Recent Studies of PV Performance Models

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- I spent 19 years with BP Solar on measurements and modelling of crystalline and thin film PV indoors and outdoors
- Since Feb 2008 I have been an independent PV consultant

Recently, clients have been asking questions such as

> ***"We've compared our modules with those of our competitors, both indoors and outdoors, so how come a simulation program gives very different answers for relative kWh/kWp from what we expect ?"***

and

> ***"We've designed a 5MWp plant with simulation program and guaranteed the banks the predicted kWh/kWp is exactly what it will produce"***

INTRODUCTION

- Some PV manufacturers claim up to 33% higher kWh/kWp than competitors (usually c-Si) due to ‘thermal, spectral, low light and angle of incidence improvements’
- Many recent independent tests worldwide show <±5% kWh/kWp

- kWh/kWp is dominated by [Pmax ACTUAL/Pmax NOMINAL] i.e. nameplate allowance vs. actual degradation and annealing

- Some PV simulation programs (PVSPs) predict >5% kWh/kWp differences (usually better for thin film)
- The assumptions made and algorithms used in five+ different PVSPs have been investigated

Recent studies have shown a smaller kWh/kWp variation than some earlier ones

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PV modules have been improving efficiency by lowering losses

- Higher Rshunt from better processing and checking
- Better light capture – AR, texturing, windows, reflectors
- Improved material performance and uniformity
- Lower cell mismatching, rejection of underperforming strings
- Smaller I^2R loss from better tabbing and finger resistivities
- Better matching of multi junction devices
- Lower degradation and less allowance from nameplate
- More accurate calibrations at manufacture

Both c-Si and Thin Film now have a more constant efficiency across different weather conditions and will expect less variation in kWh/kWp than earlier measurements may have suggested

- **You can't calibrate your models on old modules !**

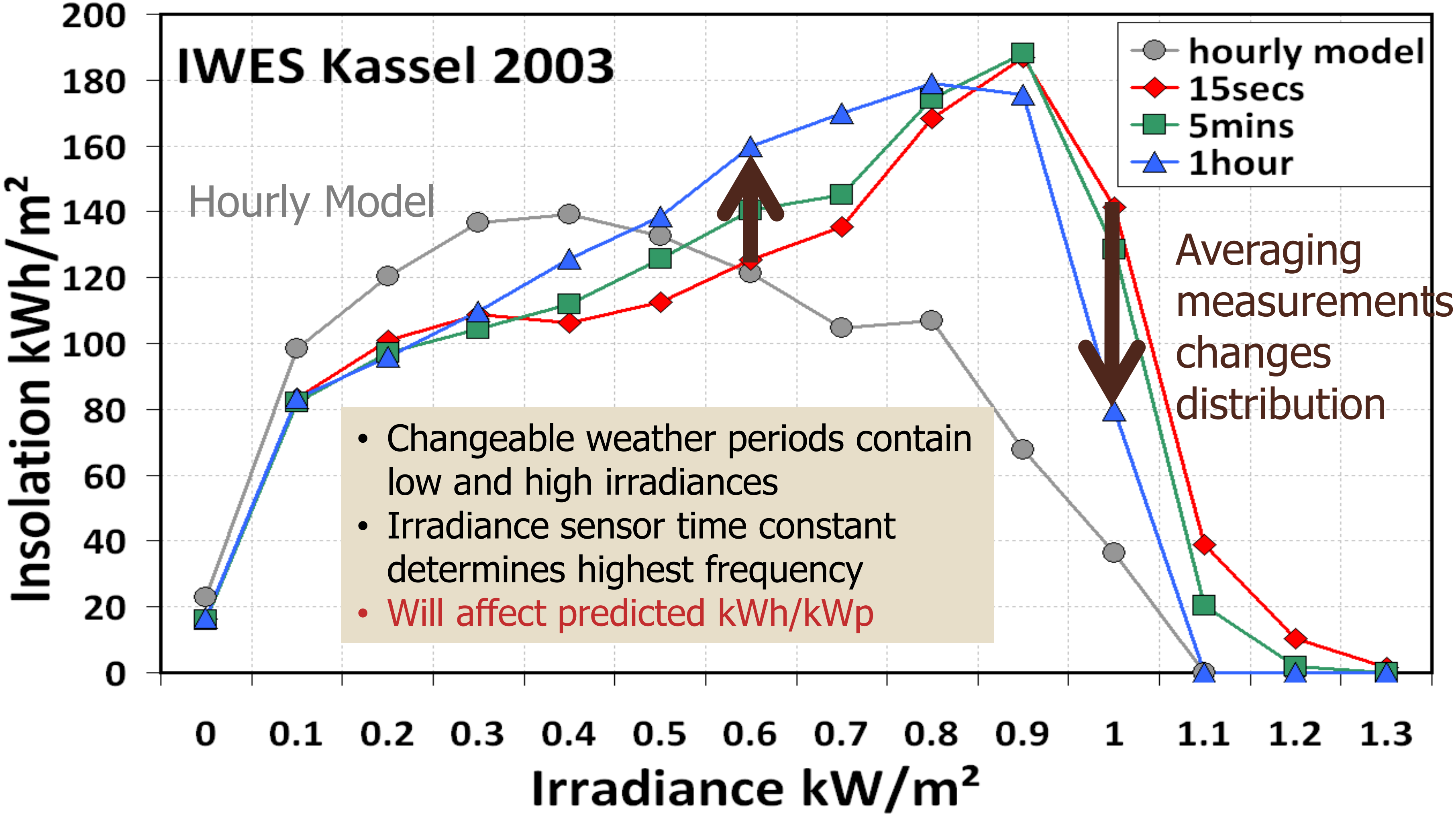
A frequent statement : “My PVSP gives approximate values of kWh/kWp therefore it is validated”

- kWh/kWp depends on the product of >4 items

Insolation (Gi, Tm)	*	Unknowns e.g. Dirt, Pmax/Nominal	*	PV Efficiency (Gi, Tm)	*	Inverter Efficiency (Gi, Tm)

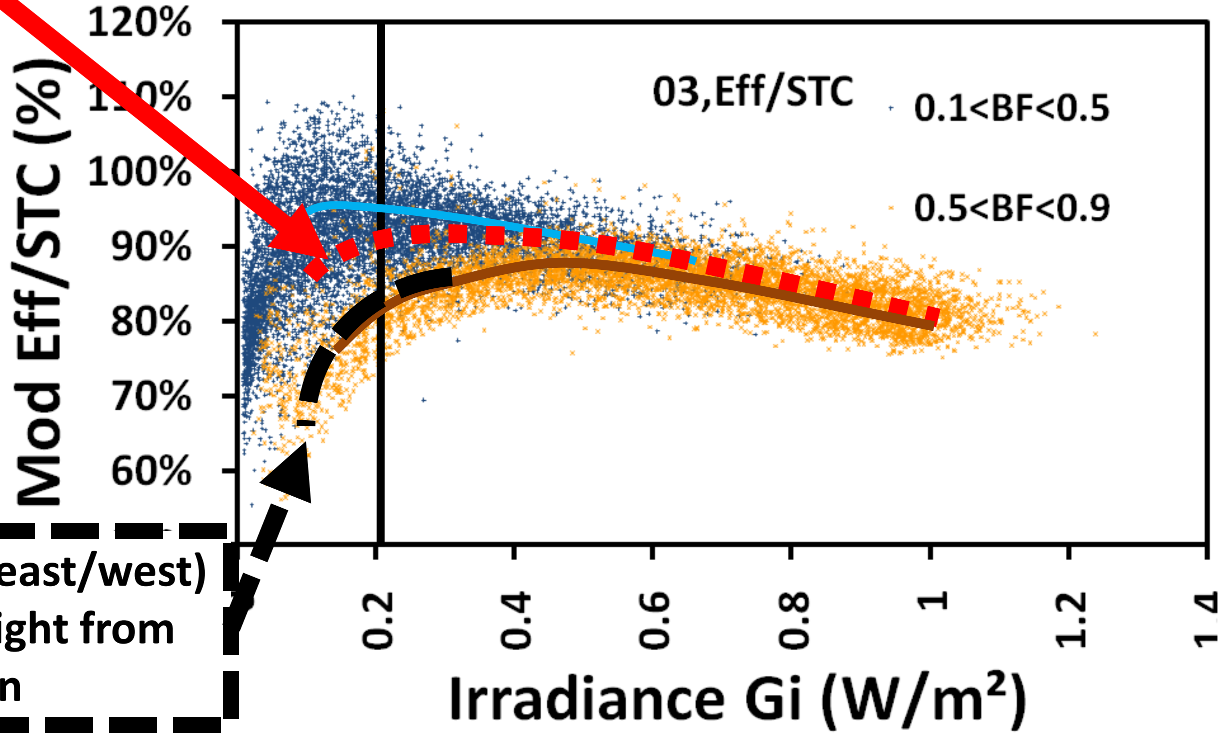
- Errors may self cancel
- Exact fits to measured kWh/kWp can be made by “adjusting” unknowns such as soiling – these are then technology or site dependent
- <u>**Every stage must be checked to be correct to validate a simulation, not just the sum of kWh/kWp**</u>
- <u>**Don’t just validate one module at one site !**</u>

Averaged (hourly) insolation vs. irradiance predicts more energy at low light level than occurs



Measured efficiency vs. irradiance
Low and High clearness conditions (IWES Kassel)

Averaged low light efficiency depends on overcast: clear ratio (site specific)



(if high horizon east/west) Hides redder light from low sun

Apparent low light performance is site specific and will depend on relative sensor spectral response

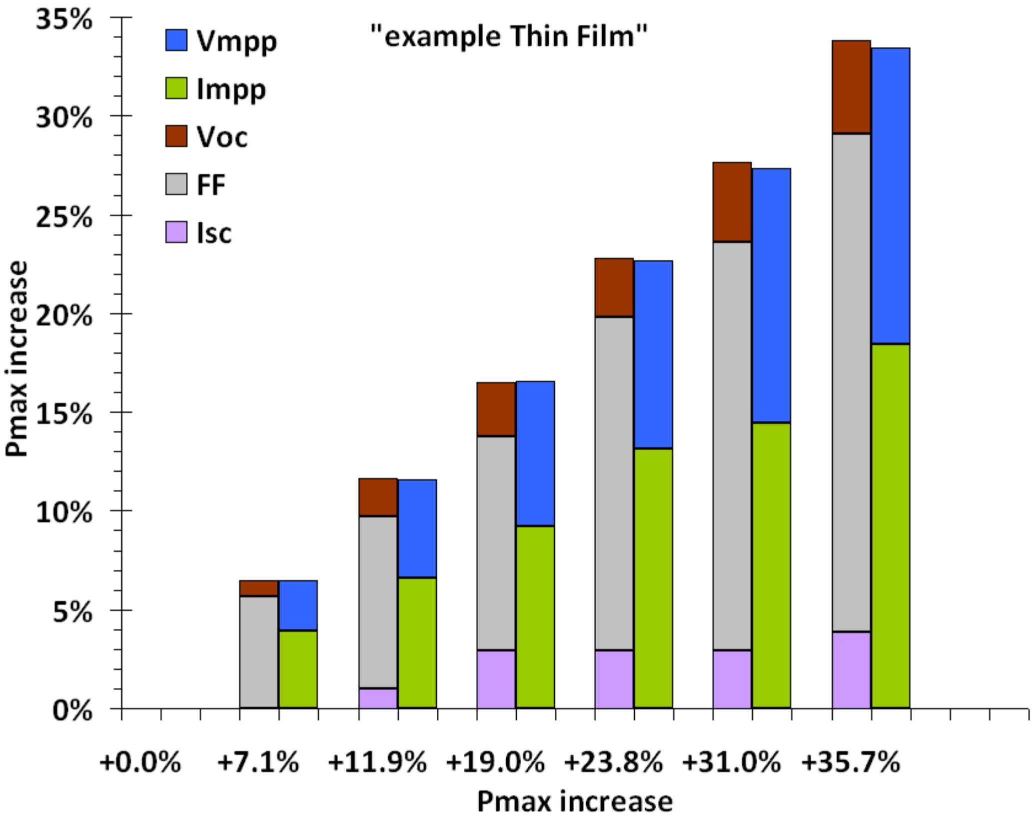
kWh/kWp modelling uncertainty depends on many factors

Reference module calibration	**>±2.5%**	c-Si, less accurate for thin films (< ±10% ??)
Flash tester repeatability	**x% (1%?)**	(Not perfect AM1.5 spectrum, capacitance)
Nameplate allowance LID/degradation	**-1 to -3%** **-10 to -35%**	B doped p type c-Si, 0% for n-type ? greater for thin films
Pmax bin width W	**~±2.5%**	e.g. 200<Pmax<210W or 78<Pmax<82 W
Insolation sensor calibration	**~±2-3%** **~±1.7-7%** **???**	Pyranometer calibration, deterioration Reference cell calibration, deterioration Satellite data, Tilted plane algorithms
Yearly insolation	**~±4%/y**	Random variations, more for el Niño etc.
Dirt loss	**?**	Site dependent, falls after ~>5mm rain
KWh/kWp	$U^2 = u_1^2 + u_2^2 \ldots u_n^2$	**Total uncertainty depends on <u>all</u> above** **- lowest possible** **$(2.5\%)^2+(1\%)^2+(2.5\%)^2+(2\%)^2 \rightarrow$ <u>4.2%</u>**

Minimum variability of PV parameters per Power bin –

example Thin Film from manufacturers' datasheet

ΔPmax = ΔVmpp + ΔImpp
= ΔVoc + ΔFF + ΔIsc

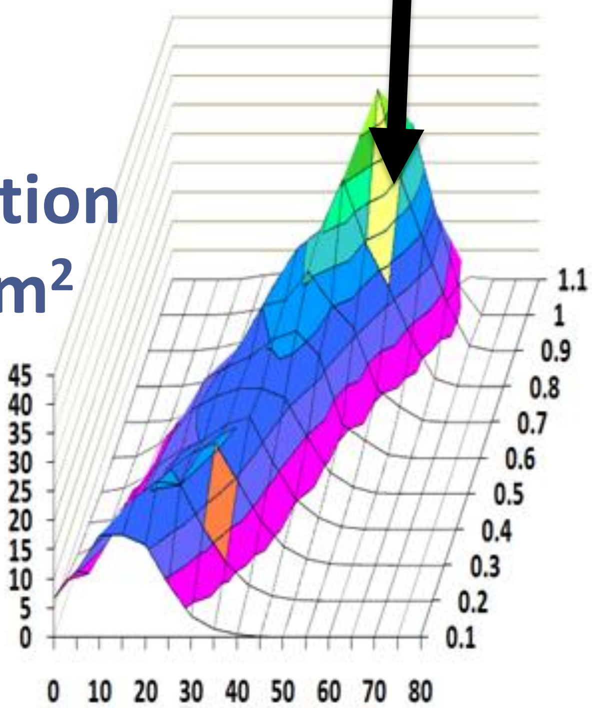


- Shows minimum parameter variation within a range of modules, reality will be higher
- e.g. TF has 6% Pmax bins so will be >3% Imp and >3% Vmp variation each Pmax bin
- c-Si : Power tends to follow Isc more than Voc or FF
- Models must account for variability

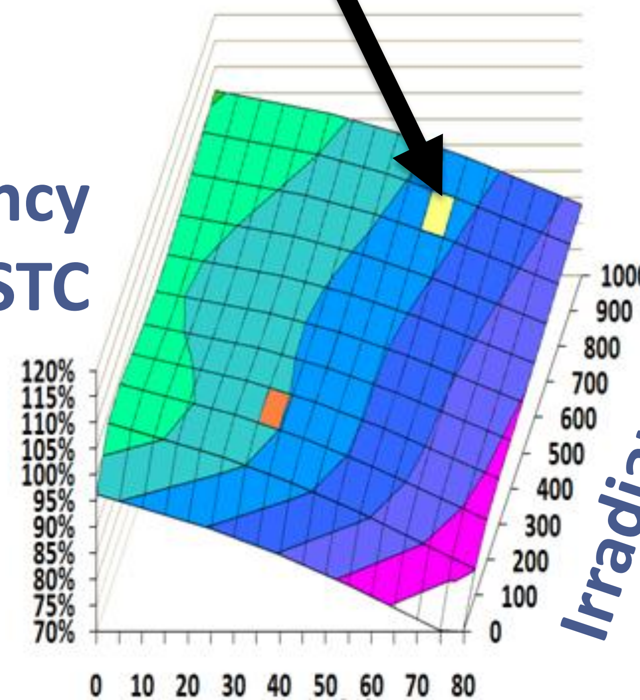
How simulation programs usually calculate kWh/kWp (Matrix method)

$$kWh/kWp \; \alpha \; \sum \text{Insolation}_{(\text{Tmod,Irradiance.})} * \text{Efficiency}_{(\text{Tmod,Irradiance})}$$

Insolation kWh/m²



Efficiency /STC



Irradiance (W/m²) →

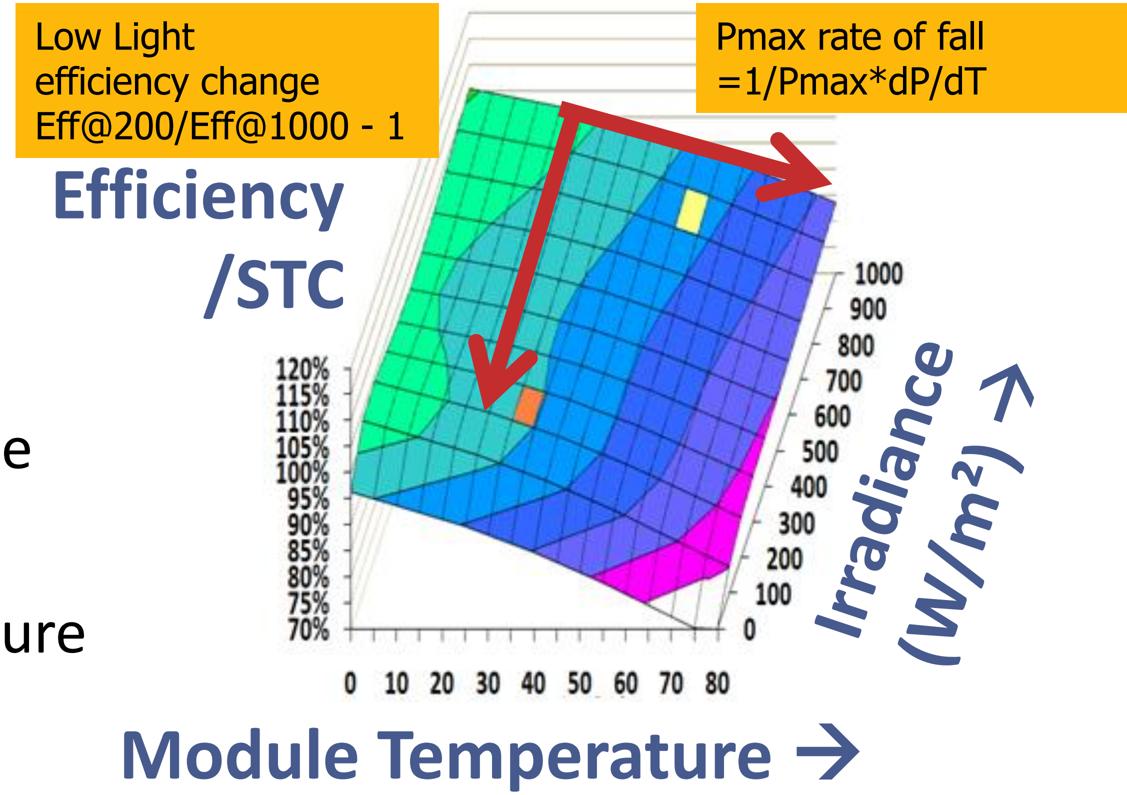
Module Temperature →

Averaging weather data to hourly values distorts the distribution towards lower irradiances

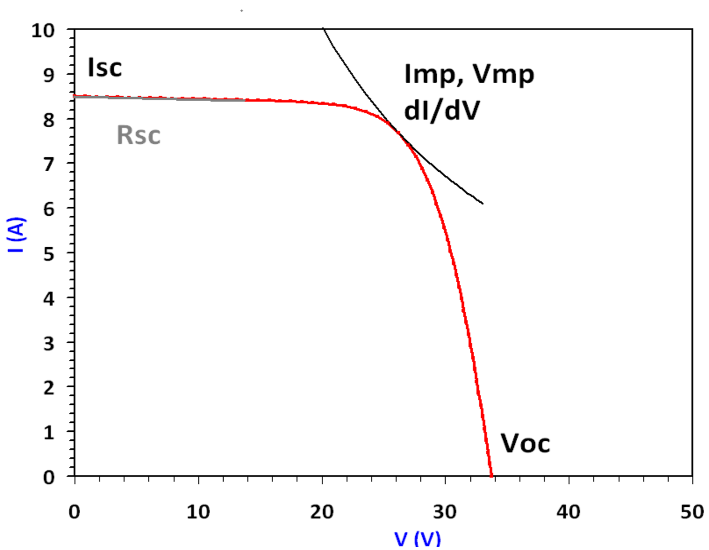
How simulation programs usually calculate efficiency (Matrix method)

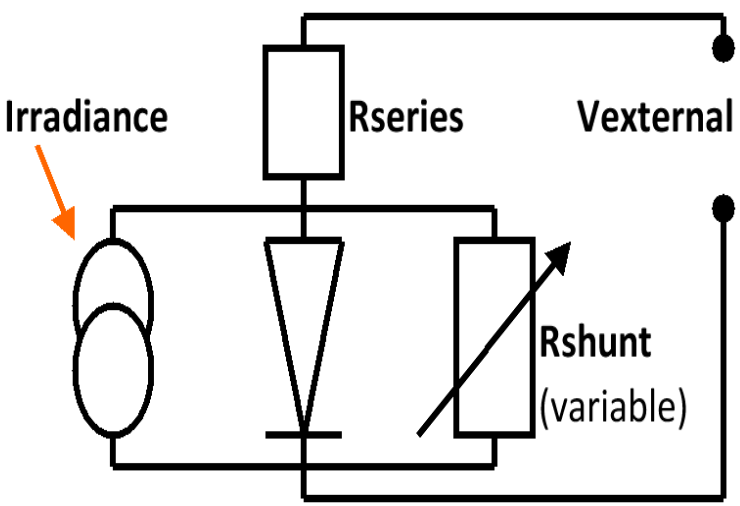
Modelled Efficiency(G,T) depends on assumed

- Low light efficiency change
- Pmax drop with temperature gamma



PVSPs usually use a <u>1 diode model</u> fitted to an IV curve

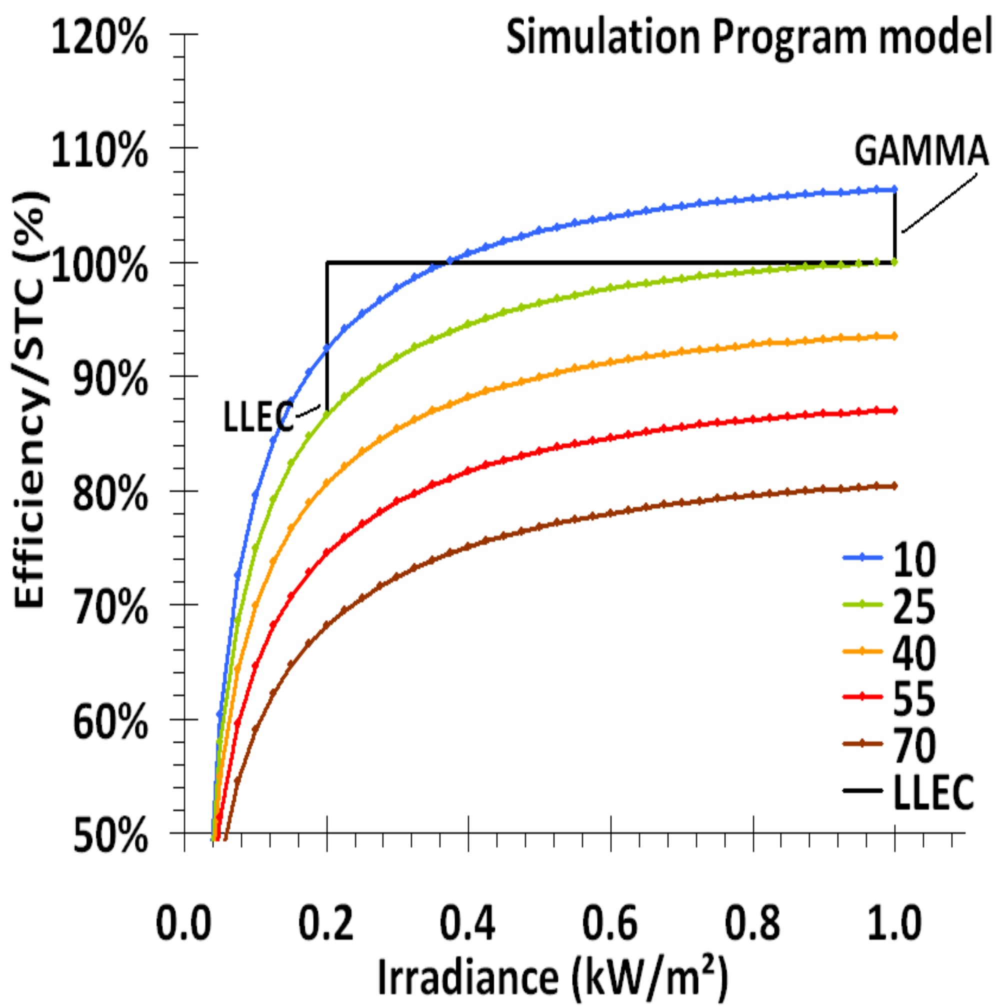




- Fitted to data sheets or a tested module
- What will variability be module to module ?
- Published model also predicts
  - Pmax temperature dependence
    - <u>not</u> IEC 61215/61646
  - LLEC "low light efficiency change"
    - <u>not</u> EN 50380
- Rsc (Resistance at Isc)
  - estimated as not on datasheet
  - will vary for each module
  - may depend on bias dependent collection and cell mismatch
  - known to rise as irradiance falls – but how best to model this ?

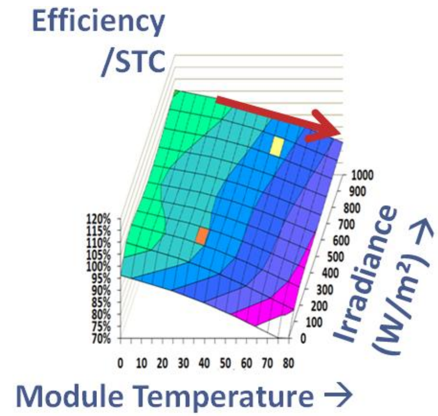
PV efficiency/nominal vs. irradiance and module temperature :

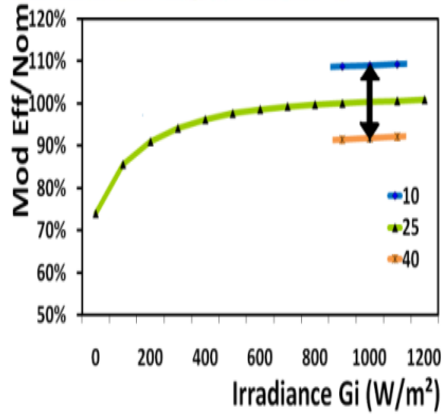
- PVSPs contain databases of physical, thermal and electrical parameters
- They can create graphs and export their values as tables to be further analysed
- Graph shows <u>how to check</u> Gamma (1/P*dP/dT) and LLEC (low light efficiency change Eff@200/Eff@1000 - 1) from datasheets with simulation programs

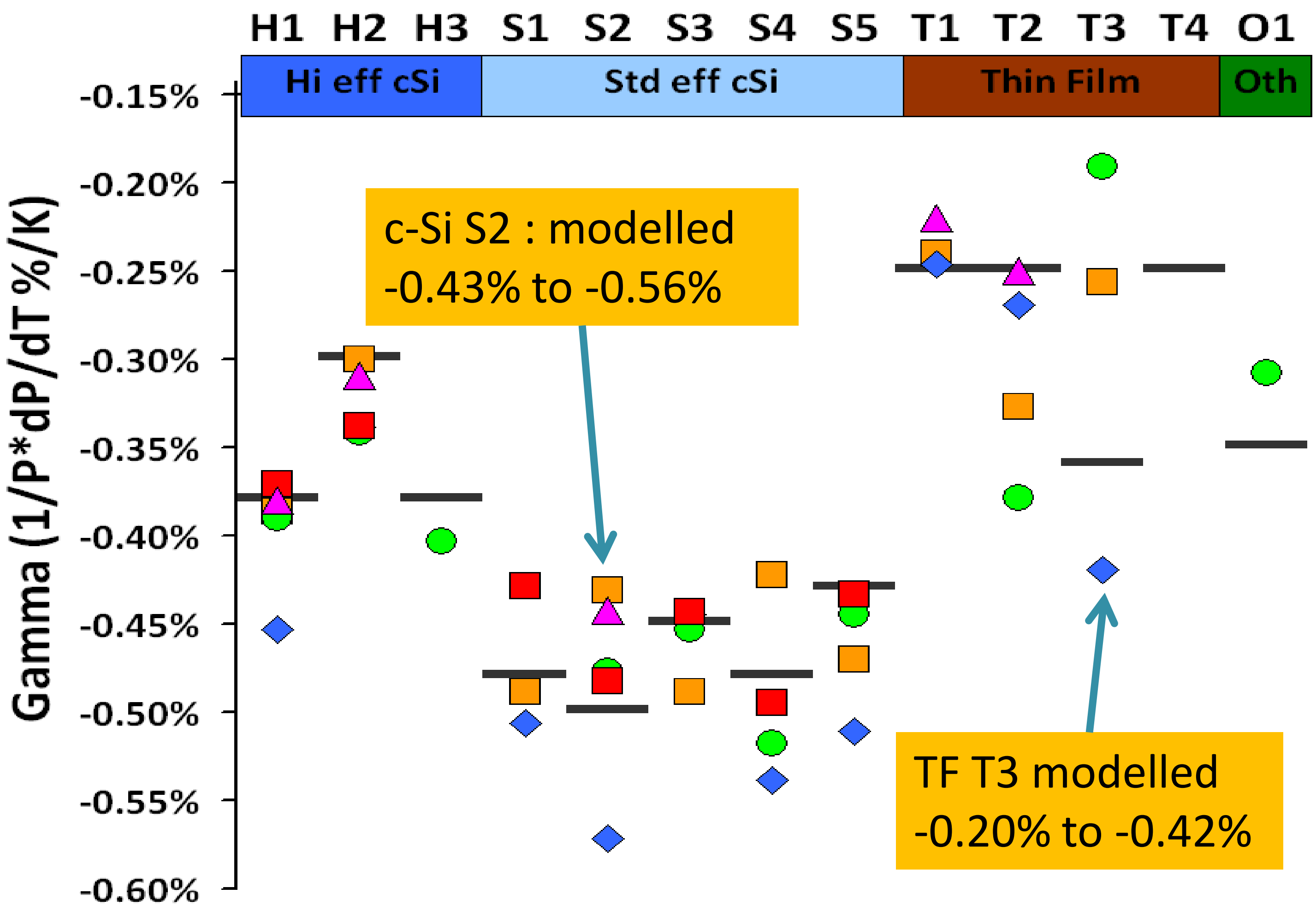


Checking gamma = 1/P*dP/dT

5 PVSPs vs. Manufacturer datasheet

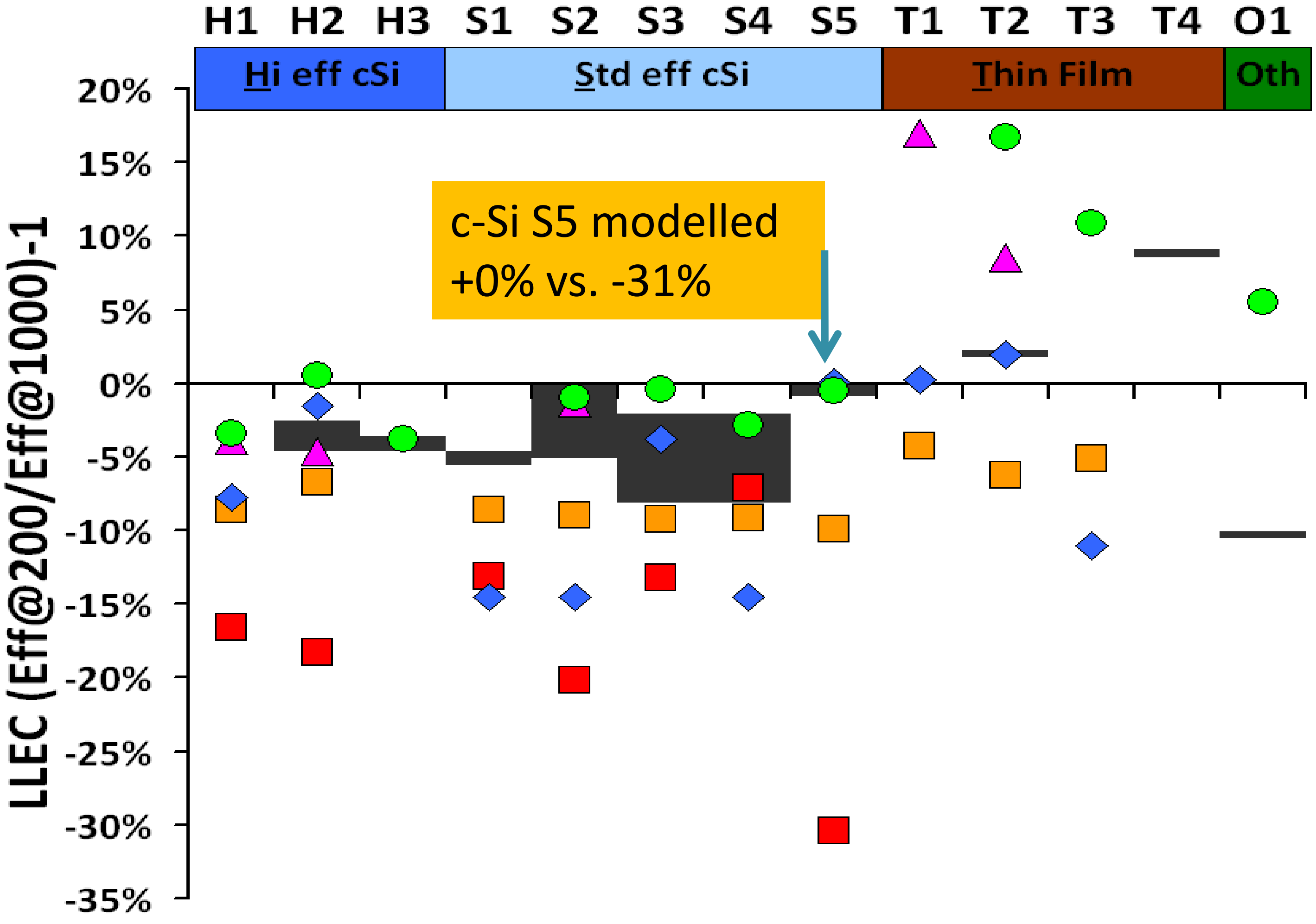


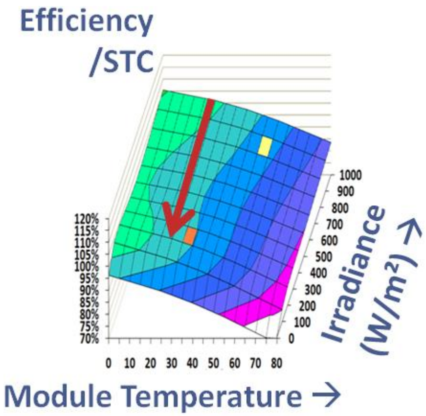


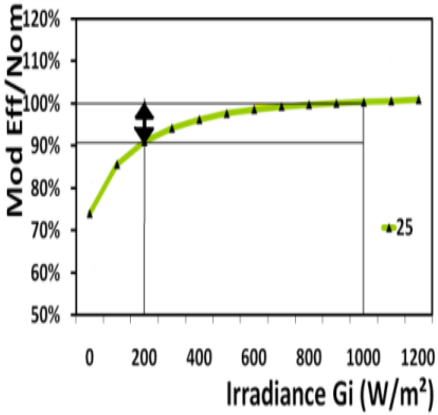


Checking Low Light efficiency changes

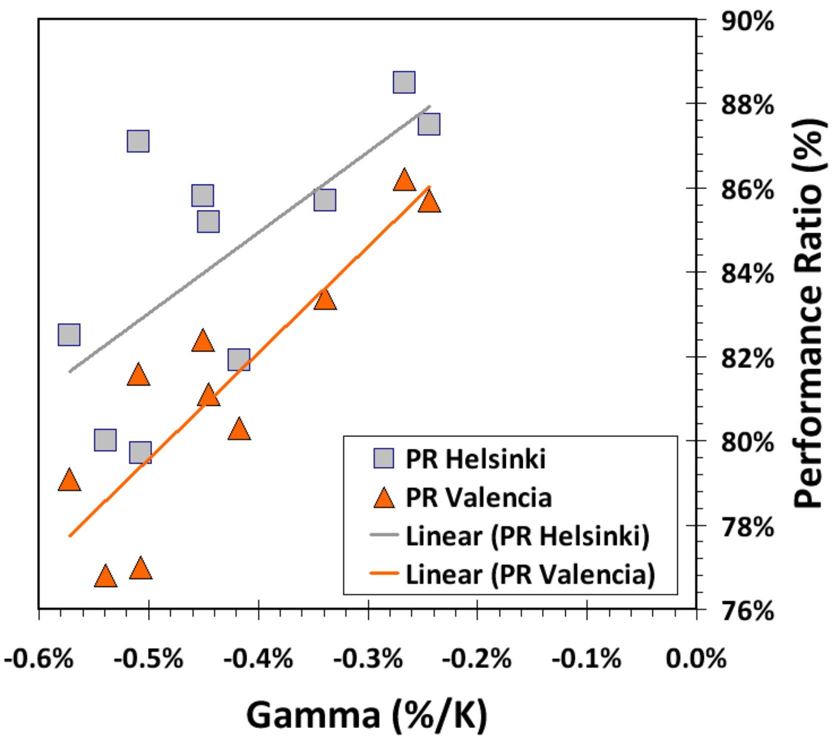
5 PVSPs vs. Manufacturer datasheet

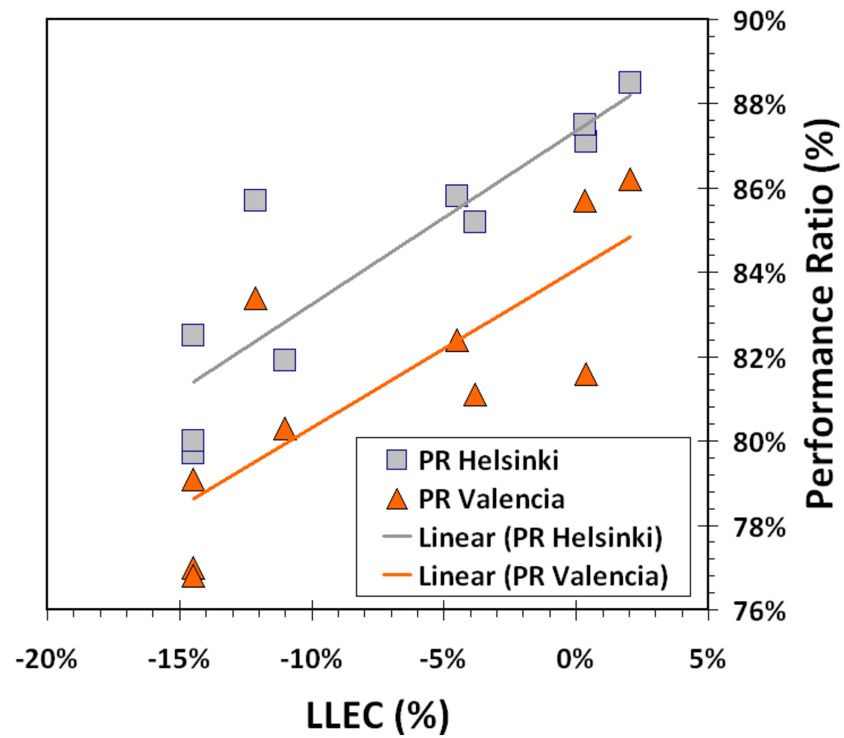






PVSP : predicted kWh/kWp vs. Gamma and LLEC in databases (not manufacturer data) for 11 PV module types





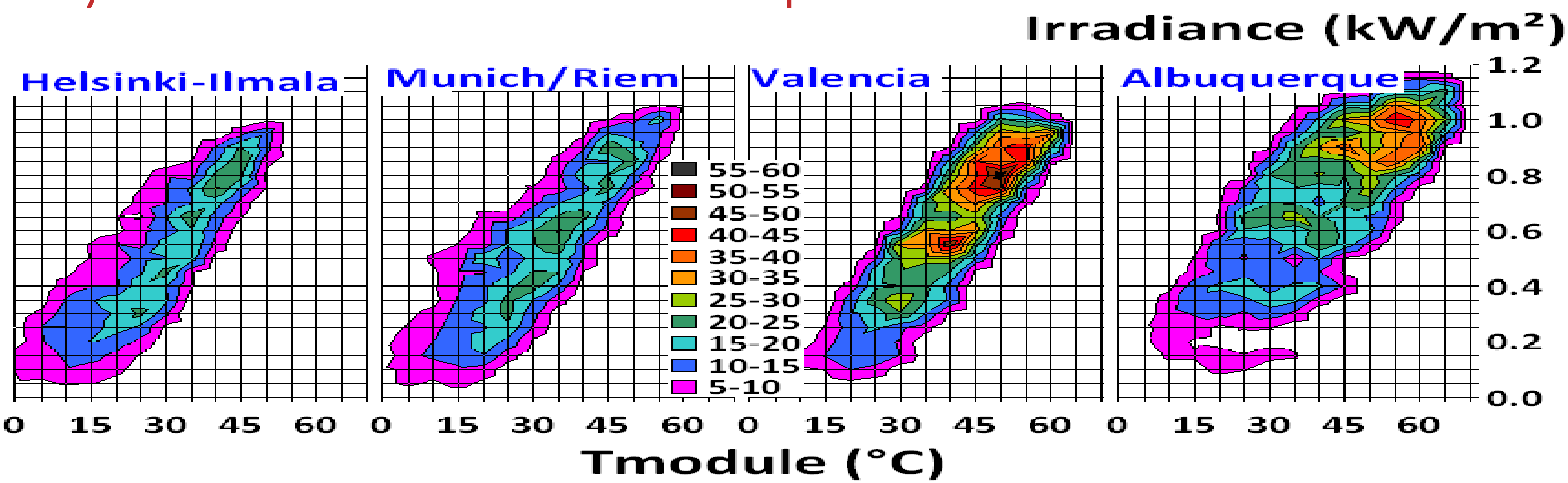
- **Strong correlation of Performance Ratio with both Gamma and LLEC**
- **Any discrepancies in data will give large errors in predicted PR**

Checking kWh/kWp sensitivities to errors at 4 sites

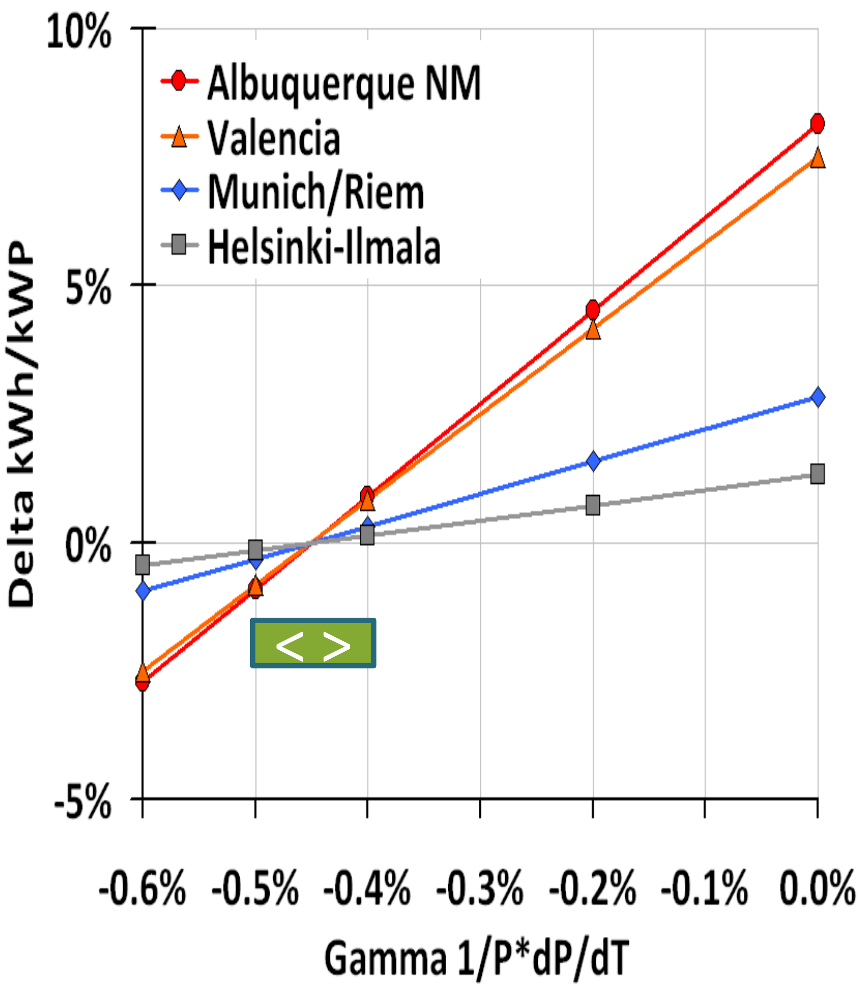
Climate summary

	Site name, Country	Latitude °	Tilted 30°S Insolation kWh/m²	Weighted Tmodule °C Σ(Tm*G)/Σ(G)
	Helsinki, FI	60°N	1150 *	29 *
	Munich, DE	48°N	1350 **	33 **
	Valencia, ES	39°N	1850 ***	42 ****
	Albuquerque NM,USA	35°N	2300 ****	44 ****

Hourly Tilted Insolation vs. Module Temperature

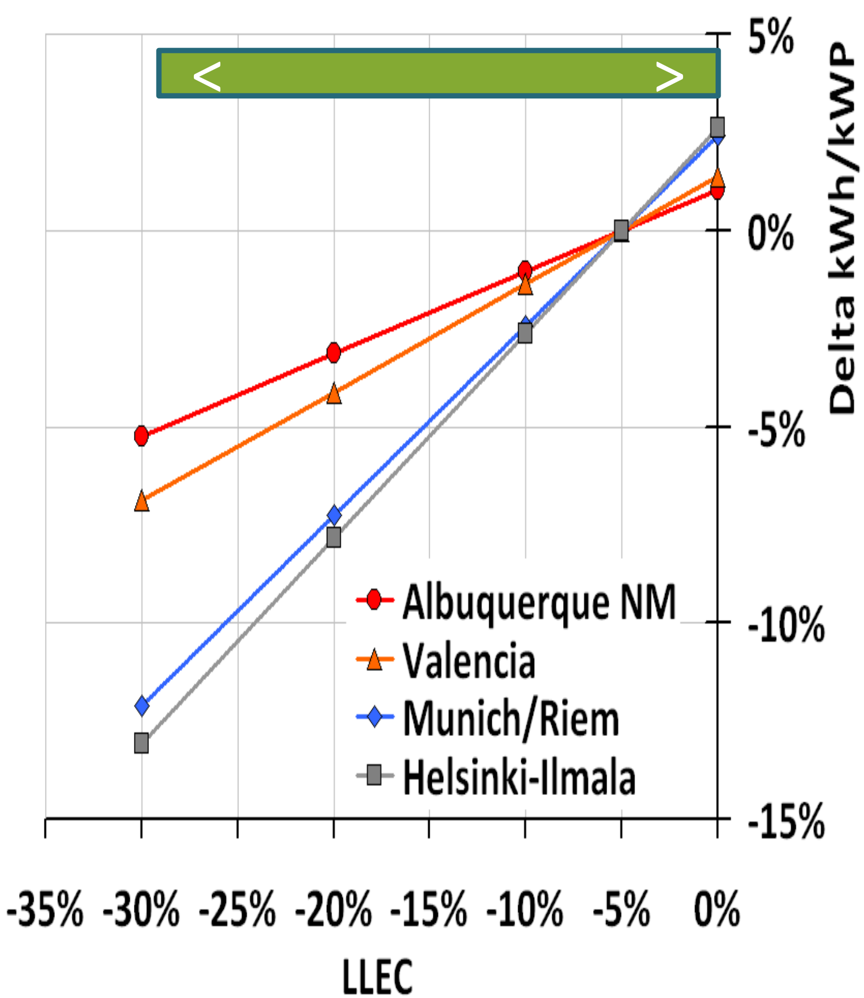


Change in predicted kWh/kWp vs. PVSP gamma error



- Discrepancies in the gamma factor Pmax temperature coefficient cause the largest errors in calculated kWh/kWp for the hottest sites (as expected)
- A gamma error (as seen in simulation programs) of **±0.05%/K** causes a predicted kWh/kWp change of ±0.5% (Helsinki) to ±1% (Albuquerque)

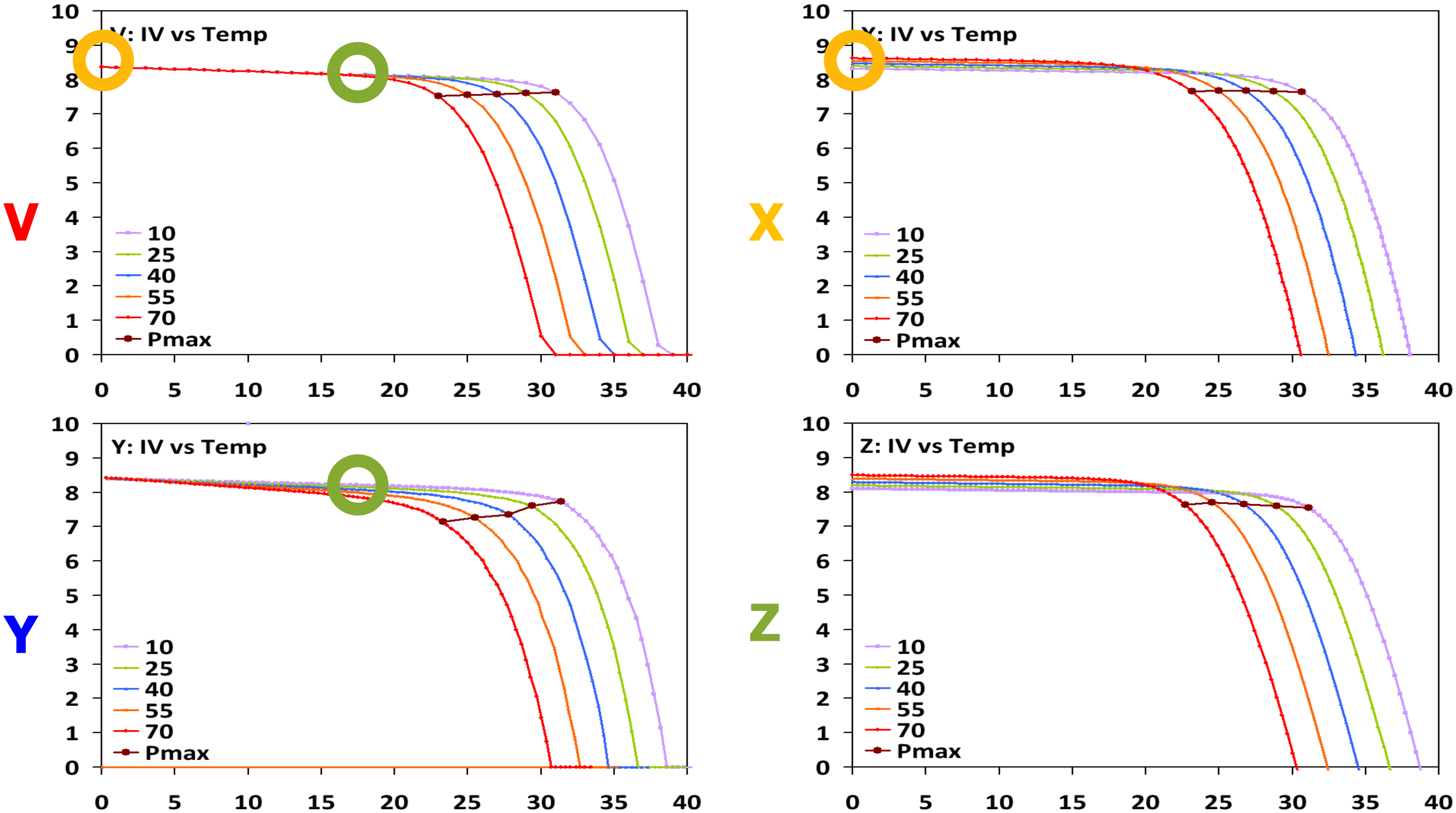
Change in predicted kWh/kWp vs. PVSP low light efficiency change error



- Discrepancies in the low light efficiency change cause the biggest errors in calculated kWh/kWp for the dullest sites (as expected)

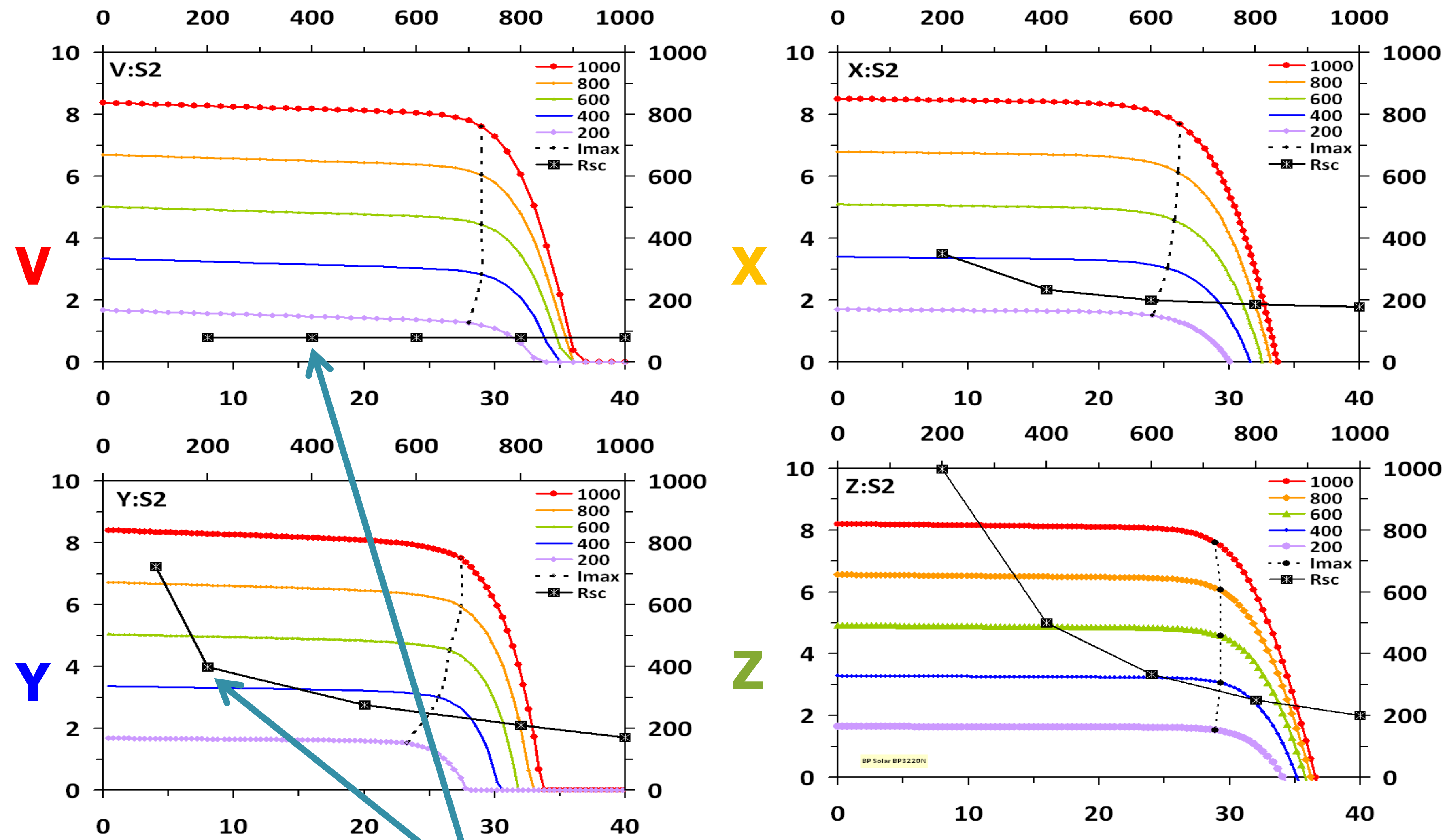
- A low light efficiency change error of **30%** (as seen in PVSPs) causes a predicted kWh/kWp change of 6% (Albuquerque) to 15% (Helsinki)

PVSP predicted IV vs. Tmodule (70C to 10C) Module S2



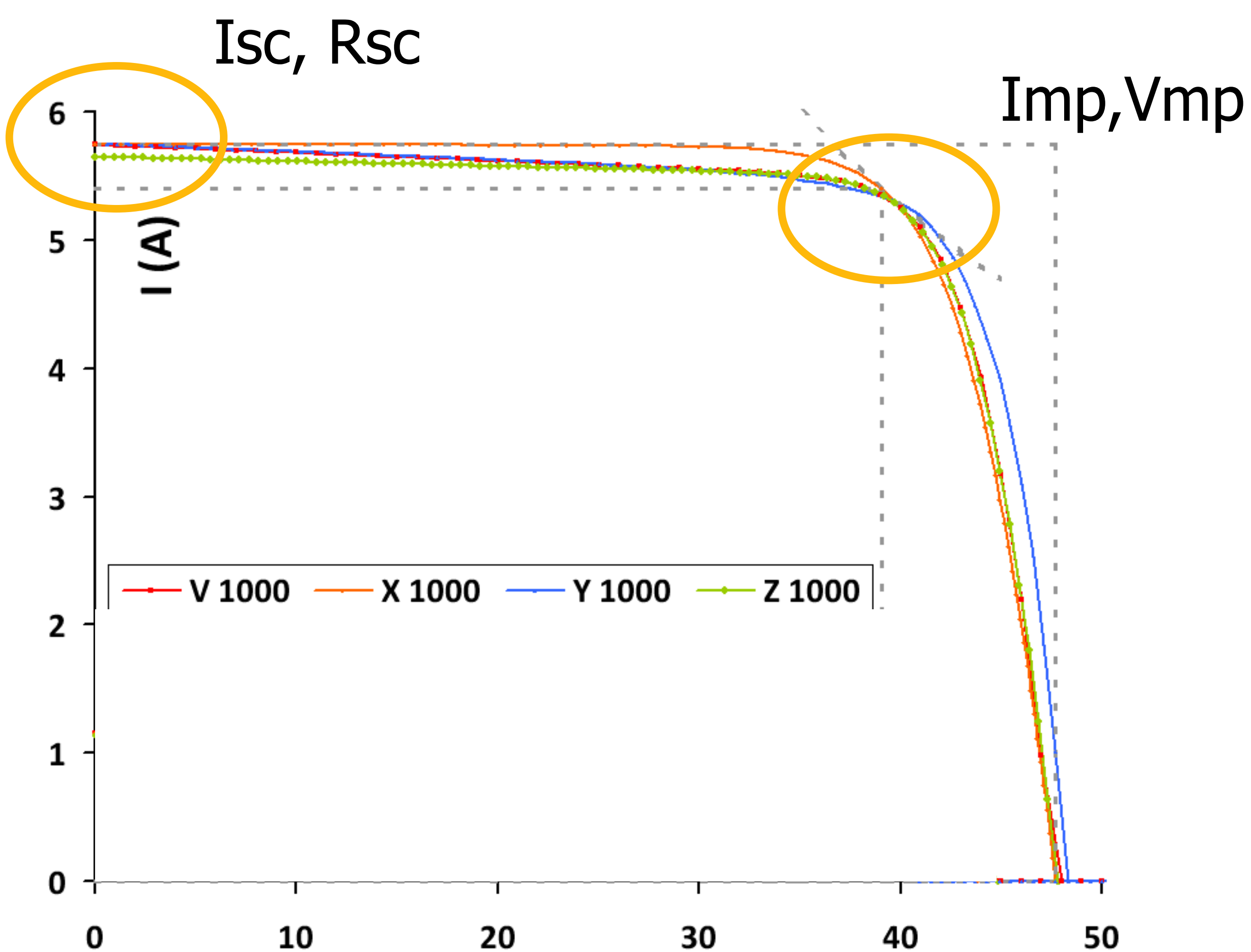
Discrepancies of 1/Isc*dIsc/dT (alpha) and Rshunt with temperature cause power temperature coefficient error

PVSP predicted IV vs. Irradiance (200-1000W/m²) Module S2

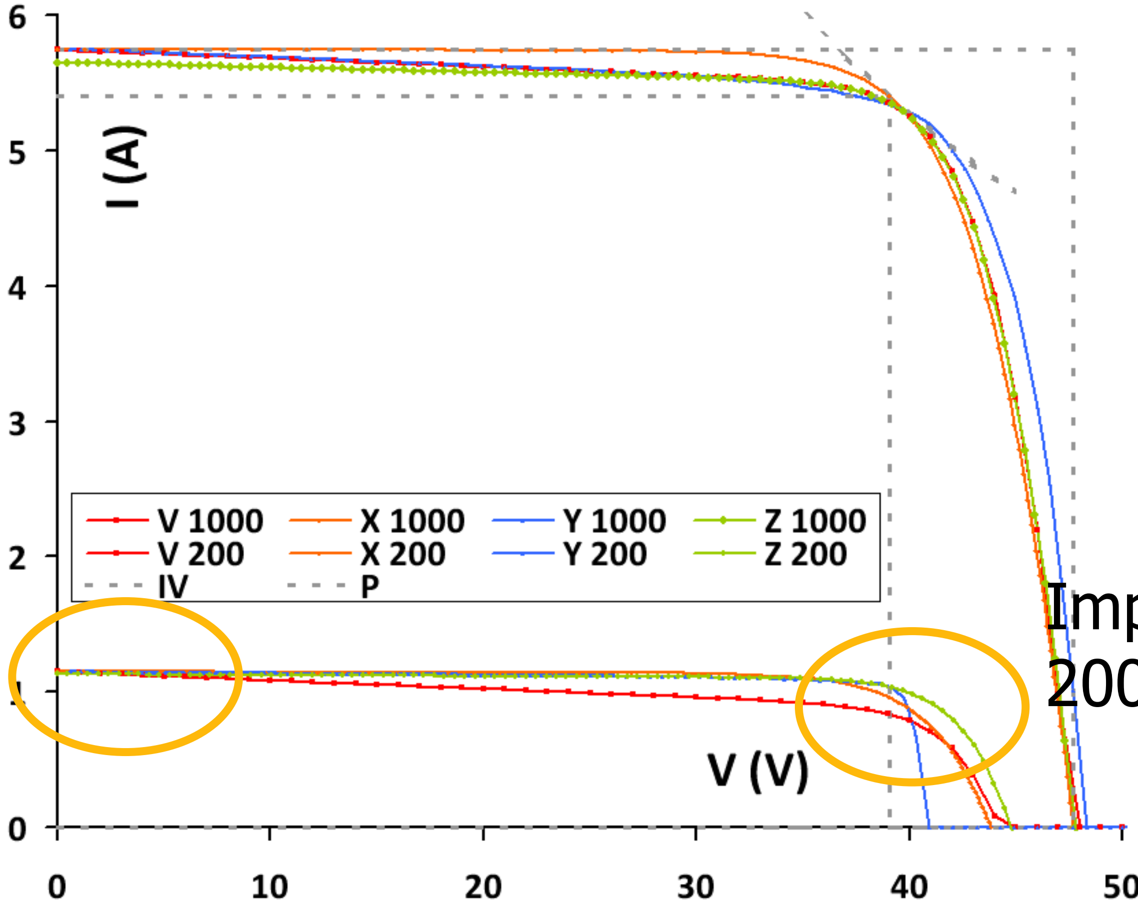


Discrepancies of Rsc(irradiance) causes LLEC difference

IV vs. Irradiance (1000W/m²) Module H2



IV vs. Irradiance (200 and 1000W/m²) Module H2



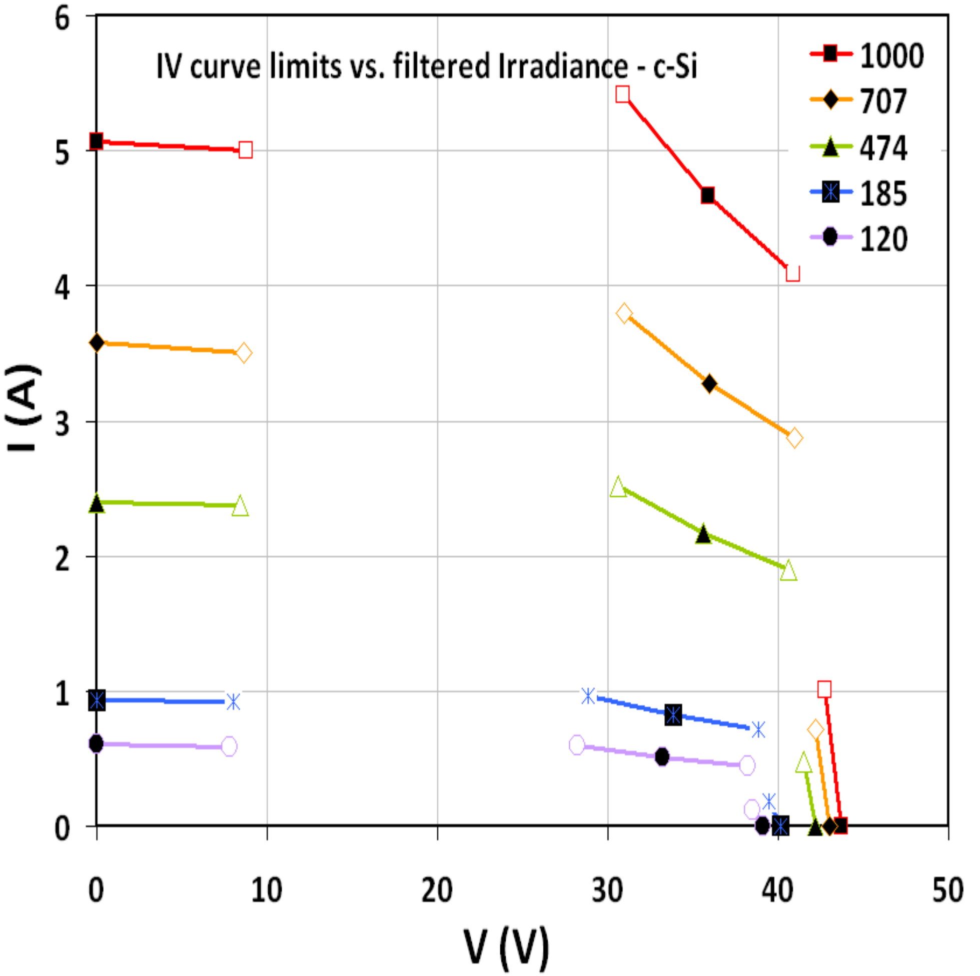
Rsc@200

Imp,Vmp@ 200

Voc@200

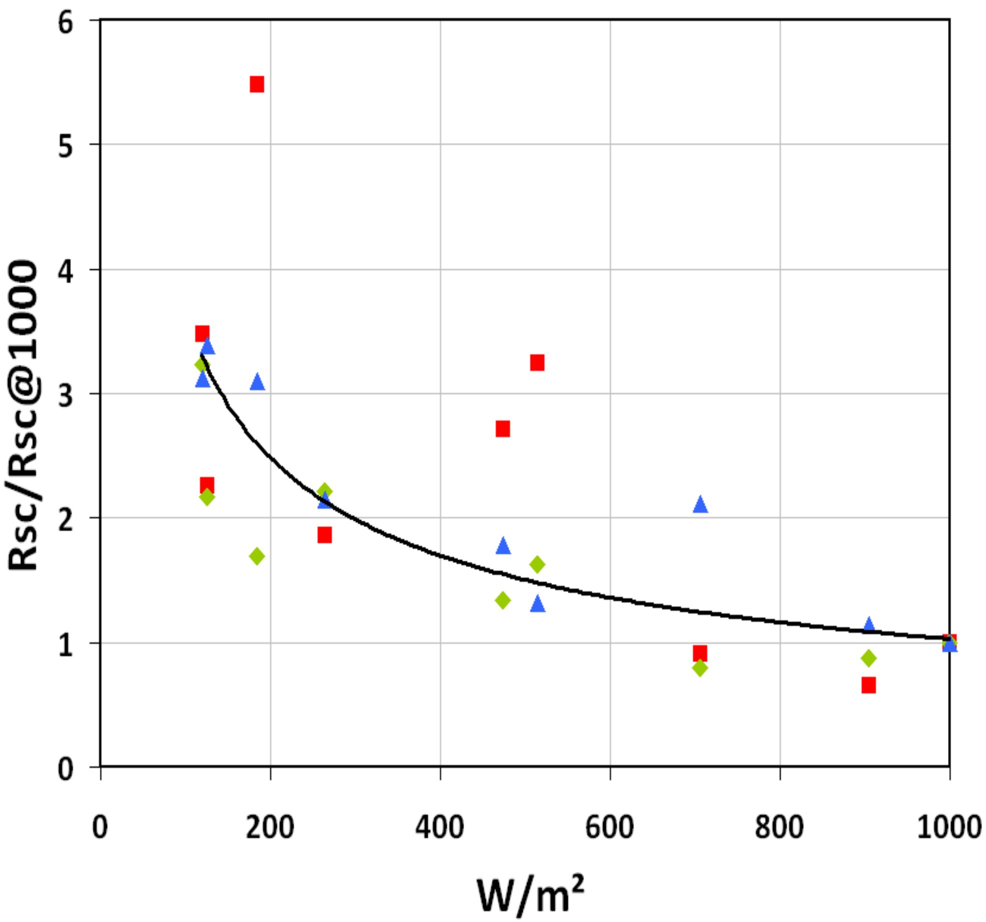
+

Measuring shunt Rsc vs Irradiance Indoor to EN50380 (Indoor flash + mesh, ND filters - BP Solar c-Si)



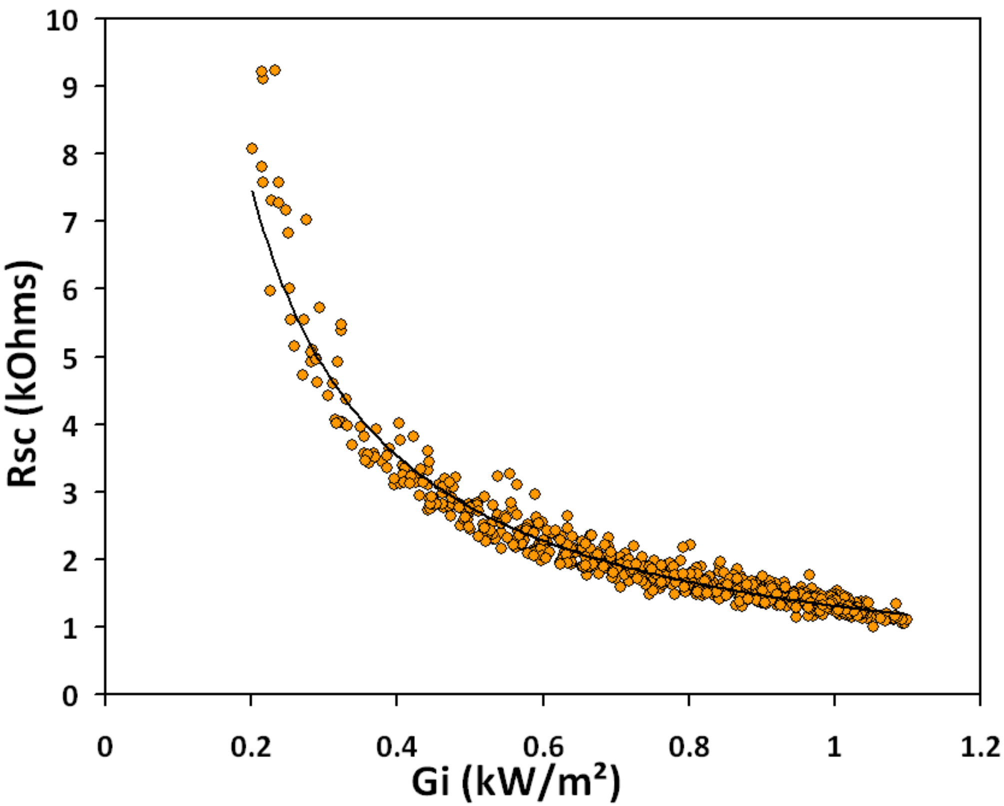
- BP Solar c-Si module measured at different irradiances using meshes and/or neutral density filters
- Black points measured
- White points tangents
- I don’t have all IV data

Shunt Rsc vs. irradiance [Rsc@?W/m²]/[Rsc@1000W/m²] Indoor flash + mesh, ND filters (BP Solar c-Si)



- Difficult to measure as Rsc is high, meshes may be non uniform, filters may not be neutral density.
- Power series fit
- 3 module types look similar
- [Rsc@200]/[Rsc@1000] may be 2.5 to 3x

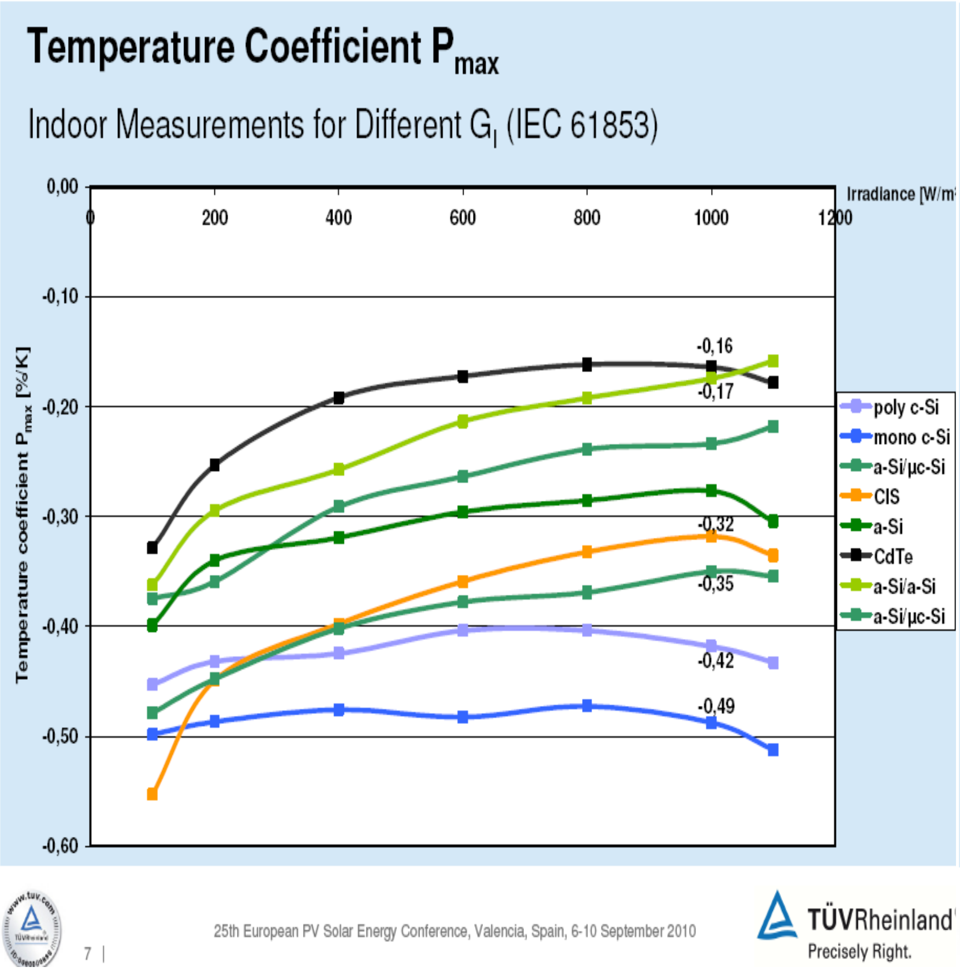
Measuring shunt Rsc vs Irradiance Outdoors (Oerlikon Solar Micromorph)



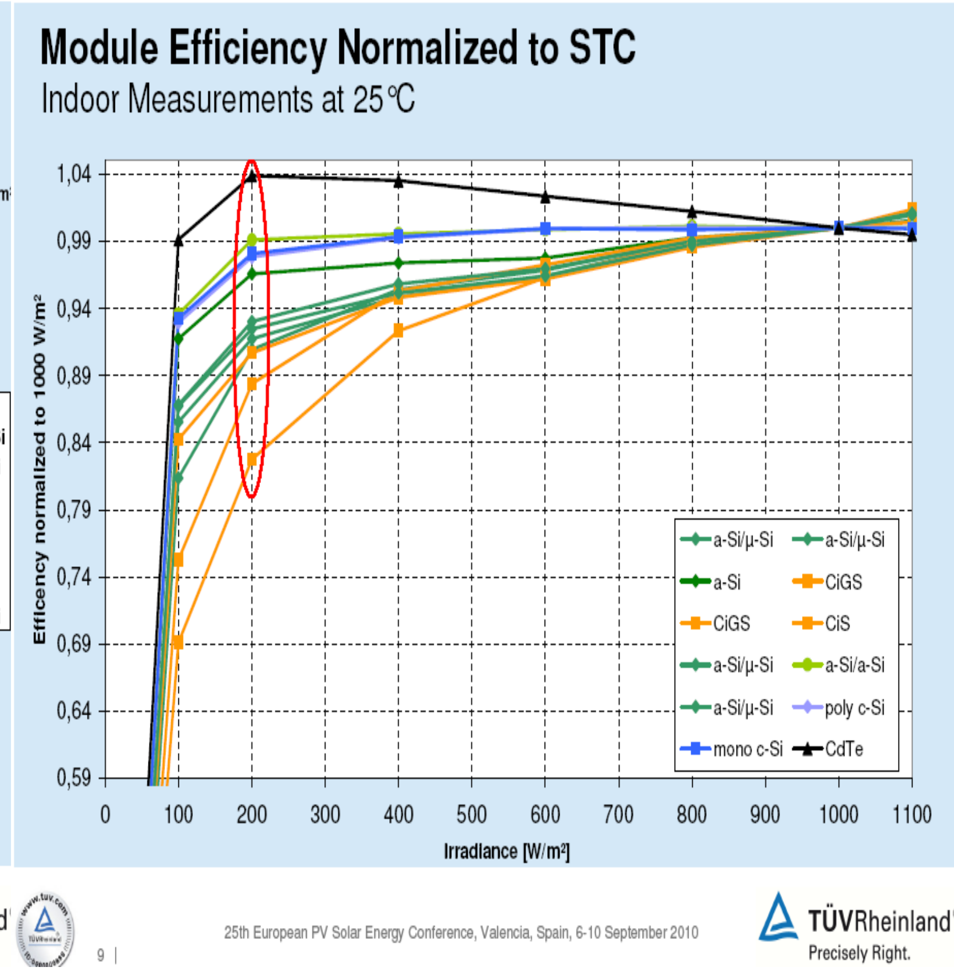
- Oerlikon Solar thin film module measured outdoors in Switzerland using IV sweep data
- Rsc (kOhm)
- [Rsc@200]/[Rsc@1000] may be 4 to 5x
- But thin film starts from a lower relative value

TUV indoor matrix measurements
Ulrike Jahn – Valencia world conference 2010

Gamma – vary with irradiance

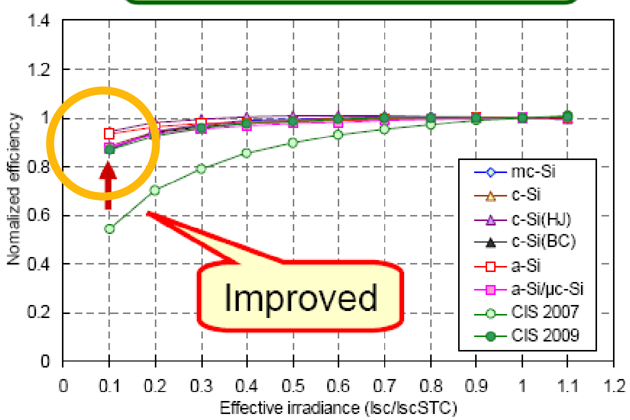


LLEC – mostly better than -8%

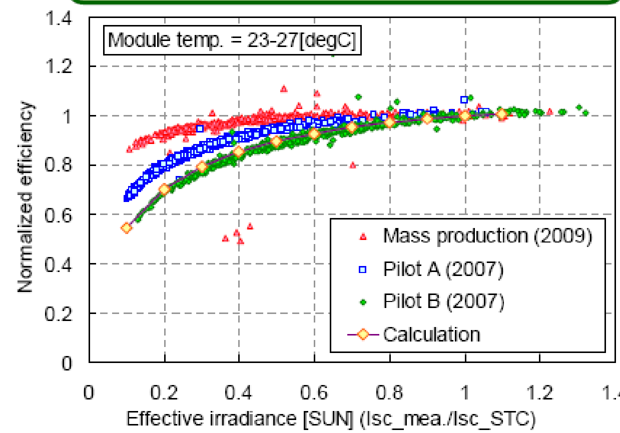


Low-light performance

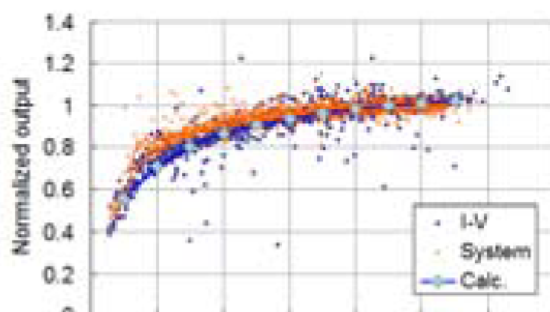
•Calculated results



•Outdoor results of CIS



•System



Impact for the P.R
2009 - 1%
2007 A - 4%
2007 B - 8%
*Simulation

Low-light performances have improved in latest modules

Research on photovoltaic power generation systems | Tokyo Institute of Technology

2010/9/10 Y.U 20

What else differentiates PV technologies and by how much ?

Independent tests of kWh/kWp < ±5%

Efficiency (5-20%) **~ 4:1**	Power rating tolerance **+3/-0% to +0/-10%**	Max. module size m² **>2:1**
Wp/kg (4-22) ~ 6:1	Lifetime @ 80% Pmax **5 10 20 25 30 40+ y**	Certification CE/IEC/TUV/UL **Y/N**?
m²/1000kg (60-250) **~ 4:1**	Initial degradation **(~2% vs. up to 30%)**	Max System Voltage **~ 500-1000 V**
Cost $/Wp **~ 1.5:1 variable**	Steady degradation **(~-0.5 to -1%/y ?)**	Aesthetics (subjective) **blue ☐ brown |||**
Wp, Imax or Vmax/mod **>> 5%**	Pmax T coefficient %/K **~ 2:1**	Tracker (higher eff.)? **Y/N**

€/kWh site dependent **±???**

Conclusions

- Simulation programs still use different values for LLEC and gamma than from manufacturers' data sheets (measured to IEC 61215/61646 and EN 50380).
- These anomalies cause up to 15% error in predicted kWh/kWp
- kWh/kWp does not differentiate the technologies well
- Rsc(Irradiance) seems very important in determining the LLEC behaviour of the PV – it's not on the specsheets
- Models need to check every stage, not just kWh/kWp/year
- Modelling one module at a site might not be able to be generalised to other modules at different locations

Thank you for your attention !

All SRCL papers : www.steveransome.com

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Spare slides