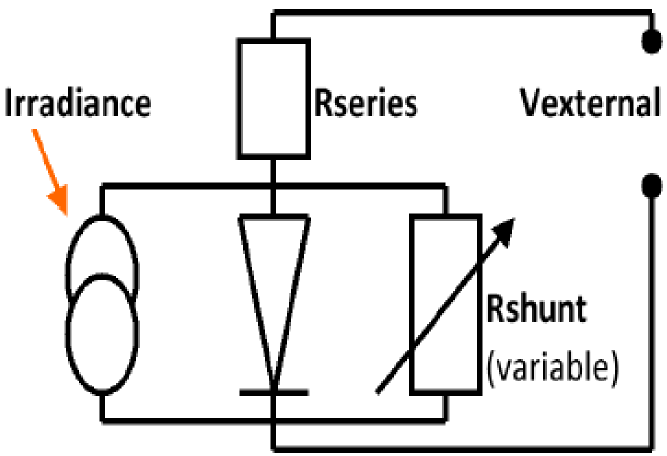
1. Estimate loss/stage for Shading, Wiring, Soiling etc.
2. Multiply loss/stage to give dc→ac loss = Π(losses)
3. **kWh/kWp = Σ dc→ac * "hourly dc model"**

- We need intermediate measurements (e.g. dc) to validate assumptions otherwise there could be self cancelling errors e.g. "Pactual/nominal vs. soiling"
- **Agreement with measured kWh/kWp doesn't guarantee every stage is correct as the same result can be achieved with different inputs (see blue bars with worse PV nameplate and better Inverter derating than nominal)**



# 2) IV curve fitting errors
# 1 diode model / n parameter model (5→7) etc.




- Fits IV curve from manufacturer datasheets or tested modules
- 4 * "knowns" - Isc, (Vmp, Imp), Voc, dI/dV|V=Vmp and 1 guess x - Rsc ~Rshunt
- Original De Soto Model (2005) coefficients determined
  - Temperature dependence (not IEC 61215/61646)
  - Low light level efficiency (not EN 50380)

$$a = \frac{q}{nkT};\ \frac{a}{a_{ref}} = \frac{T_c}{T_{c,ref}}$$

$$\frac{Io}{Io,ref} = \left[\frac{Tc}{Tc,ref}\right]^3 e^{\frac{\varepsilon Ns}{a_{ref}}\left(1-\frac{Tc,ref}{Tc}\right)}$$

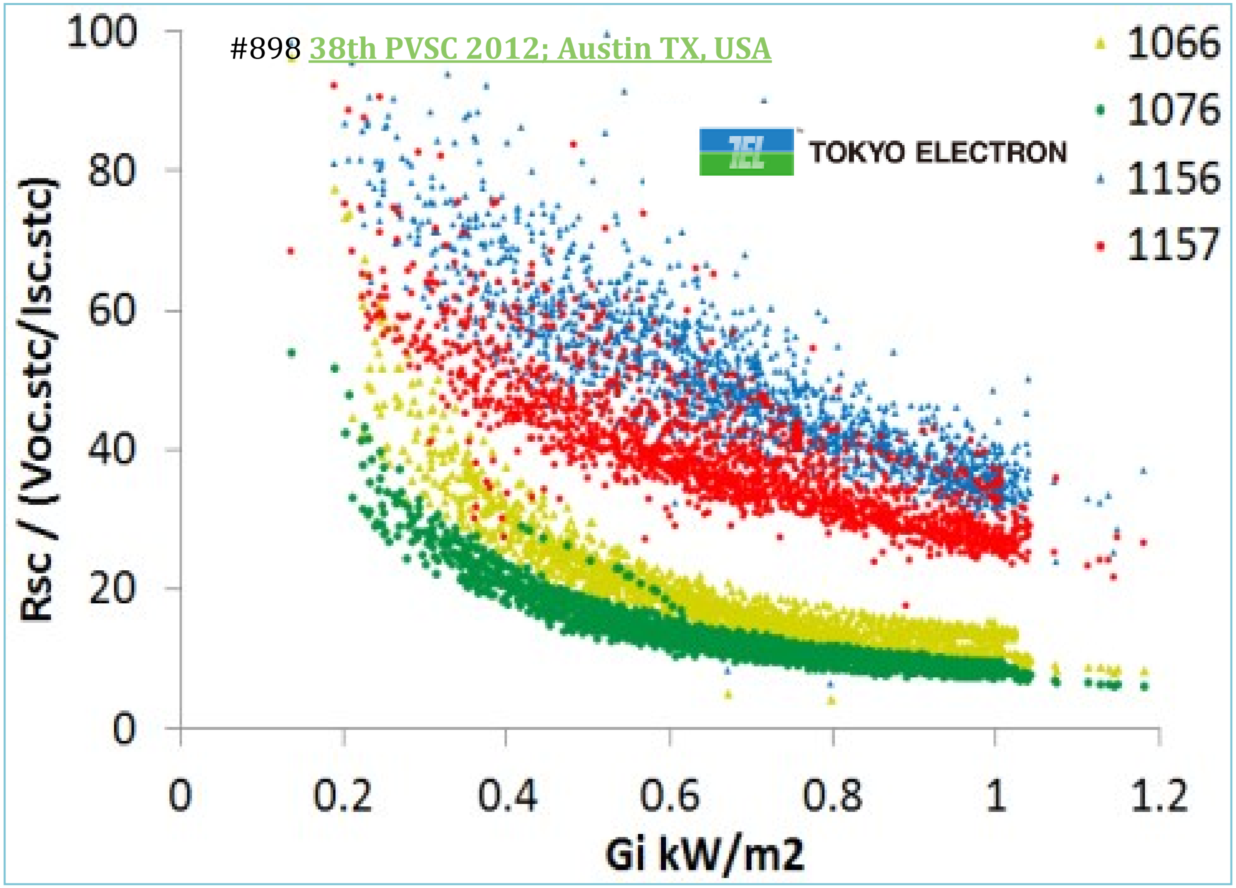
- **Some later models alter the n and Io behaviour to try to match the correct temperature coefficients**
- **1 diode is not a perfect model – it would need variable coefficients to model reality better**

# 2) IV curve fitting errors
# 1 diode model / n parameter model (5→7) etc.

- Low light behaviour depends mostly on how Rsc rises as irradiance falls - but this is not yet fully quantified or understood

- Data shows “normalised” Rsc vs Irradiance for 4 different thin film modules in Switzerland. C-Si has a similar shaped behaviour but higher scatter as it’s harder to measure as Rsc is much higher for c-Si

- Several models use different Rsc(Gi) behaviours (constant, linear, exponentially varying with irradiance)

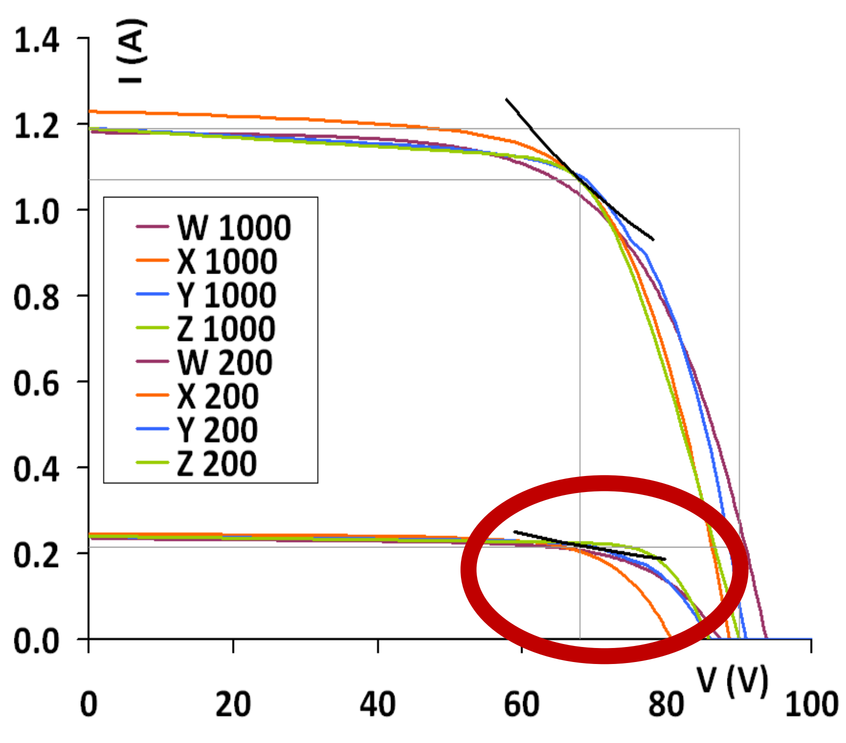


# 2) IV curve fitting errors

# 1 diode model / n parameter model (5→7) etc.

**Errors in modelled vs. datasheet IV and low light efficiency Rsh=f(Gi)**

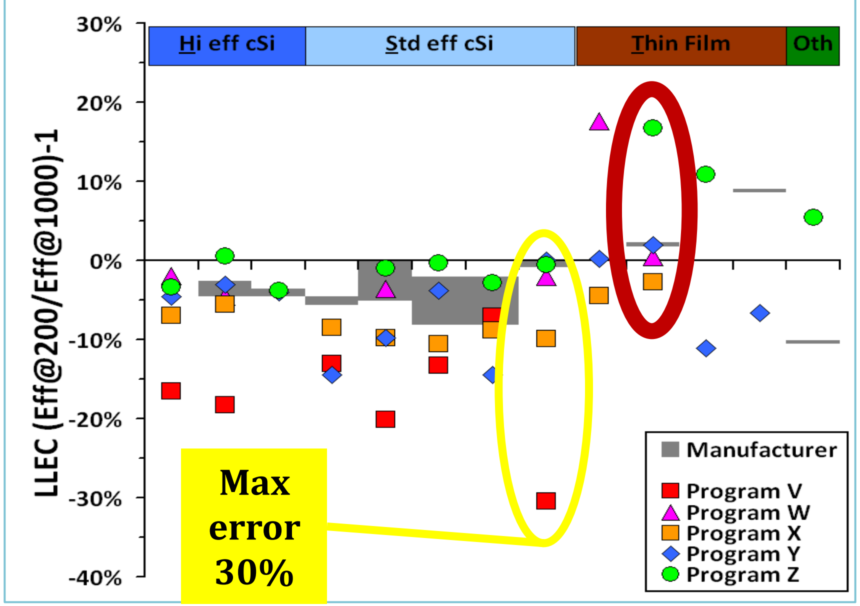
### Fits by 5 different 1-diode based simulation programs to typical IV data for 1J-TF at 1000 and 200 W/m²




**Check your own modules and programs**

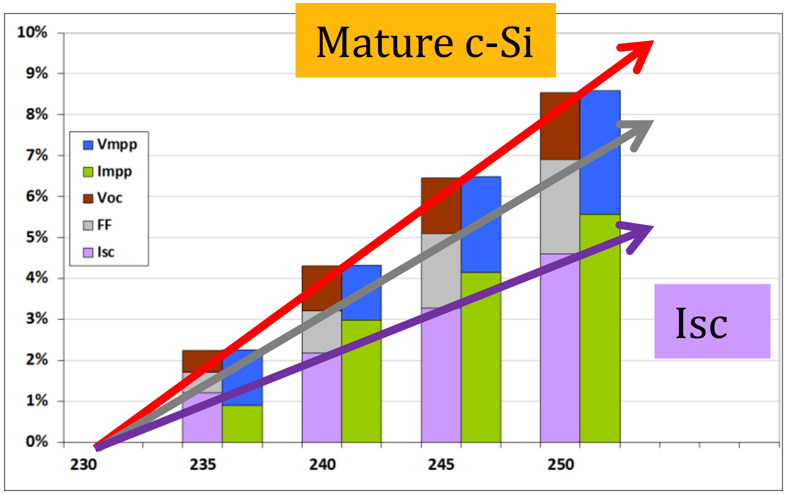
### Low light efficiency @ 200W/m²

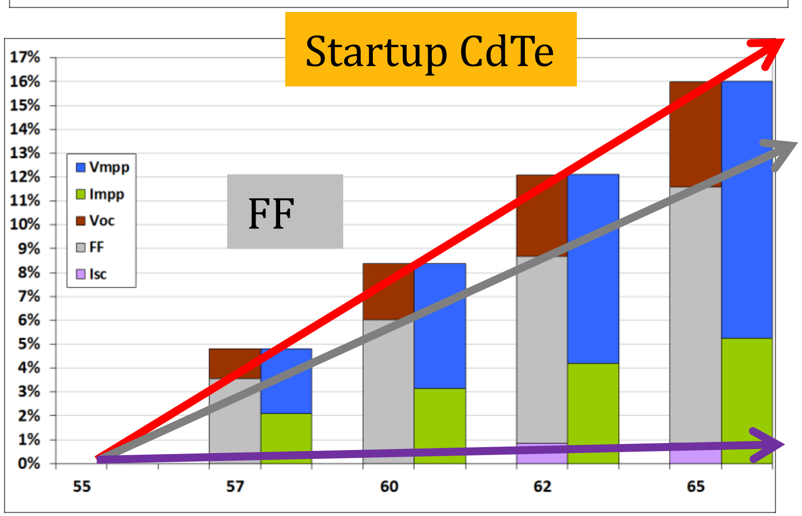
**13 PV technologies, 5 simulation programs, reported since 2008**
**( SRCL started studying this in 2008, this is 2011 data )**




Low light efficiency and dPmax/dT discrepancies seen (all PV technologies + simulation programs)
**These bias kWh/kWp towards "optimistic" fits**
up to 16% energy yield errors have been seen

# 3) Module performance variability in $P_{MAX}$ bins from datasheets – changes with technology and maturity




Better $P_{MAX}$ bins tend to have higher $I_{SC}$, $V_{OC}$ etc.

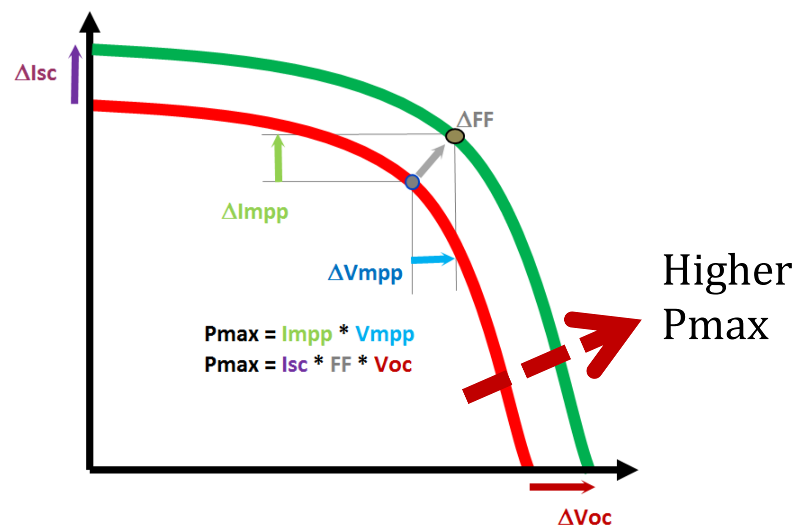
$\Delta P_{MAX} \approx \Delta V_{MPP} + \Delta I_{MPP} \approx \Delta V_{OC} + \Delta FF + \Delta I_{SC}$

Values are <u>absolute minimum variation</u> within $P_{MAX}$ bins (assuming perfect Isc and Voc correlation)

Also shows maturity of process

Mature c-Si – Isc↑↑↑ FF↑↑ Voc↑

Startup CdTe – FF↑↑↑ Voc↑↑ Isc↑ (Rshunt↑, Rseries↓)



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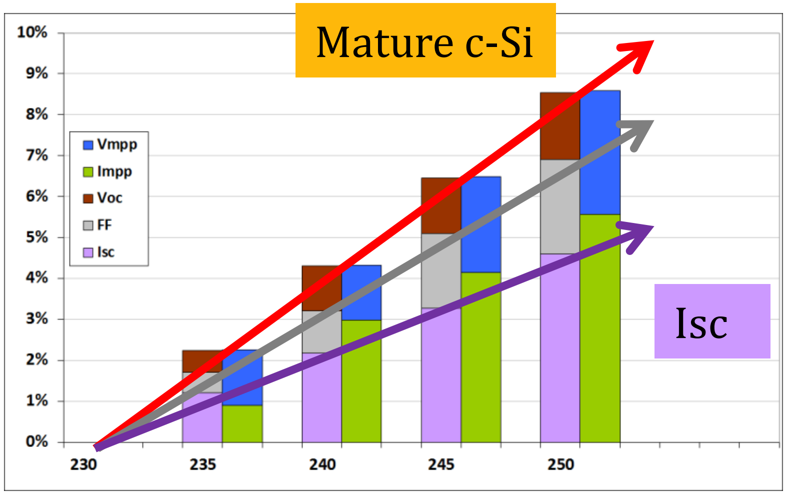



Better $P_{MAX}$ bins tend to have higher $I_{SC}$, $V_{OC}$ etc.

$\Delta P_{MAX} \approx \Delta V_{MPP} + \Delta I_{MPP} \approx \Delta V_{OC} + \Delta FF + \Delta I_{SC}$

Values are <u>absolute minimum variation</u> within $P_{MAX}$ bins (assuming perfect Isc and Voc correlation)

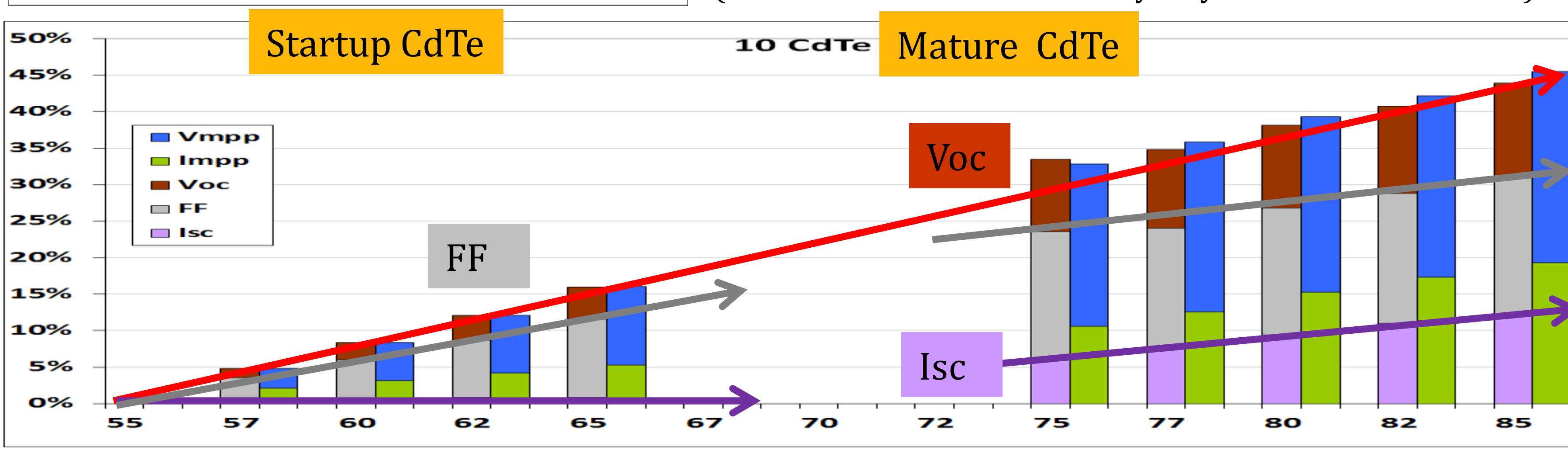
Also shows maturity of process

Mature c-Si – Isc↑↑↑ FF↑↑ Voc↑

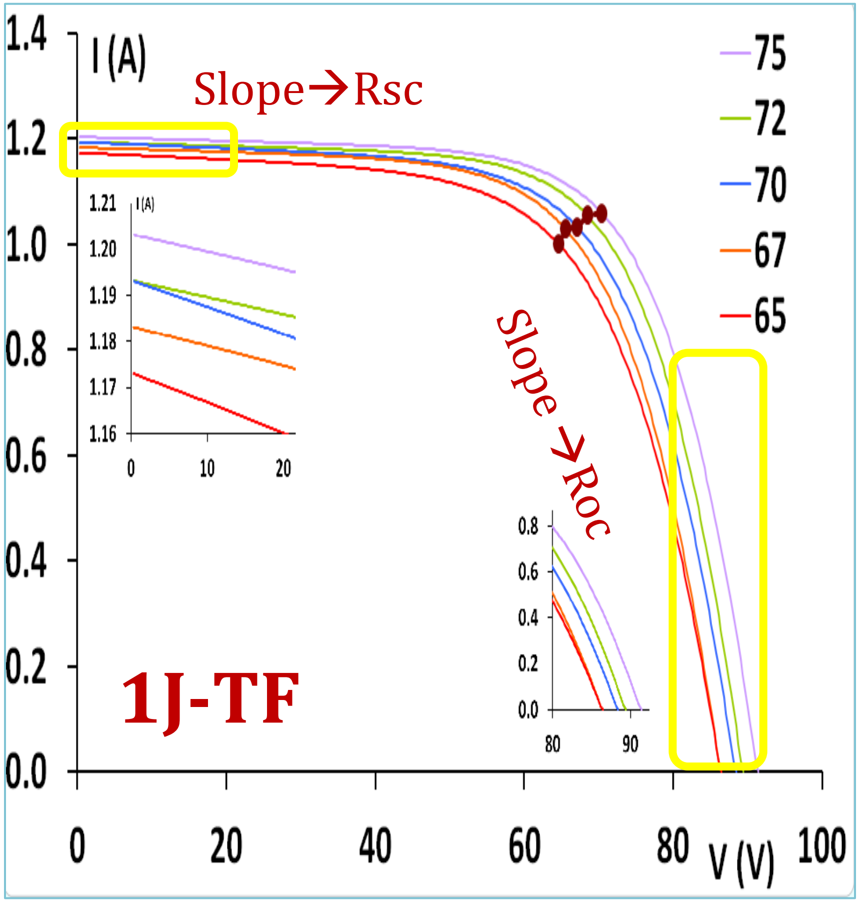
Startup CdTe – FF↑↑↑ Voc↑↑ Isc↑ (Rshunt↑, Rseries↓)

Mature CdTe – more FF↑↑ Isc↑ Voc↑

(latest CdTe > 18% – sensitivity may differ as eff. saturates)



# 3) Module variability from Random module IV curves vs. Pmax bins → kWh/kWp prediction errors




Some manufacturers datasheets have "smooth Isc and Voc changes per W bin"
(e.g. 1.0 1.1 1.2A ; 80 81 82 V ... )

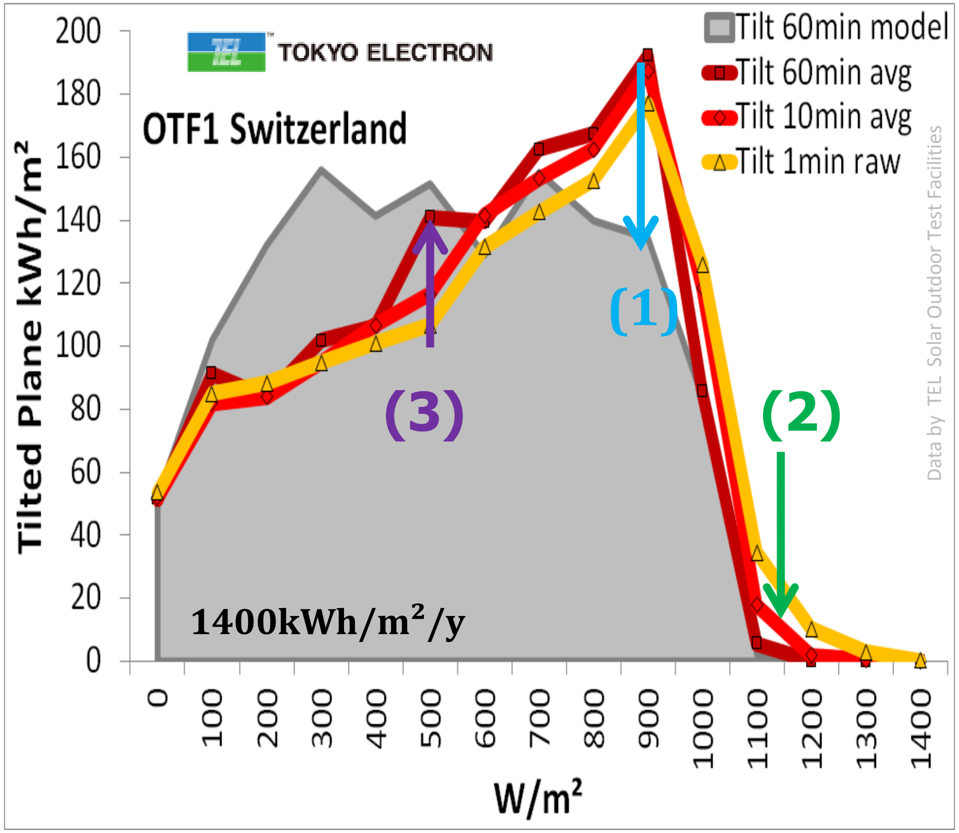
Others (see left) have "random" modules per W bin having

- Non linear $I_{SC}$, $V_{OC}$, $I_{MP}$, $V_{MP}$ vs. bin
- Non constant $R_{SC}$ and $R_{OC}$

- **Predicted kWh/kWp will vary between $P_{MAX}$ bins due to random modules in the database rather than averaged interpolations**
  - **Lower Rsc poor at low insolation sites**
  - **Higher Roc poor at high insolation sites**

# 5) Distribution of irradiance vs. measurement. frequency

## Insolation (kWh/m²) vs. irradiance (kW/m²)




- Measured irradiance near 900W/m² much higher than modelled **(1)**
- Averaging irradiance by time merges scattered cloud conditions **(2)** (high irradiance with reflection interspersed with diffuse) into "dull data" **(3)**
- Much more frequent than 1min measurements don't show much higher spikes because of relatively slow cloud speeds and also the time constant of pyranometers (~10secs)
- Discrepancies are less (but non zero) at higher insolation sites
- **This distribution change gives errors in any kWh/kWp simulations where Efficiency vs. Irradiance is not constant.**
- **Up to 3% errors in kWh/kWp found**

**33rd PVSC 2008 San Diego #521**

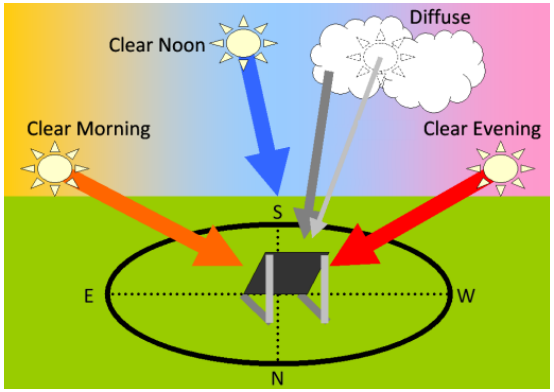
# 6) Weather variability and difference from STC

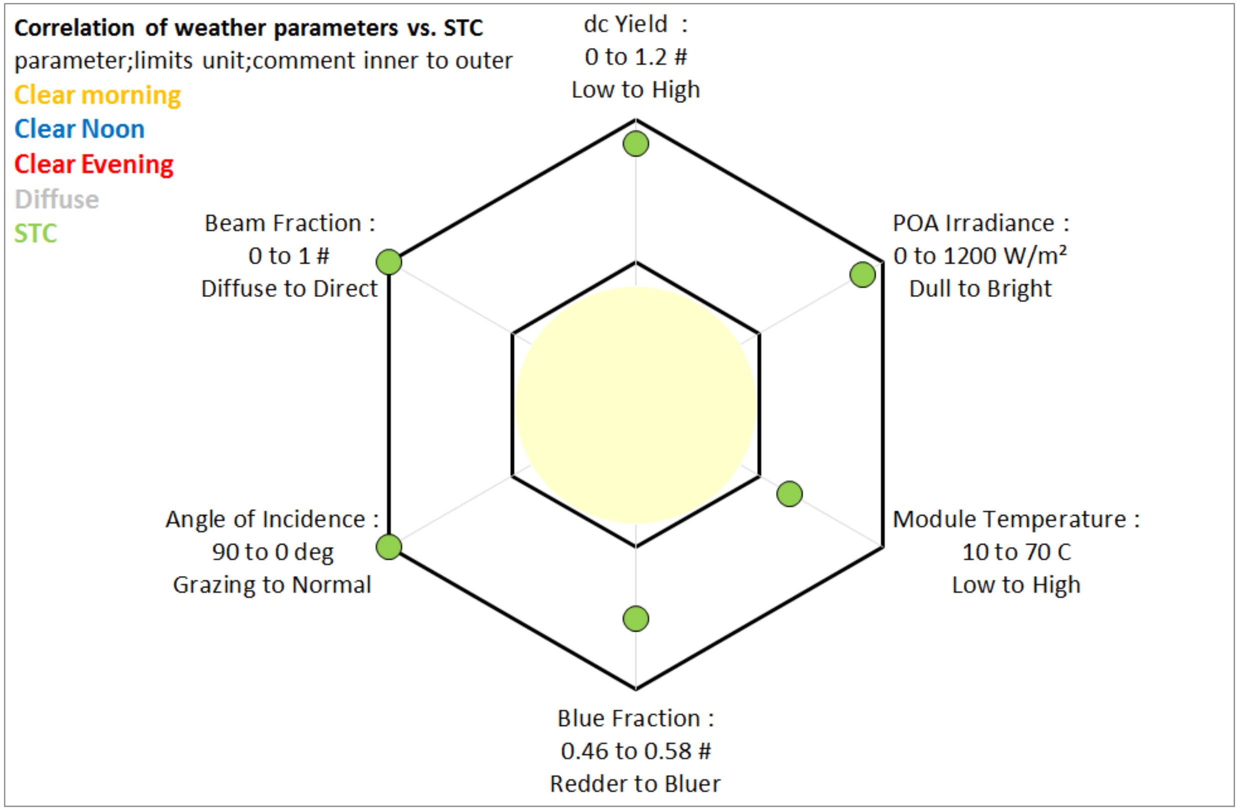
**Most characterisation indoors with independent Irradiance and Tmodule**

Plotting correlation of energy yield vs. 5 important weather parameters –

Outer ring
~ "high energy yield weather"

Inner ring
~ "lower energy yield weather"

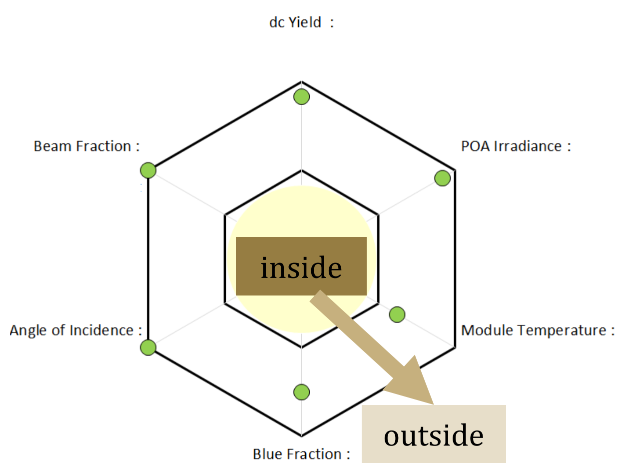


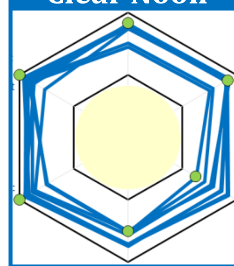
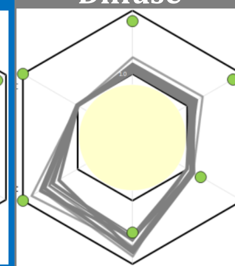
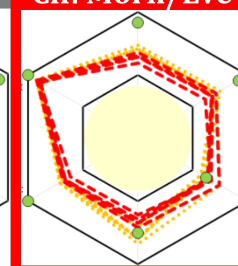

**Blue fraction = G(350-650nm)/G(350-1050nm)**

# 6) Weather variability and difference from STC

## Most characterisation indoors with independent Irradiance and Tmodule




Blue fraction = G(350-650nm)/G(350-1050nm)

| Values | STC defaults | Clear Noon  | Diffuse  | Clr. Morn/Eve  |
|---|---|---|---|---|
| POA Irradiance | 1kW/m$^2$ | Brighter | Lower light | Lower light |
| Module Temperature | 25C | Hotter | Colder | Colder |
| Blue Fraction | 52% | Bluer (sky) | Bluer (cloud) | Redder |
| AOI | 0° normal | Near normal | Any | High angle |
| Beam Fraction | 1 (all beam) | Mostly beam | Mostly diffuse | Mostly beam |

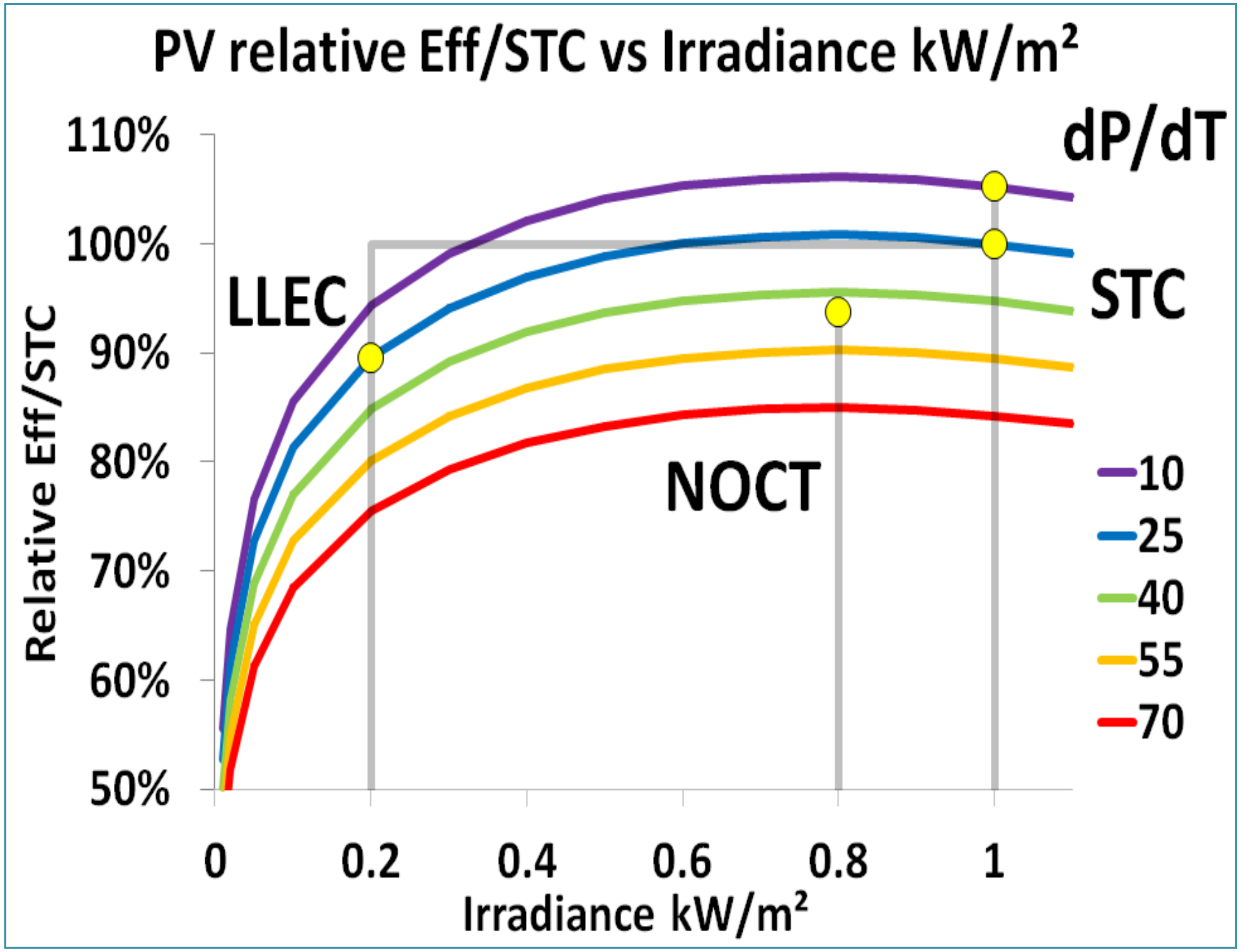
- When determining outdoor coefficients <u>all</u> other parameters need to be measured and corrected for e.g. when measuring temperature coefficients we need to correct for spectrum, aoi … as they all have an effect.
- Thin film temperature coefficients may appear positive if spectrum and annealing aren't corrected properly
- Weather correlation means horizon shading removes irradiance under red rich, high aoi, cooler conditions etc. – don't "double count" losses

# Typical model output
# Efficiency(Irradiance, module temperature)

**Gamma dP/dT**
$1/\eta * d(\eta)/dT_{mod}$

**Low light LLEC**
$(\eta_{200}/\eta_{1000})$ W/m²

**NOCT**
(Irrad = 800W/m²,
AM = 1.5,
$T_{AMB}$ = 20C,
wind = 1ms$^{-1}$)



# SRCL simulation program

**to evaluate energy yield algorithms and sensitivity**

Program runs hourly checks of losses at each of the stages

User defaults

Monthly sums and averages

Monthly losses per stage

Thermal

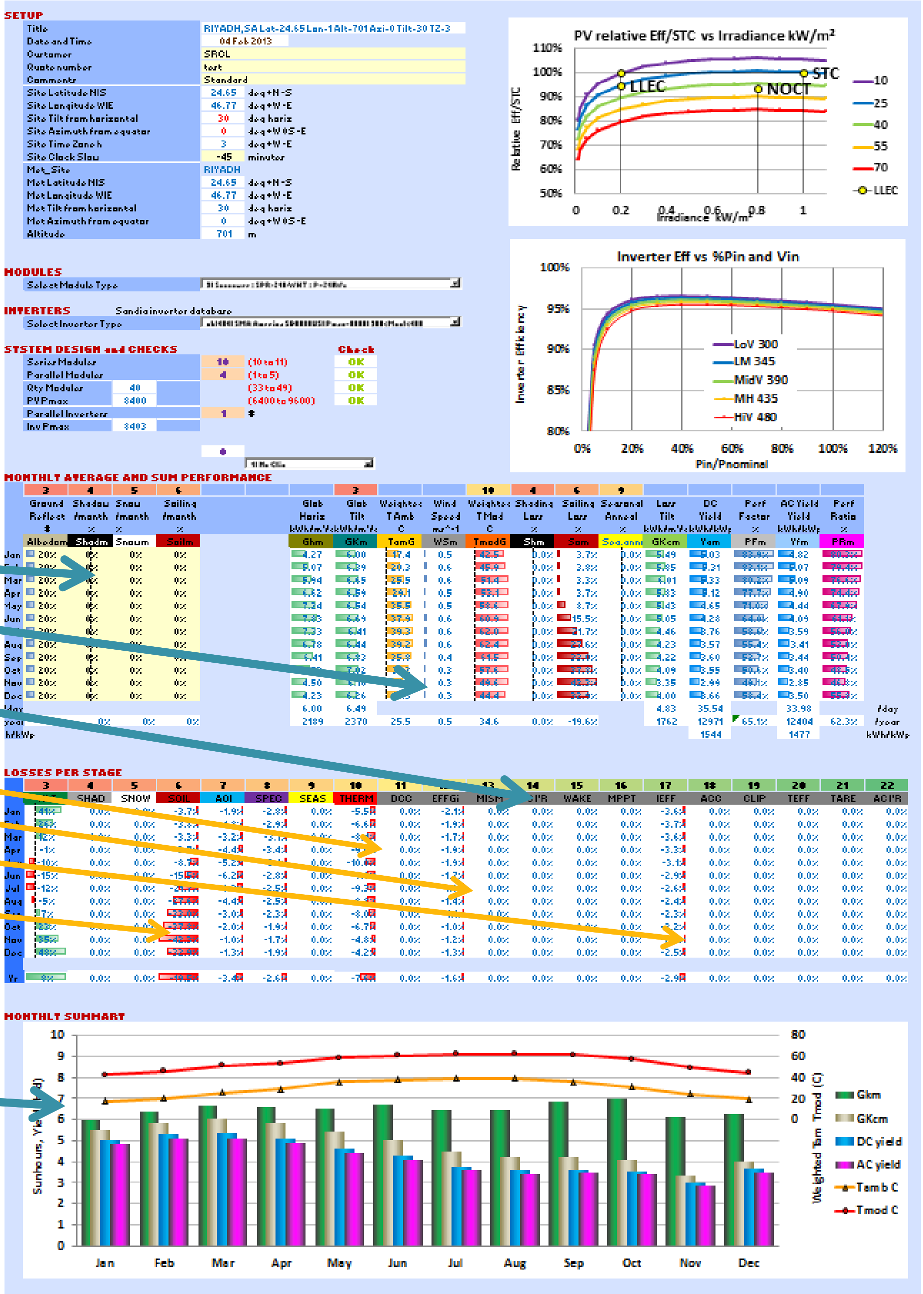
Low light

Inverter efficiency

Soiling

Monthly output summary

**Vary algorithms and inputs, calculate sensitivity**



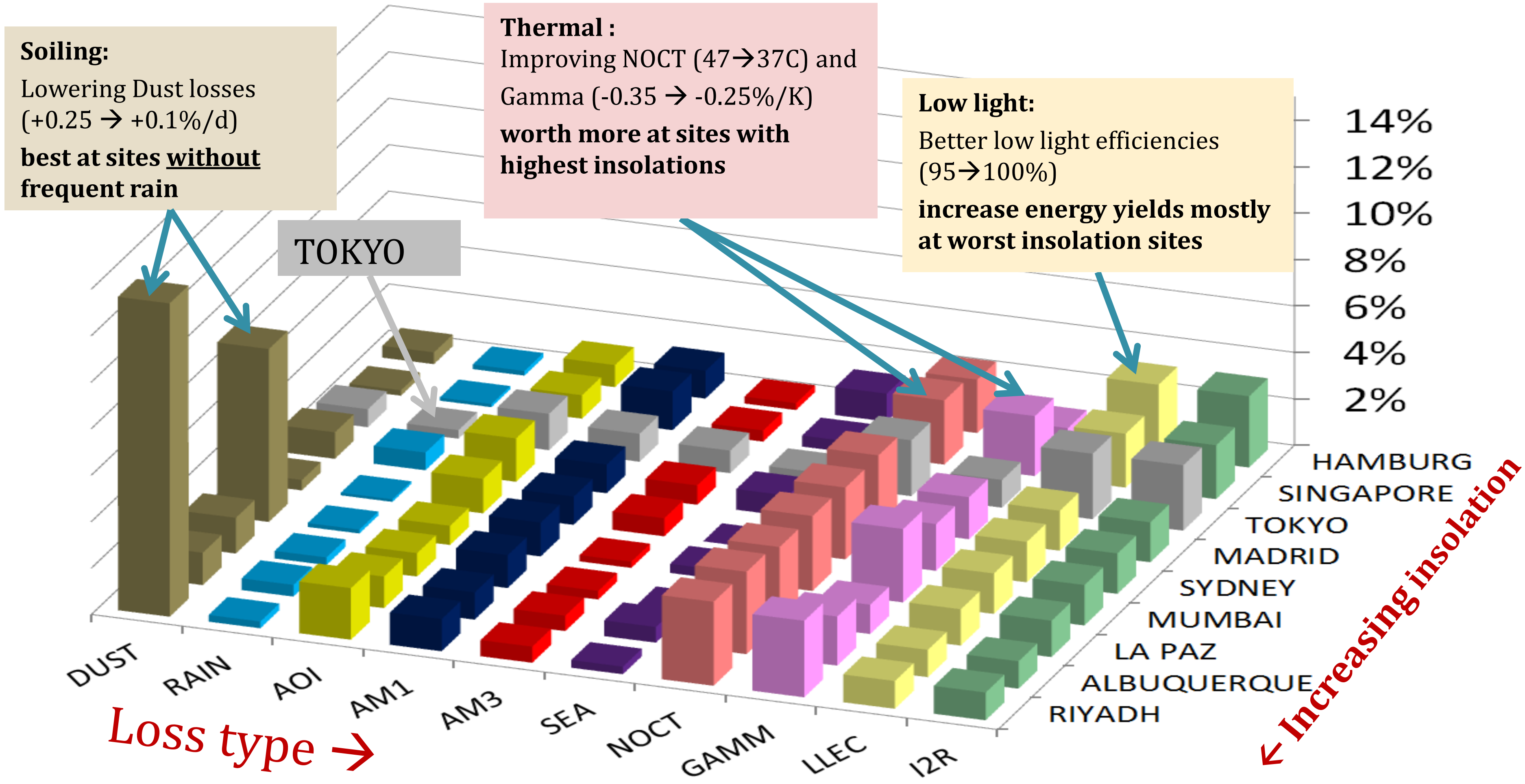
# "Default" and "Better" inputs for simulation and how their values may be improved

**also shows sensitivity to unknowns or errors**

| Input: Comment (How to improve ?) | Default | "Better" |
|---|---|---|
| **Dust: Daily soil increase** (washing, cleaning ?) | +0.25 %/d | +0.1 %/d |
| **Rain: Min. day rainfall to clean** (stay clean coating ?) | 2 mm | 1 mm |
| **AOI: Angular reflectance** (ARC, textured glass) | 85% @ 75° | 95% @ 75° |
| **AM1, AM3: Eff@AM3 or AM1 /Eff@AM1.5** (Improve red or blue response for multijunction) | 95% | 98% |
| **Seasonal Anneal: Oscillation -Spring +Autumn** (see seasonal anneal section) | ±0 % | ±3%/K |
| **NOCT: (Nominal operating cell temperature)** (Passive cooling fins ?, forced ventilation ) | 47 C | 37 C |
| **Gamma: $1/P_{MAX} * dP_{MAX}/dT$** (reduces with high Voc) | -0.35 %/K | -0.25 %/K |
| **LLEC: Low light efficiency $Eff_{200}/Eff_{1000}$ W/m²** Improve Rshunt, uniformity | 95 % | 100 % |
| **I2R: Series resistance loss in cell** (Lower Rseries, better bus bars, tabbing etc.) | 95% | 100% |

# Energy yield sensitivity to input changes or errors - compare with extra manufacturing cost for LCOE

**See SRCL talk in PVSC Tampa 2013 for more details**



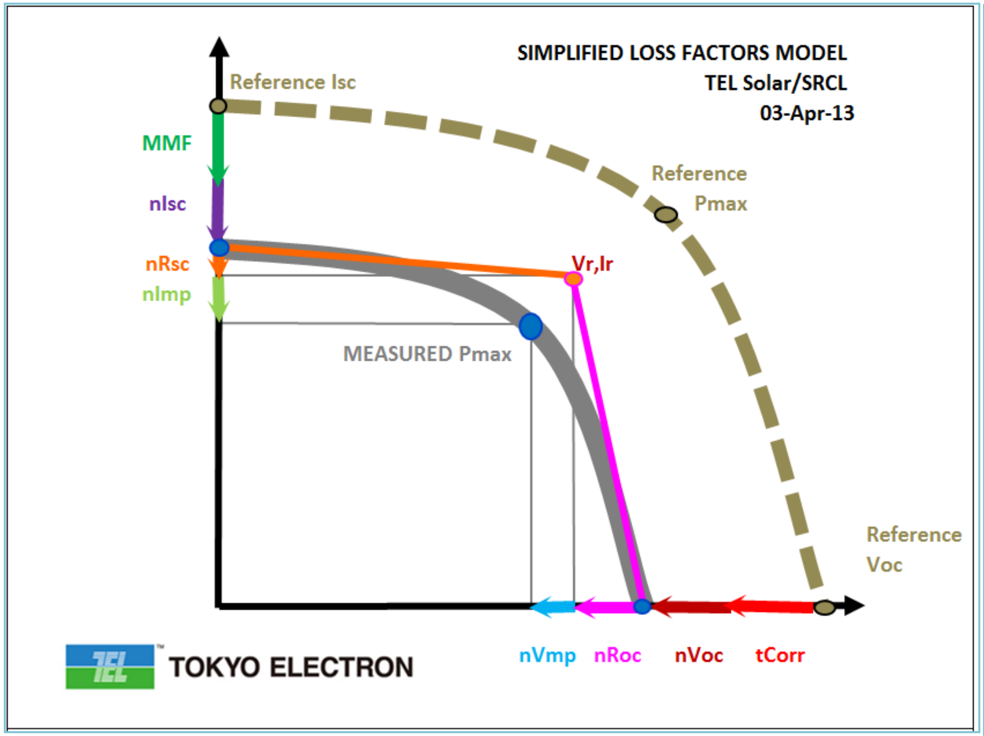
# 7) Energy yield determining effects - which can be included / improved for better PV modelling **(see Juergen Sutterlueti's talk tomorrow)**

- 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 (LID)
- Soiling & cleaning impact (see Dust Detection System by TEL TWN team)
- Production quality distribution
- …

All required for improved kWh/kWp or ct/kWh analysis!

# Loss factors model(LFM) IV curve fit

**[TEL1] "Understanding Module Performance further: validation of the novel loss factors model and its extension to ac arrays" Sellner et al, 27th PVSEC Frankfurt 2012**




**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**

# Conclusions

- Models need to check <u>every stage</u> not just kWh/kWp (self cancelling errors)
- <u>Rsc vs. Irradiance</u> affects low light efficiency most, it's not on datasheets
- Modelled low light and temperature coefficients must agree with IEC measurements - discrepancies cause errors up to 16% kWh/kWp
- We need a better understanding of
  - **Module variability – ΔIsc, ΔVoc, ΔFF etc. are technology dependent**
  - **Irradiance and module spectral response**
  - **Irradiance averaging frequency**
  - **Correlated weather parameters**
  - **Seasonal annealing (for some thin films)**
  - **Measurements vs. Irradiance sensor type etc.**
- LFM is being developed with TEL Solar to overcome many of these modelling problems – but it needs spectral measurements and seasonal anneal modelling for thin film - Further talk tomorrow by Juergen Sutterlueti (TEL)

# Some links

[TEL1] "Understanding Module Performance further: validation of the novel loss factors model and its extension to ac arrays“ Sellner et al, TEL, 27th PVSEC Frankfurt 2012 http://www.steveransome.com/PUBS/2012Frankfurt_4EO35_OutdoorPerformance_LFM_Sellner_et_al.pdf

[TEL2] "Characterising PV Modules under Outdoor Conditions: What's Most Important for Energy Yield“ Sutterlueti et al 26th PVSEC Hamburg 2011 http://www.steveransome.com/pubs/2011Hamburg_4AV2_41.pdf

[Hans] “Calibration of the Sandia Array Performance Model Using Indoor Measurements” Hansen et al, Sandia, 38th PVSC Austin 2012

[TUV] “COMPARISON OF DIFFERENT THIN-FILM TECHNOLOGIES - PERFORMANCE CHARACTERISTICS OBTAINED FROM LABORATORY AND FIELD TESTS” 25th PVSEC Valencia 2010

[Stein] ”The Photovoltaic Performance Modelling Collaborative (PVPMC)“ www.pvpmc.org

[Tok2] “PERFORMANCE DEGRADATION ANALYSES OF DIFFERENT KINDS OF PV TECHNOLOGIES IN HOKUTO MEGA SOLAR PROJECT” UEDA et al Tokyo institute of Technology 26th PVSEC Hamburg 2011

[BPS] "How well do PV modelling algorithms really predict performance?" Ransome 22nd PVSEC Milan 2007 http://www.steveransome.com/PUBS/2007Milan_4EP_1_1_paper.pdf

[DKA] http://www.dkasolarcentre.com.au/go/gallery/gallery

[SRCL] http://www.steveransome.com

[King] http://energy.sandia.gov/wp/wp-content/gallery/uploads/075036.pdf

[PVGIS] http://re.jrc.ec.europa.eu/pvgis/

[Pvsyst] http://www.pvsyst.com

[TMY] http://www.nrel.gov/docs/fy08osti/43156.pdf

[TEL] Tel Solar http://www.solar.tel.com/

[PVWATTS] http://rredc.nrel.gov/solar/calculators/pvwatts/version1/US/US_text_only.html

# Thank you for your attention !

steve@steveransome.com

past papers available at

www.steveransome.com

acknowledgements : TEL Solar

**Next conferences/visits planned**

39th PVSC 16-21 Jun 2013 Tampa, Florida, USA

**"Estimating the Sensitivity of Energy Performance from Optimising Different PV Technologies World Wide"**
**by Steve Ransome (SRCL) and Juergen Sutterlueti (TEL)**
**System Performance Modeling, 17 June 2013 @ 3:30PM**

28th EU PVSEC 30 Sep-04 Oct 2013 Paris, France

**2 abstracts submitted – awaiting status (1 oral 1 poster accepted)**

# Spare slides

# Simple Empirical equations (similar to PVUSA method)

**[SRCL] 35th PVSC 2010**

- Simple equations with ~5 independent parameters to model PV performance (Module Temperature, Vmax, Pmax) 1
- Interpolations/extrapolations find performance at given conditions such as STC or PTC 2
- Normalise for validity and applicability e.g. Pmeasured/Pnominal.stc

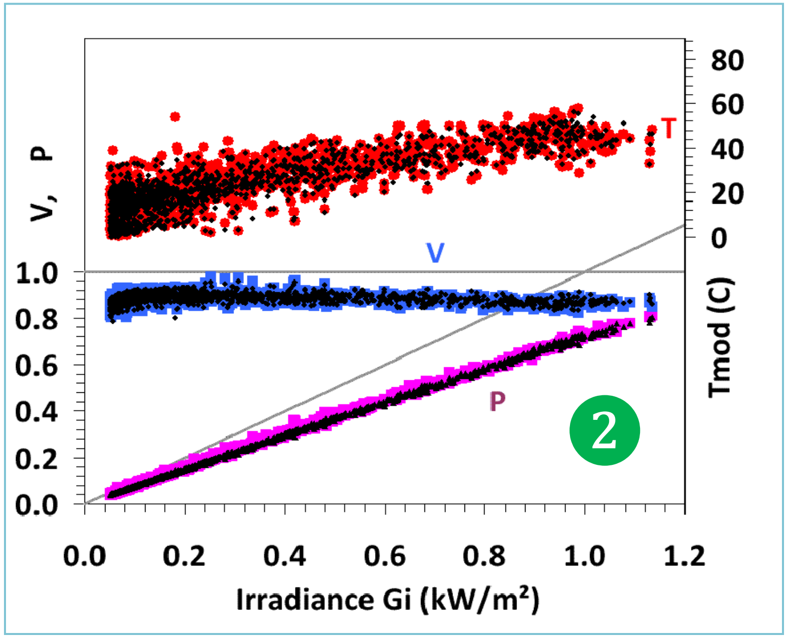
- **Best use**
  - **Commissioning (in non optimum weather)**
  - **Estimating Pmax.actual/Pmax.nameplate**
  - **check for degradation (slow changes)**
  - **failure checking (rapid changes)**
  - **simulating inline performance**

$P = G * (A + B * G + C * T_{MOD} + D * Ws)$ PVUSA

$T_{MOD} = C_{TM} * T_{AMB} + G * (A_{TM} + D_{TM} * WS) + E_{TM}$

$V_{MP}/V_{MP.STC} = A_{MP} * LOG_{10}(G) + B_{MP}/G + C_{MP} * T_{MOD} + D_{MP} * WS + E_{MP}$

$YA = P_{dc}/P_{dc.STC} = G * (A_{YA} + B_{YA} * G + C_{YA} * T_{MOD} + D_{YA} * WS) - E_{YA}$ Normalised 1



# System performance - Sophisticated Verification method

**[Tok2] "PERFORMANCE DEGRADATION ANALYSES OF DIFFERENT KINDS OF PV TECHNOLOGIES IN HOKUTO MEGA SOLAR PROJECT" UEDA et al Tokyo institute of Technology 26th PVSEC Hamburg 2011**

**Series of independent losses to model system efficiency**

1. Shading (*S*)
2. Effective array peak power (*AP*)
3. Reflection (*R*)
4. Spectral mismatch (*SM*)
5. Module temperature (*T*)
6. PCS capacity shortage (*PS*)
7. Grid voltage (*GV*)
8. Operating point mismatch (high voltage) (*MH*)
9. Fluctuation (*F*)
10. DC circuit (*DC*)
11. PCS (Inverter) (*PC*)
12. PCS Off / PCS Standby (*off*)
13. Miscellaneous loss and error (*Er*).

**Unknown what PV efficiency model is used …**

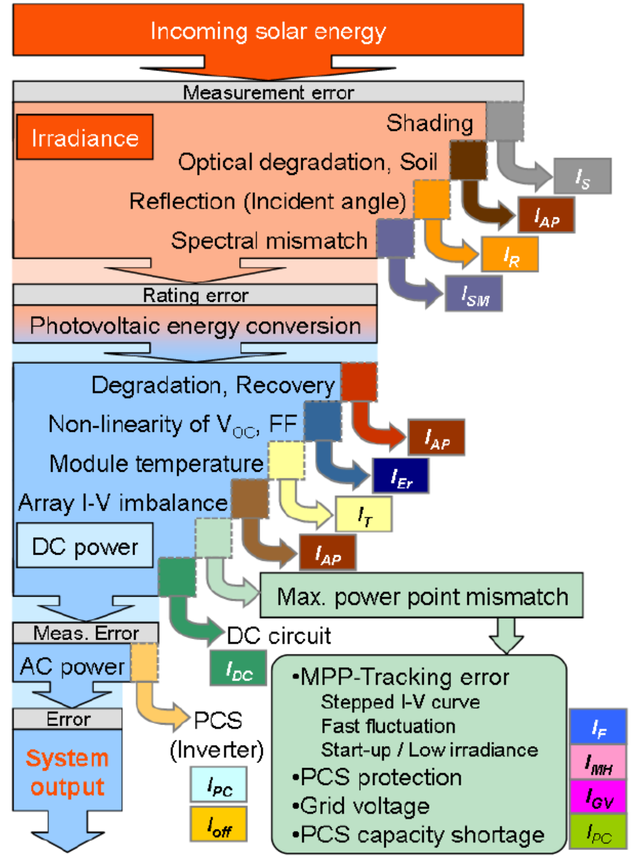


**Figure 2:** Photovoltaic energy conversion loss analysis model of PV systems