kWh/kWp : Comparing modelling, claims and measurements

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Introduction

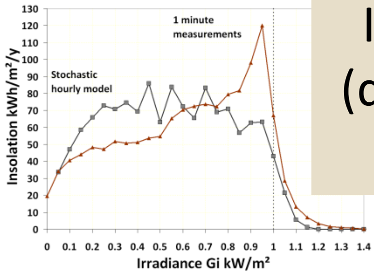
- 19 years with BP Solar : indoor and outdoor measurements, modelling and simulation programs
- For the last two years as an independent PV consultant working with clients worldwide
- Studying kWh/kWp on many PV technologies since 1998

What are the main differences between kWh/kWp simulations and measurements ?

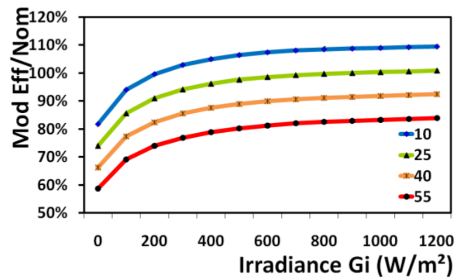
- Some manufacturers have claimed up to 30% higher kWh/kWp than their competitors
- Several recent independent tests show mostly < ±5% between different technologies and manufacturers – dominated by [Pmax ACTUAL/Pmax NOMINAL]

- 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



Insolation vs. irradiance (depends on frequency of measurement)



Model of Efficiency vs. irradiance and module temperature

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.

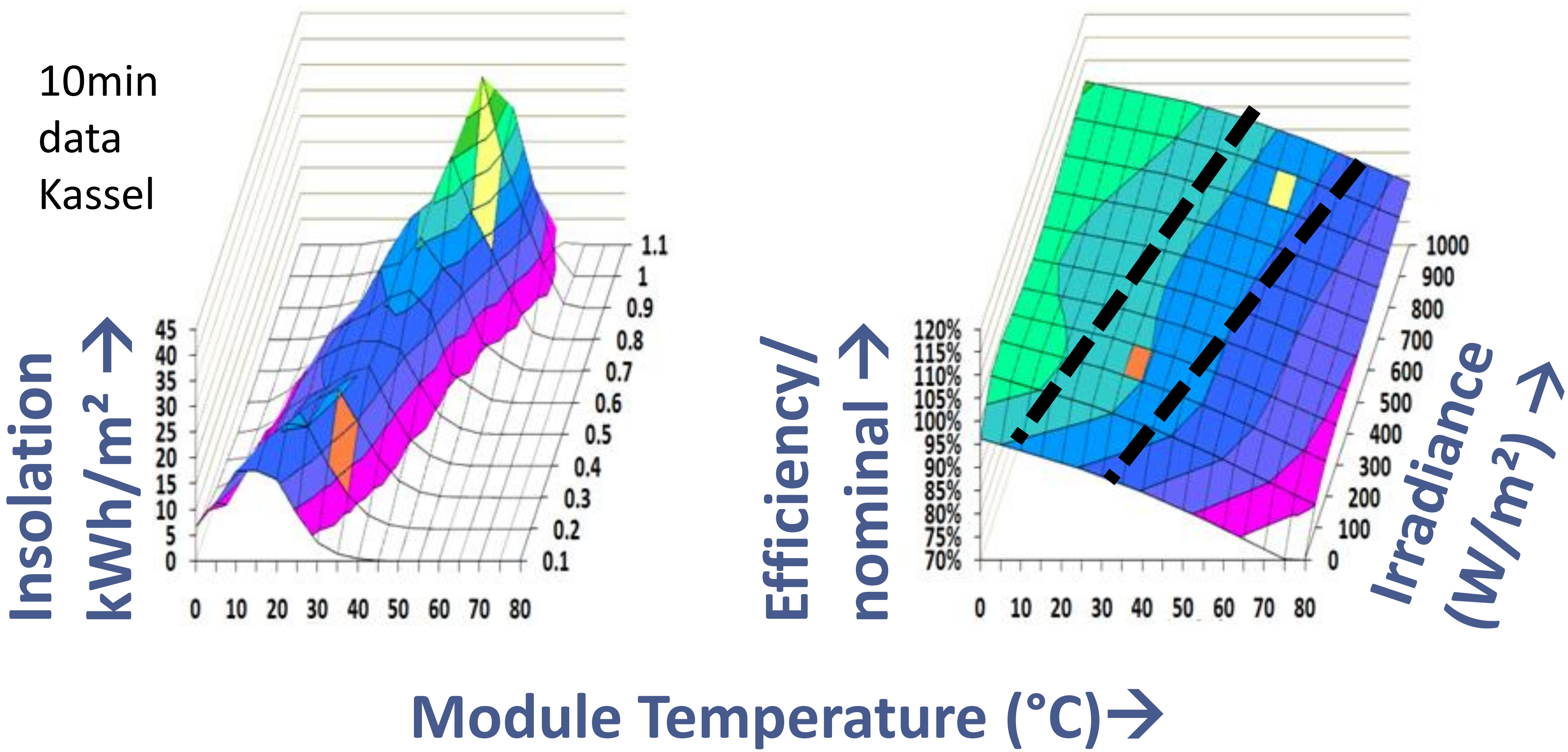
4) DC losses : Dirt, Mismatch, Shading etc

5) AC Losses : Vmp tracking Inverter efficiency, clipping etc

User inputs
e.g. dirt, Pmax/Pnominal

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

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



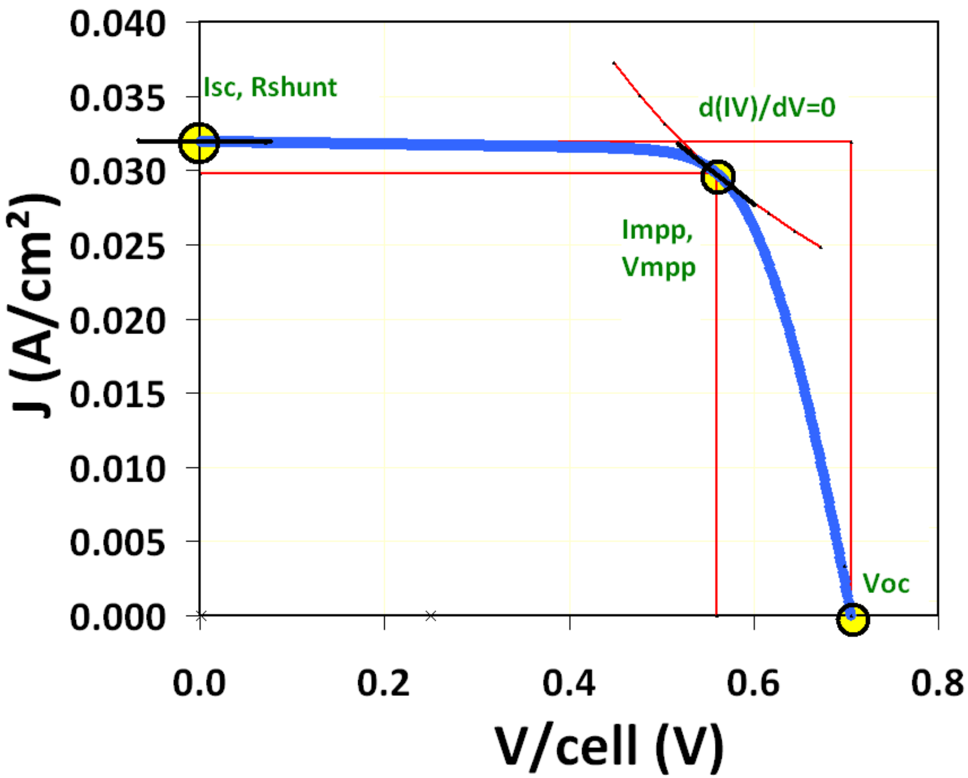
A frequent statement : "My simulation program gives approximate values of kWh/kWp therefore it is validated"

- 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"

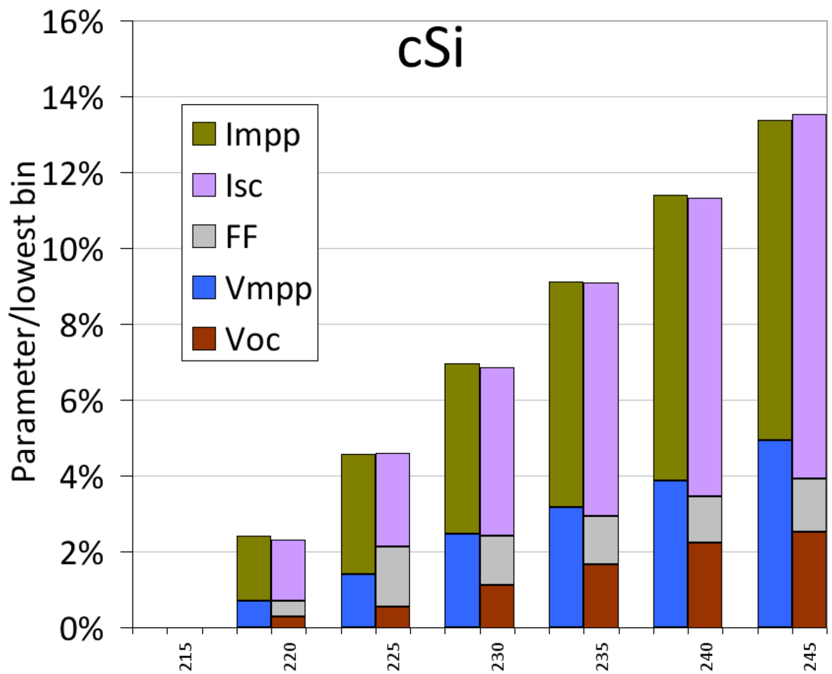


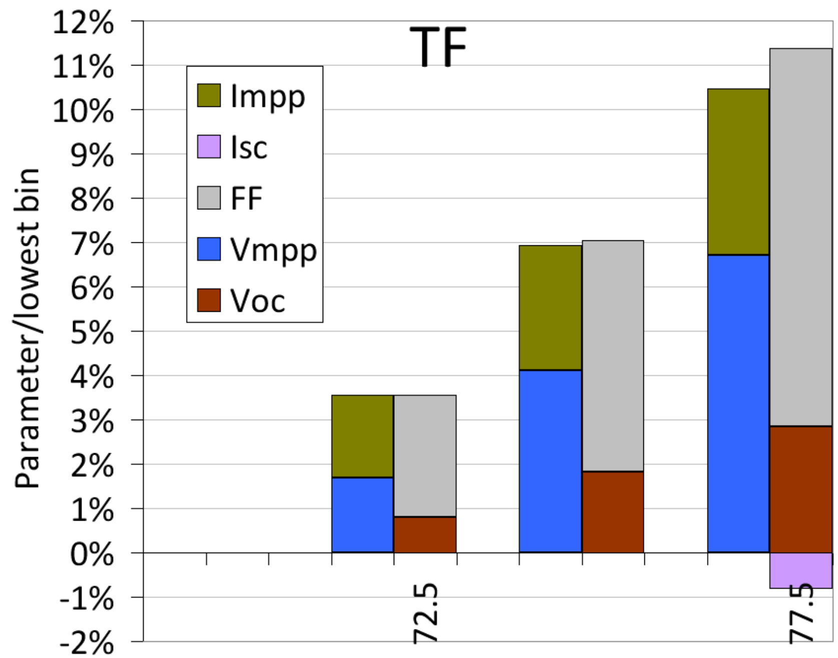
- Usually fitted to manufacturers' data sheets or a tested module
- 1 diode model is not a perfect fit to c-Si or thin film
- Problems fitting c-Si with high Rsh
- Diode theory is used to predict temperature dependence (rather than use IEC 61215 / 61646 standard measurements)
- Equation also predicts 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)





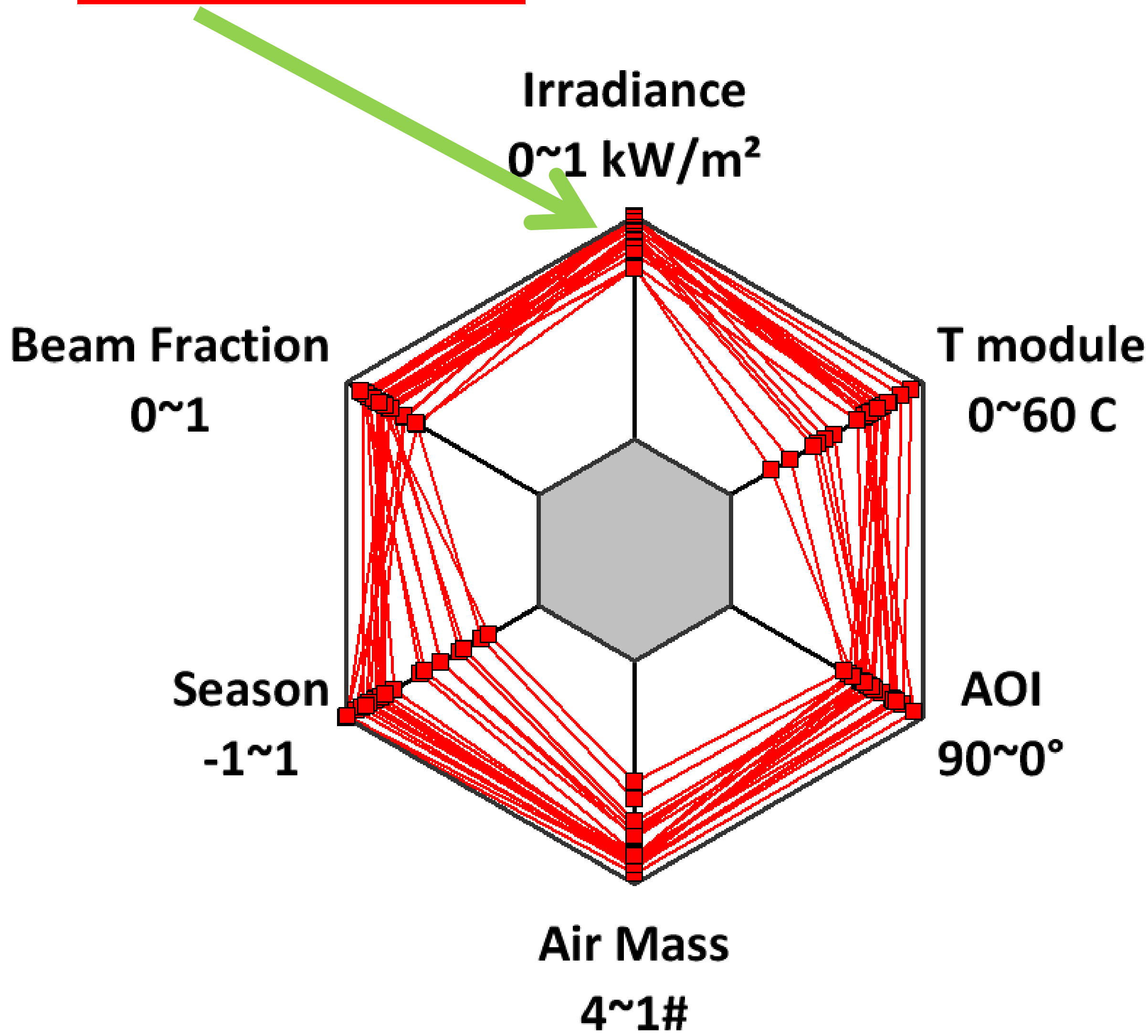
Pmax = Impp*Vmpp ; Pmax = Isc*Voc*FF

kWh/kWp modelling error depends on <u>all</u> the uncertainties in measurements

Calibrated reference module Pmax W	>±2.5%	for c-Si, less accurate for thin films
Flash tester W	x% (1%?)	Repeatability error (Not perfect AM1.5 spectrum, capacitance/timing issues)
LID/Pmax degradation allowance %	-1 to -3% -10 to -35%	B doped p type c-Si greater for thin films
Pmax bin width W	~±2.5% ~±2.5%	e.g. 200<Pmax<210W or 100<Pmax<105W
Insolation kWh/m²	~±2-3% ~±1.7-7% ???	pyranometer reference cell Satellite data, Tilted plane algorithm, site interpolation
Module temperature	~3°C/sun ~0.5 to 1.5%	$(T_{JUNCTION}-T_{BACK})$ % Pmax error (assuming gamma is -0.15 to -0.5%)
Yearly insolation	~±4%/y	random variations, more effects such as el Niño etc.
Micro climate	?	<u>Can't linearly interpolate</u> near coasts, mountains etc.
Shading loss	?	Varying tree cover, new buildings, self shading
Dirt loss	?	Site dependent daily rise, falls after clean or ~>5mm rain
Snow cover	?	Winter when low daily insolation – small effect ?
Mounting C	?	High temperatures from close mounting, BIPV etc.

Correlation of meteorological parameters

High Irradiance

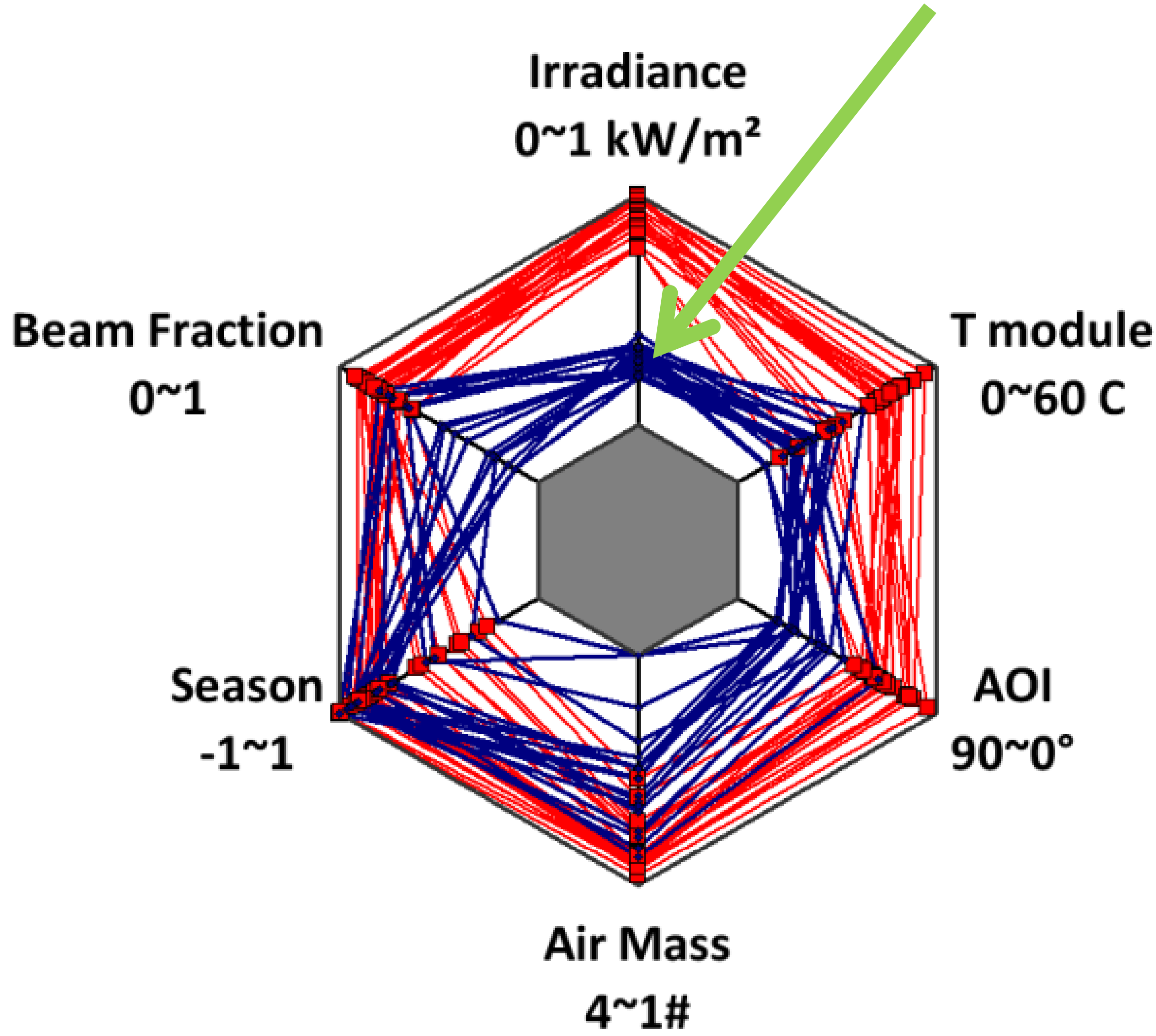


High Irradiance correlates with

- High Temperatures
- Low Angle of incidence
- Low Air Mass
- Summer
- High Beam Fraction

Correlation of meteorological parameters

High Irradiance vs. Low Irradiance



High Irradiance

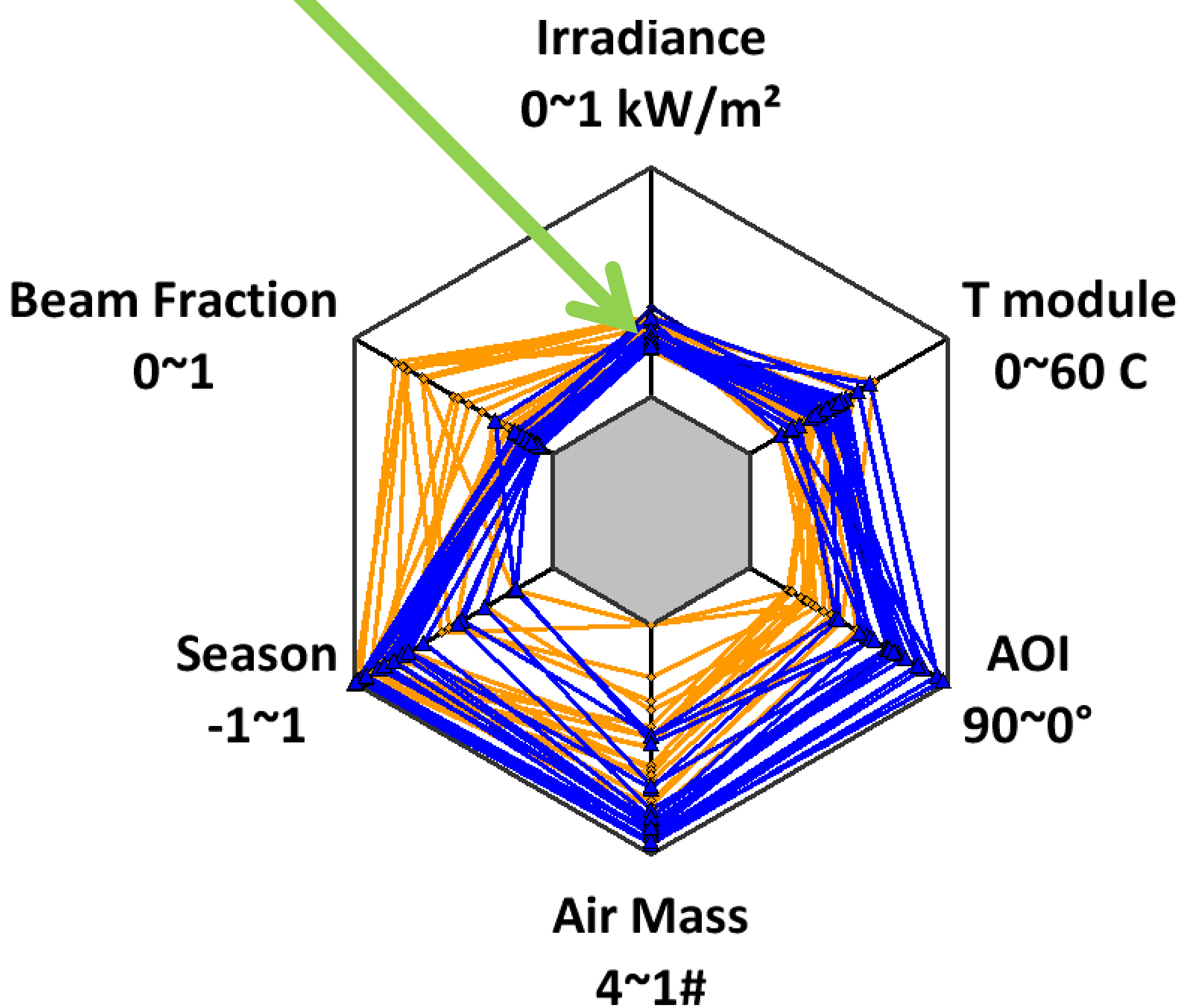
correlates with

- **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

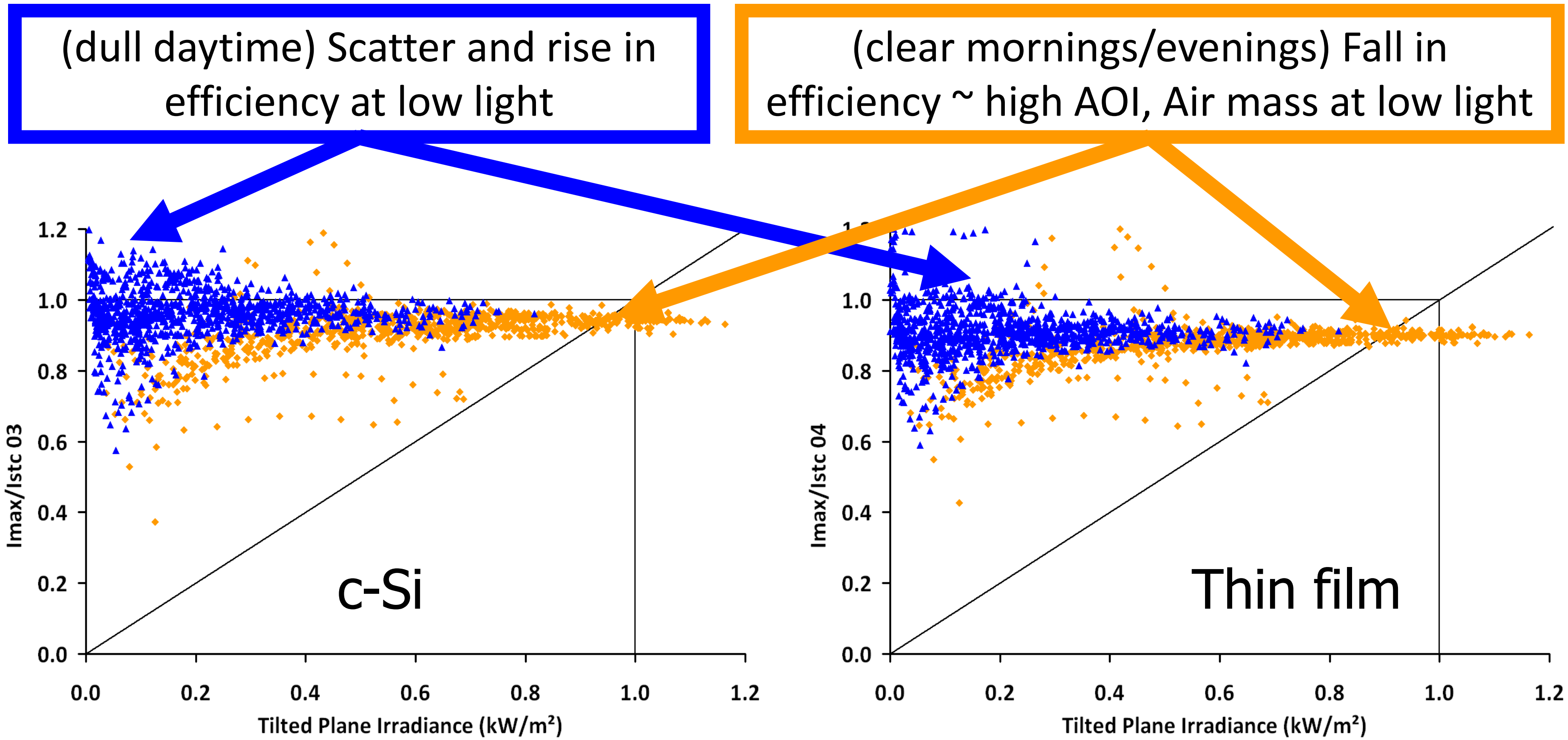
Low Clearness

→dull daytime

→ Lower angle of incidence and overcast sky

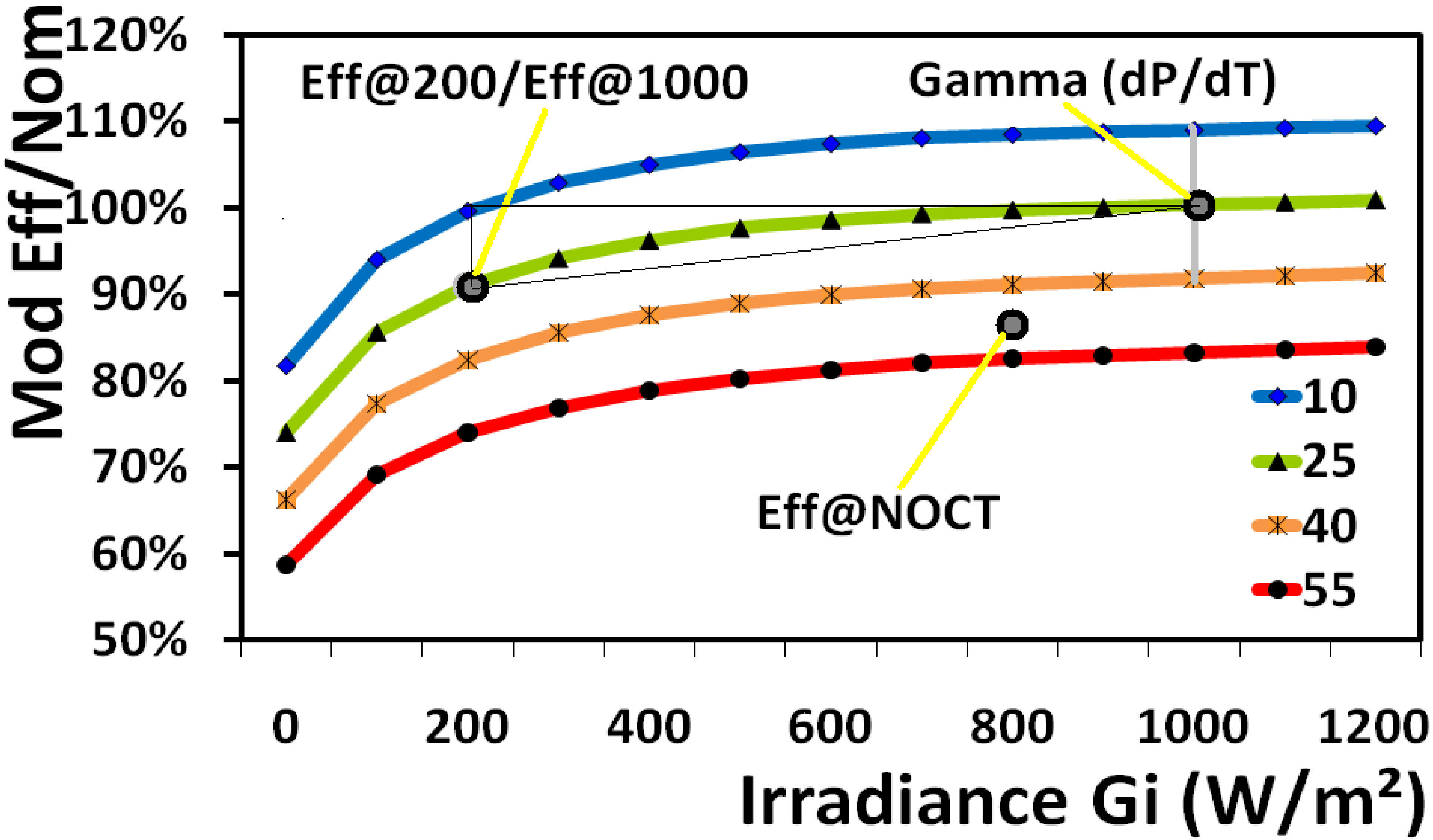
Measured outdoor low light level efficiency will be a site dependent mix of these two conditions

Measured efficiency vs. light level for Low and High clearness conditions (IWES Kassel)



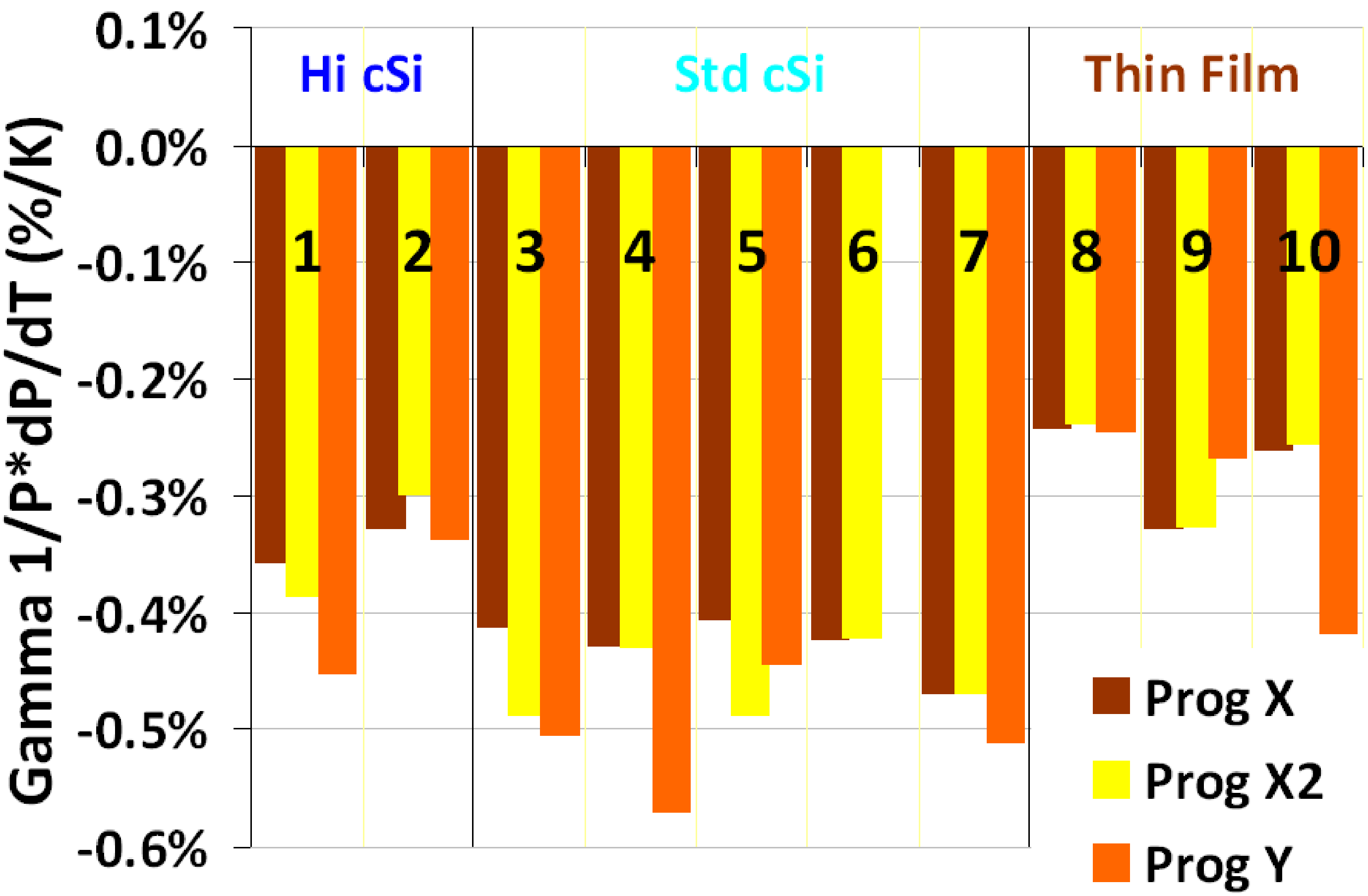
- Low light value depends on sensor spectral response
- Averaged low light value depends on overcast: clear ratio (site specific)

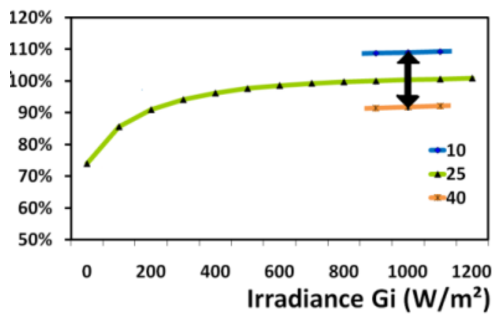
Calculating IEC standard values from PV efficiency/nominal vs. irradiance and module temperature :



Comparing power temperature coefficients (Gamma = 1/Pmax*dPmax/dT)

Simulation programs

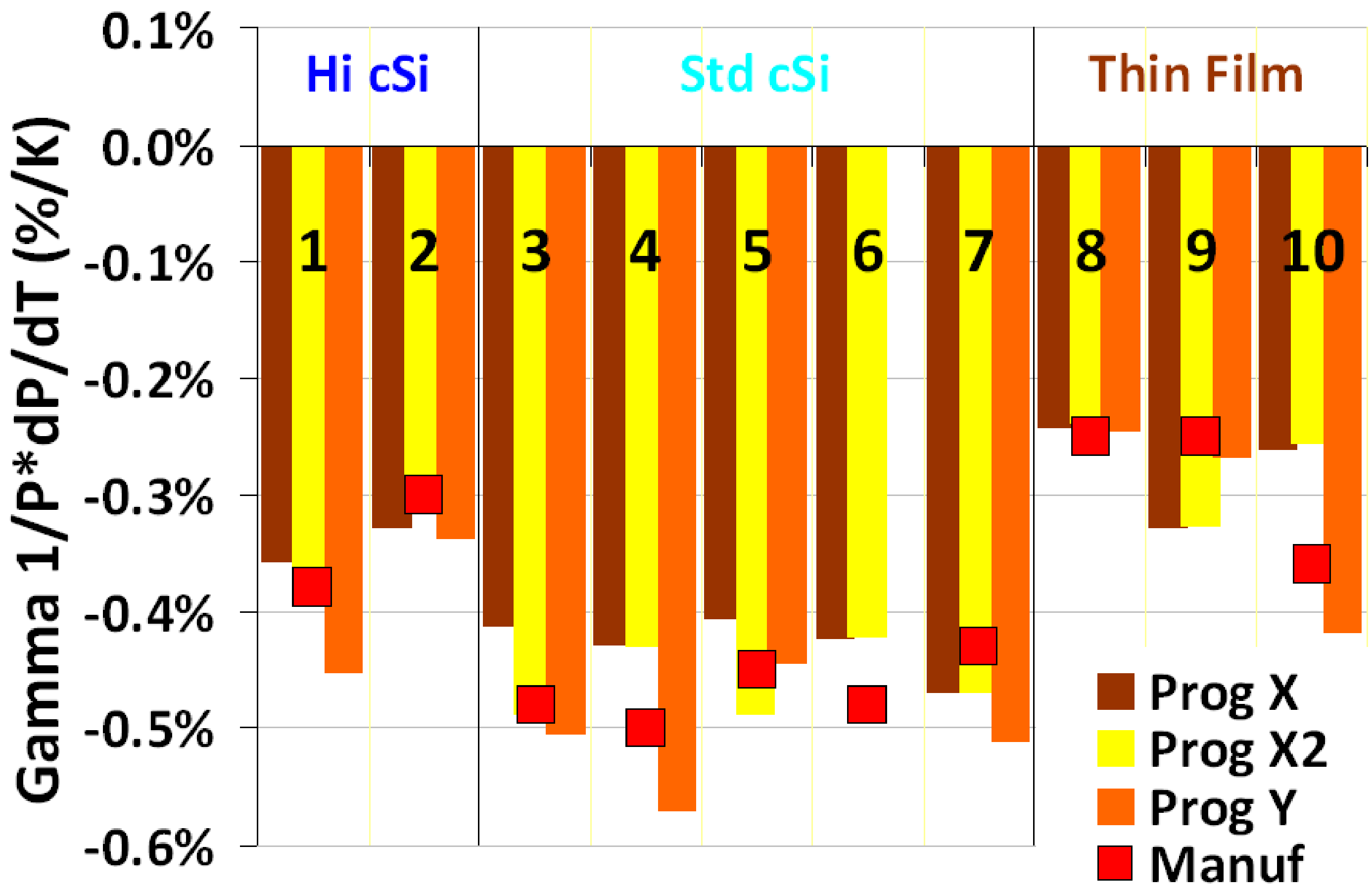


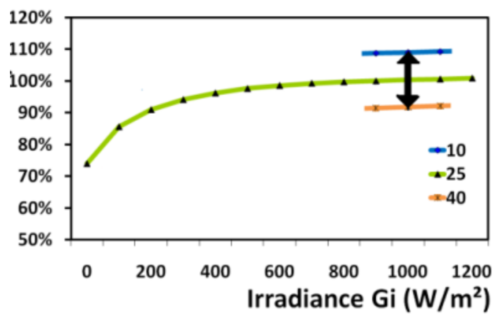


Disagreement between program version values

Comparing power temperature coefficients (Gamma = 1/Pmax*dPmax/dT)

Simulation programs vs. Manufacturer datasheet

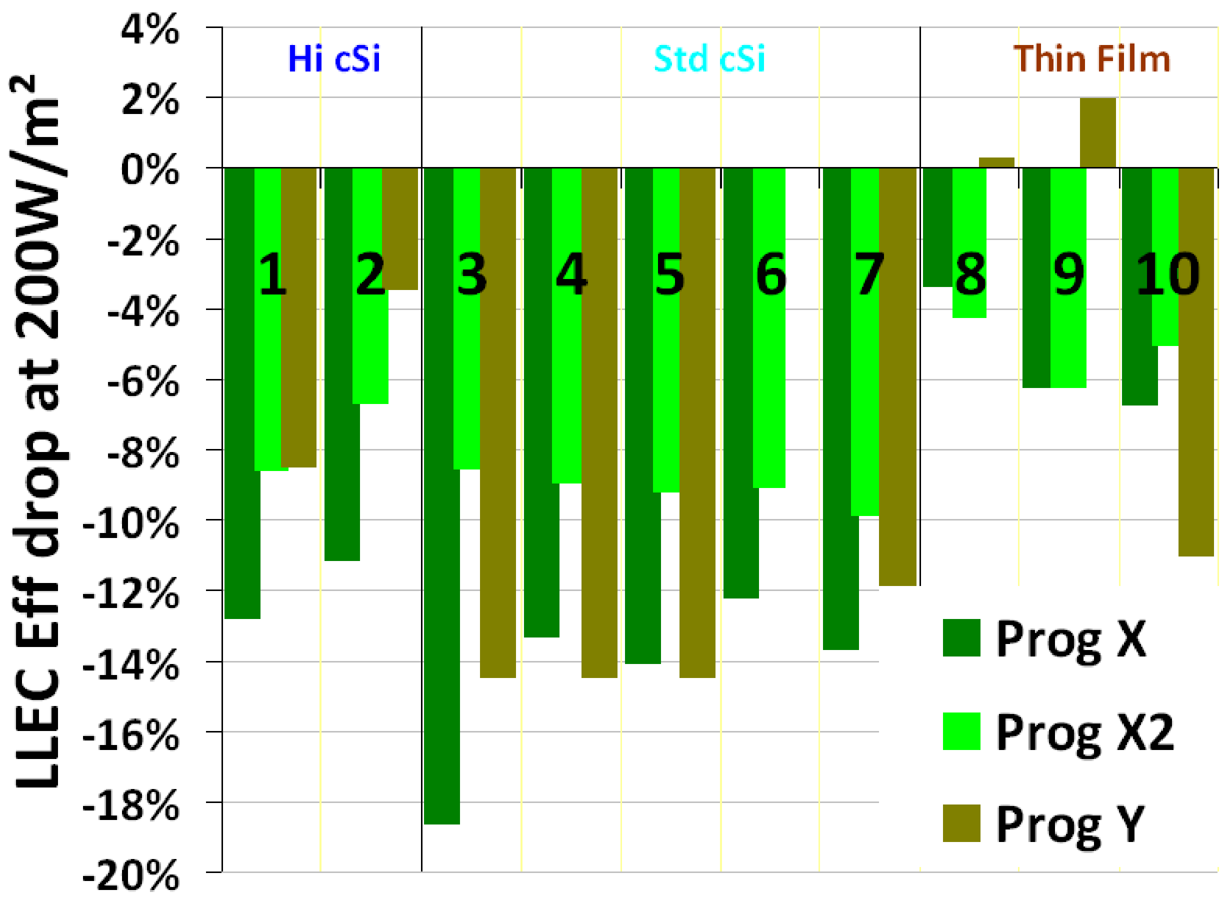


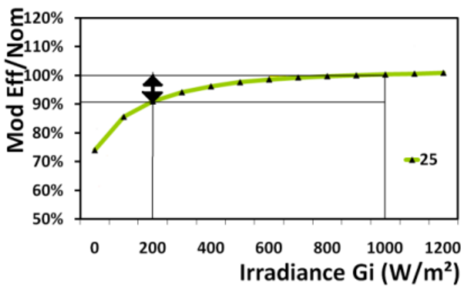


Also disagreement with manufacturer datasheet

Comparing Low Light efficiency changes (LLEC = Eff@200/Eff@1000-1)

Simulation programs





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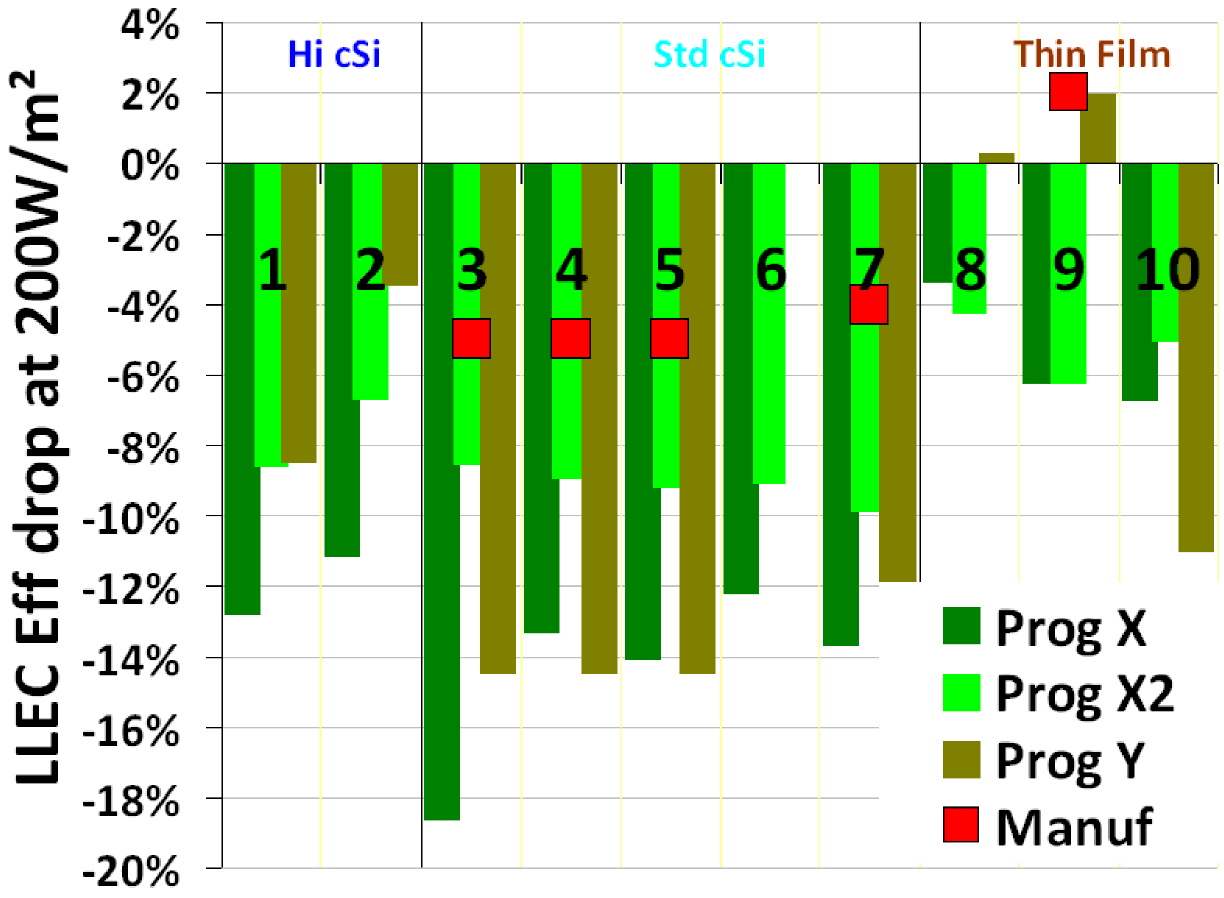
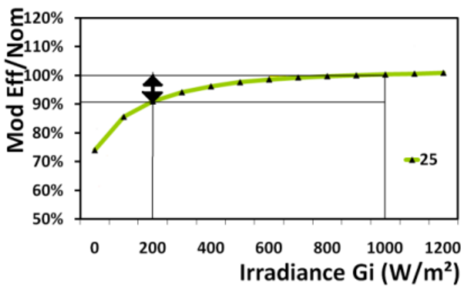
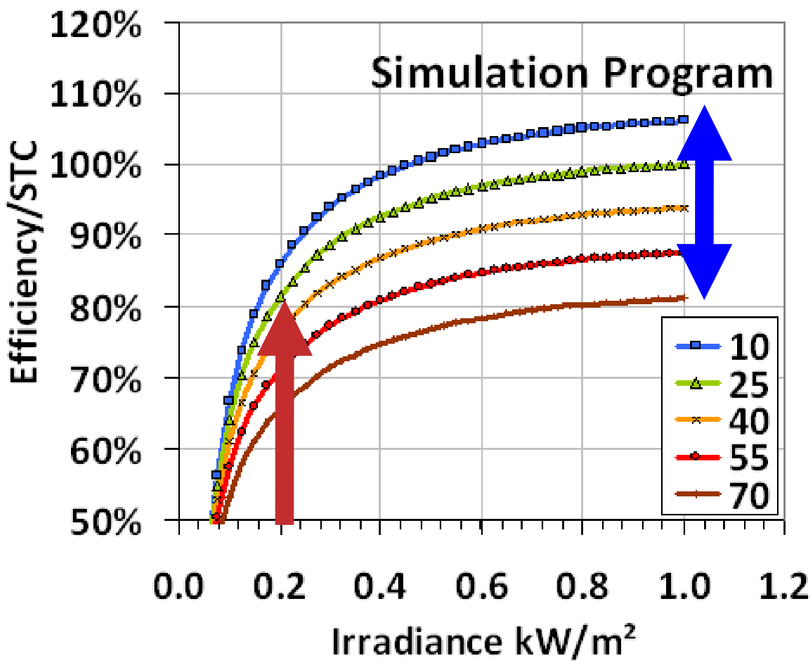


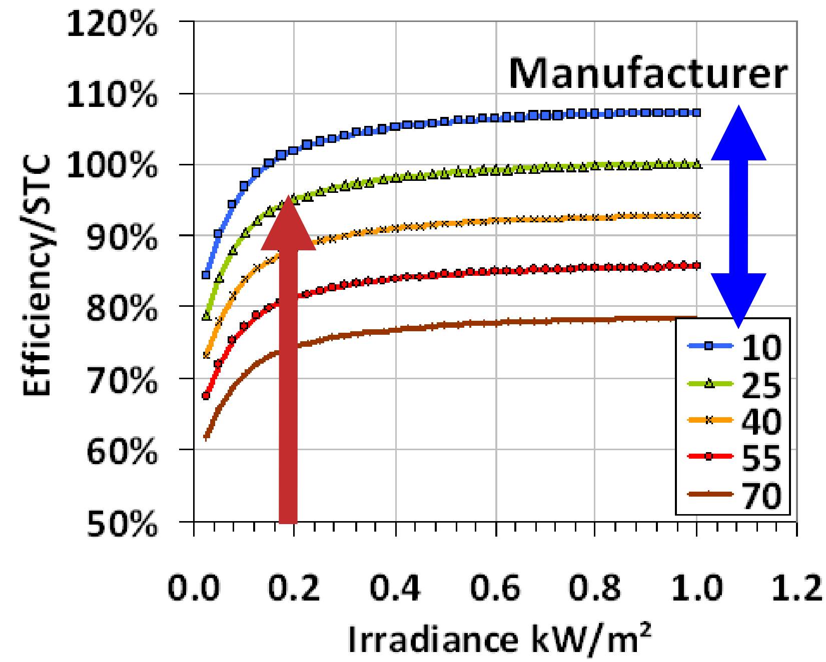


Also disagreement with manufacturer datasheet

Correcting simulation program efficiency to manufacturer's datasheet : c-Si #3

Gamma (1/Pmax * dPmax/dT)
-0.42%/K → -0.48%/K



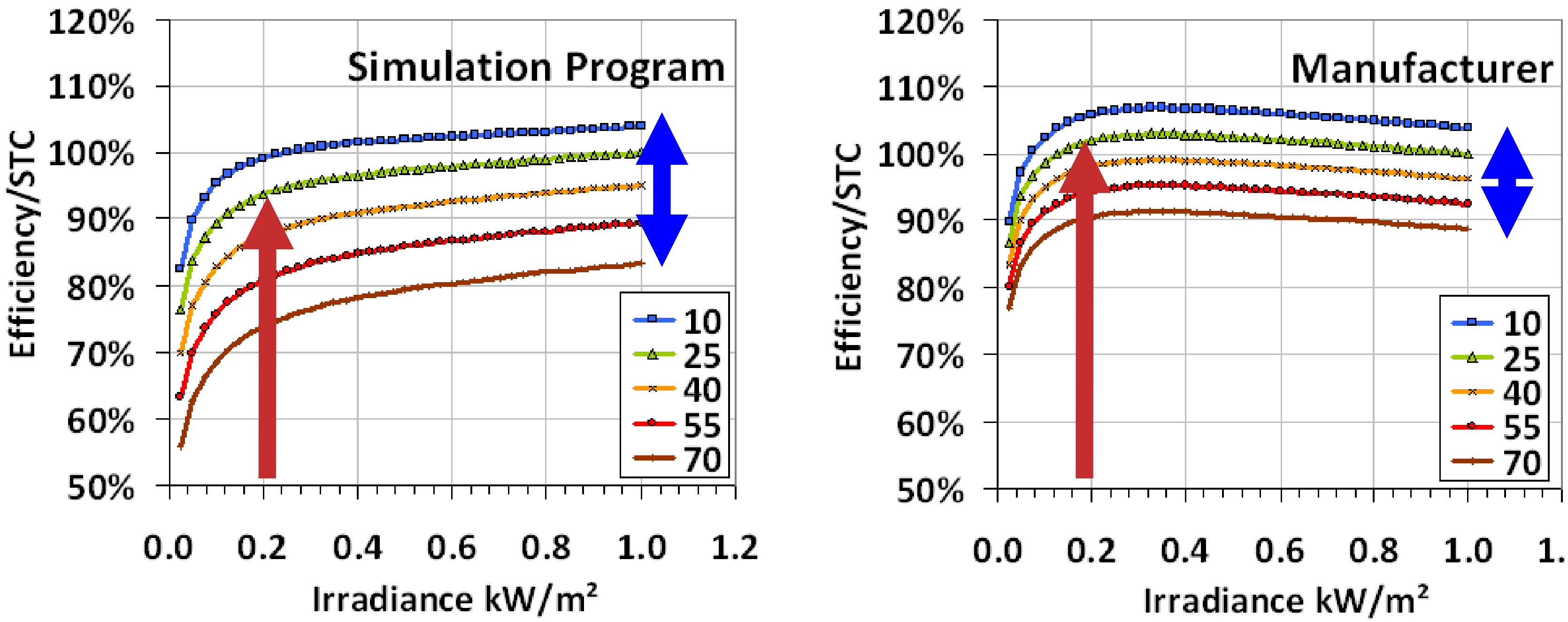


Low light efficiency change
82% → 95%

•High Rshunt gives high efficiency down to low light levels for c-Si

Correcting simulation program efficiency to manufacturer's datasheet : Thin film #9

Gamma (dPmax/dTemperature)
-0.32%/K → -0.25%/K



Low light efficiency change
94% → 102%

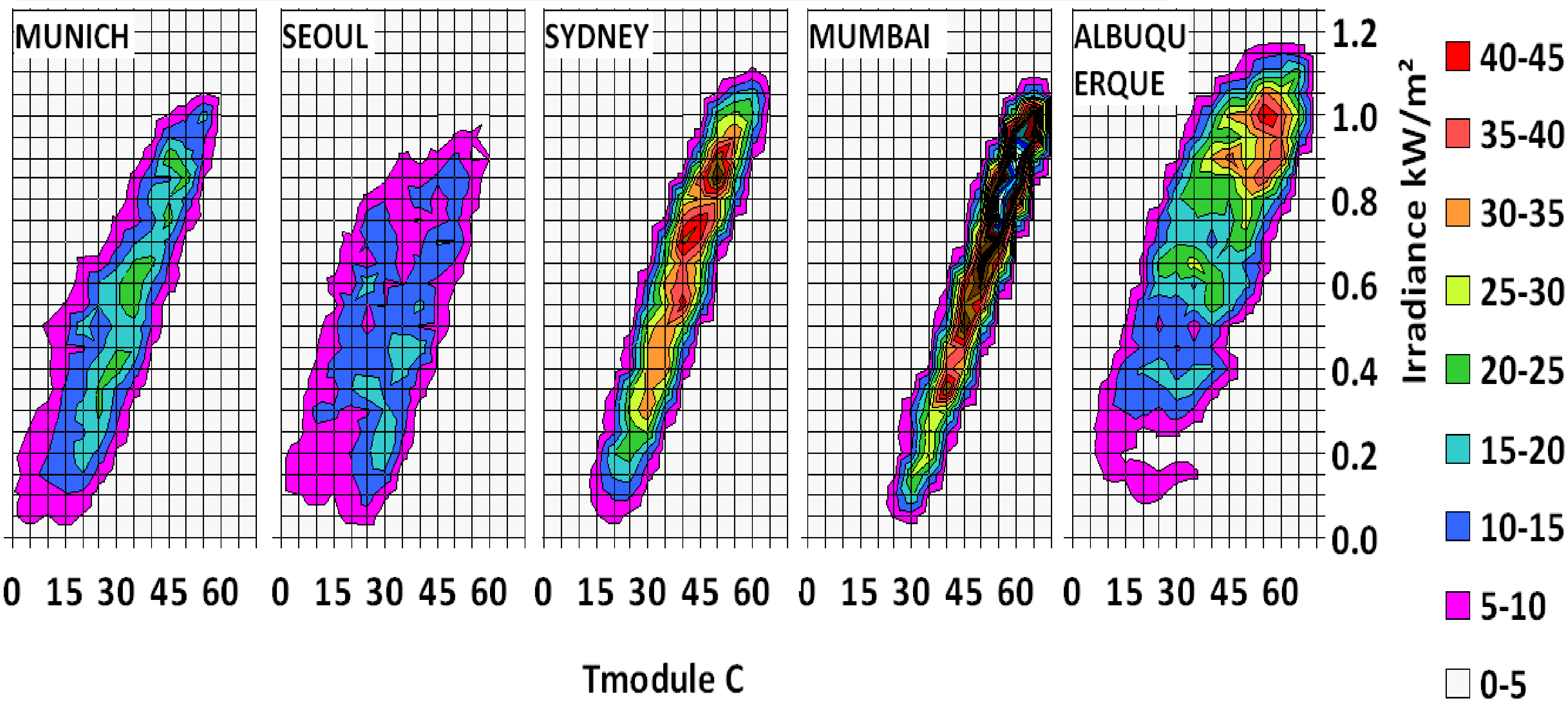
High Rseries causes efficiency to fall at high light levels due to I^2R loss

Checking kWh/kWp simulation errors at 5 sites worldwide

	Site name, Country Insolation, temperature	Latitude °	POA Insolation kWh/m²	Weighted Tambient °C
1	Munich, DE →Dull, cool	48°N	1345 *	14.3 *
2	Albuquerque NM, USA →Very bright, warm	35°N	2336 ***	18.7 **
3	Mumbai, IN →Bright, Hot	19°N	1988 **	30.3 ***
4	Seoul, KO →Dull, cool	38°N	1299 *	15.4 *
5	Sydney, AU →Bright, warm	34°S	1797 **	20.8 **

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

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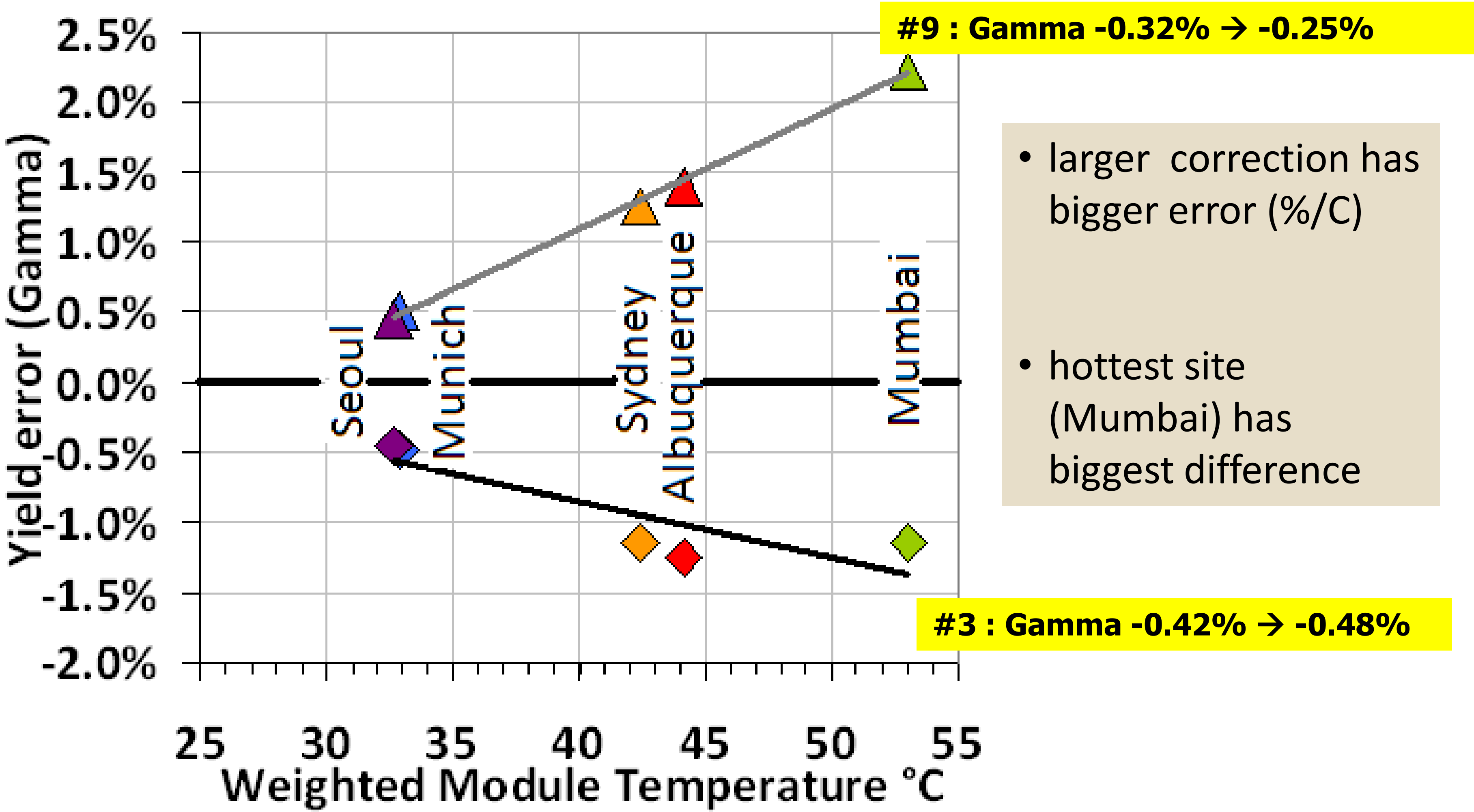
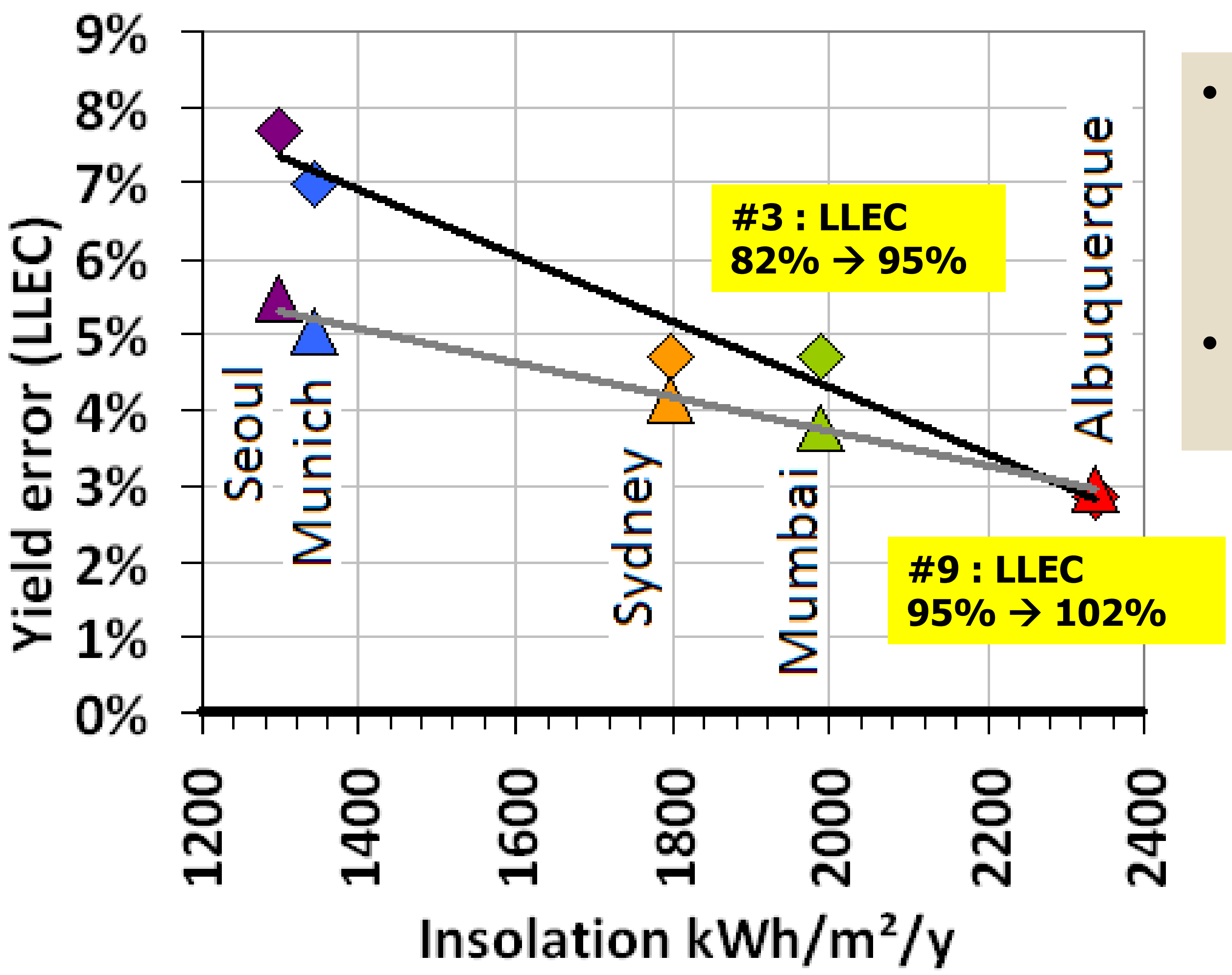


- larger correction has bigger error (%/C)
- hottest site (Mumbai) has biggest difference

Simulation program modelled kWh/kWp vs. Low light efficiency change error



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

Conclusions

Measured kWh/kWp < ~±5% from several independent studies, dominated by [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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