Errors and uncertainties in kWh/kWp modelling, predictions and measurements

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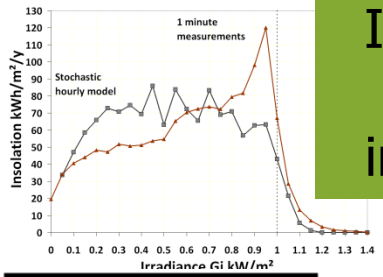
What are the differences between kWh/kWp simulations and measurements ?

- **Some manufacturers have claimed up to 30% higher kWh/kWp than their competitors**
- **Recent independent tests show mostly < ±5% between different technologies and manufacturers**

- **Simulation programs often predict > 5% kWh/kWp difference (usually suggesting better for thin film)**

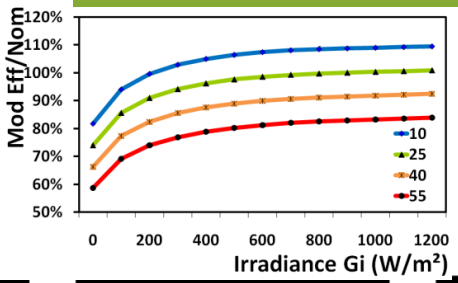
- **Discrepancies have been found in the assumptions made and algorithms used in some simulations**

Simulation program flow chart to calculate kWh/kWp



Insolation vs. irradiance

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.

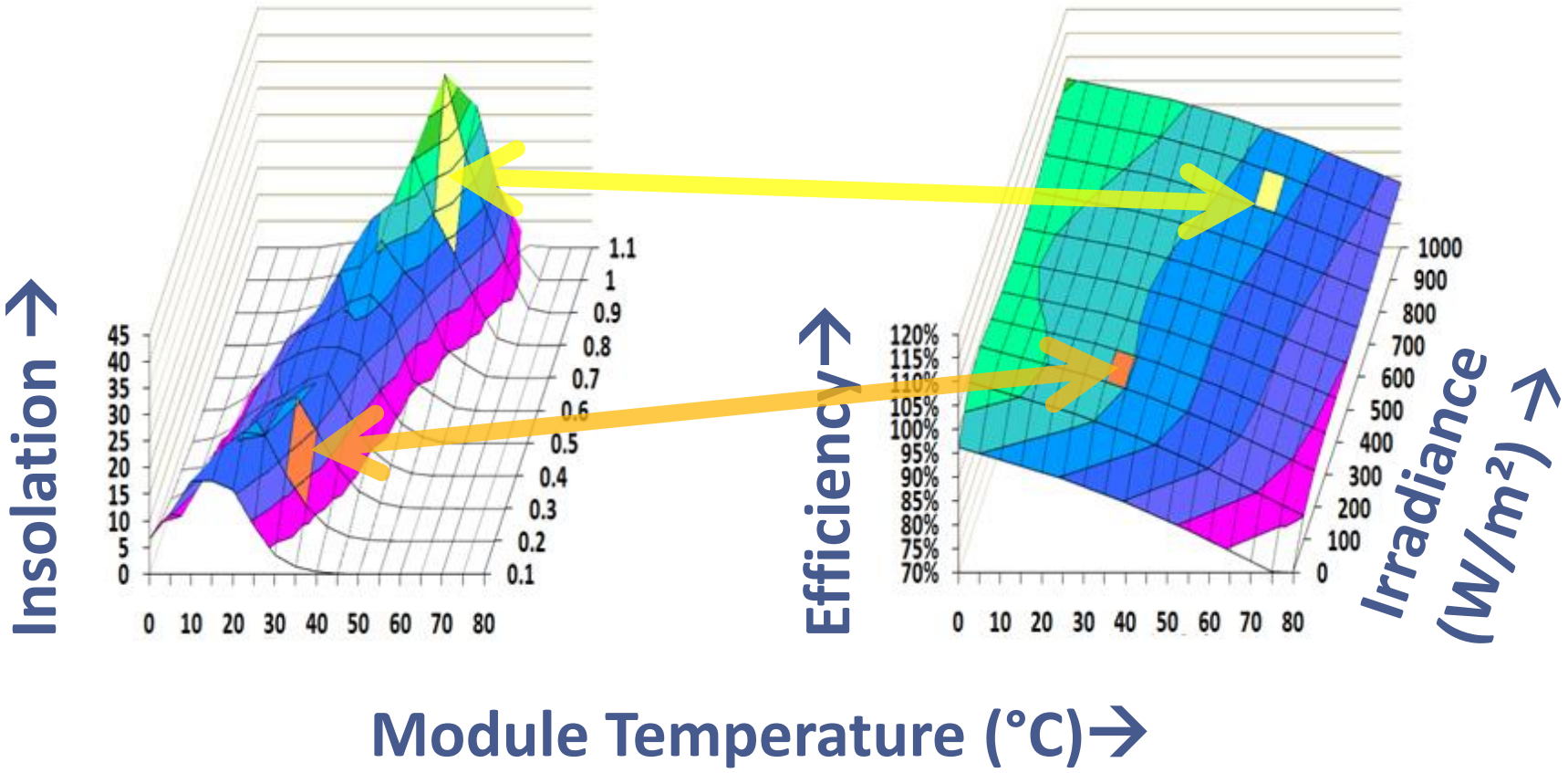
4) DC losses : Dirt, Mismatch, Shading etc

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

User input e.g. dirt. Pmax/Pnominal

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

kWh/kWp~$\Sigma_{Tmodule,Irradiance}$(Insolation*Efficiency)



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

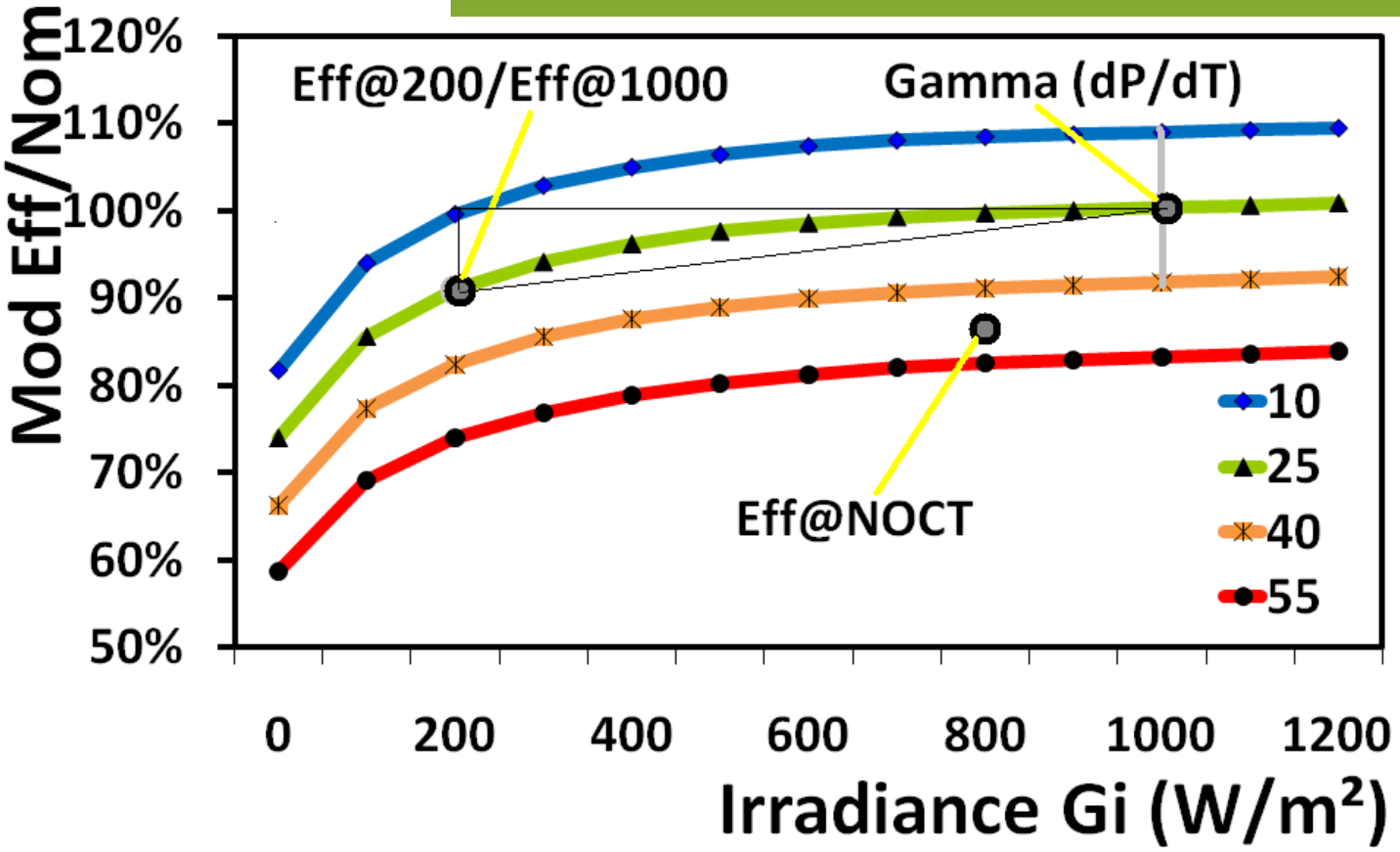
- **kWh/kWp depends on the product of >4 items**

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**
- **Every stage must be checked to be correct to validate a simulation, not just the kWh/kWp**

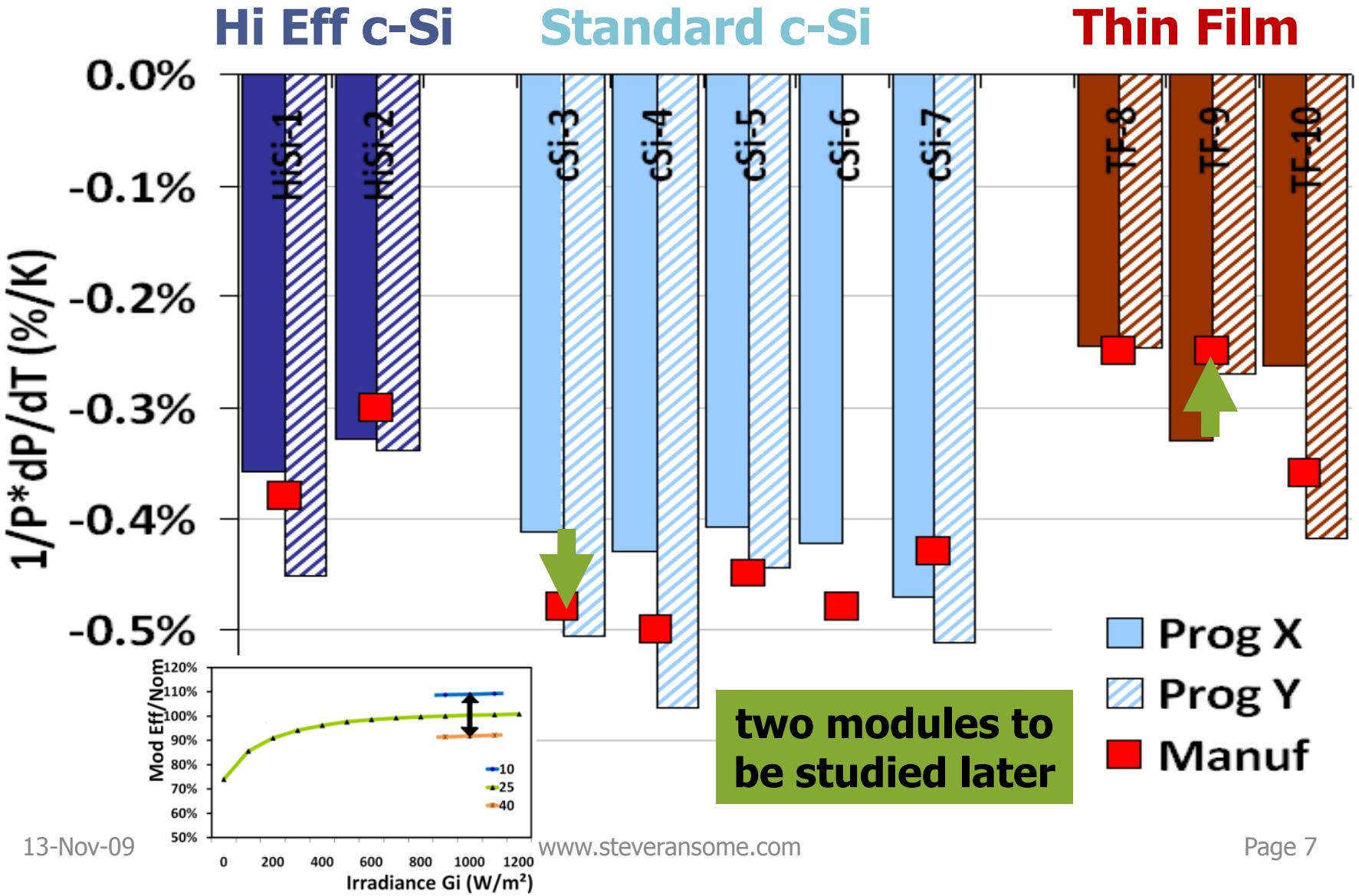
PV efficiency/nominal vs. irradiance and module temperature :

Simulation program values should match manufacturer data sheets !



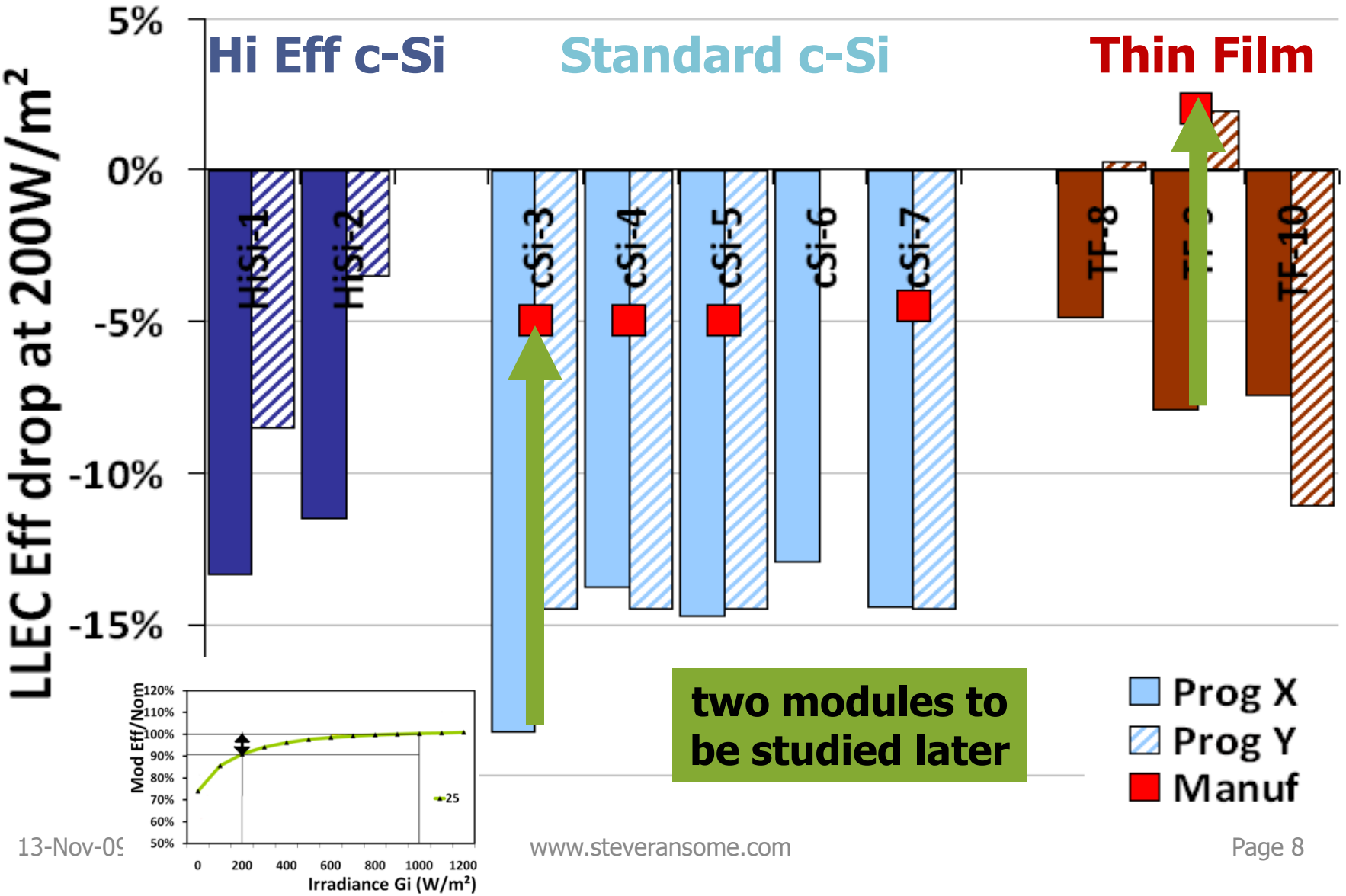
Comparing Gamma values (1/P*dP/dT)

Simulation programs vs Manufacturer data



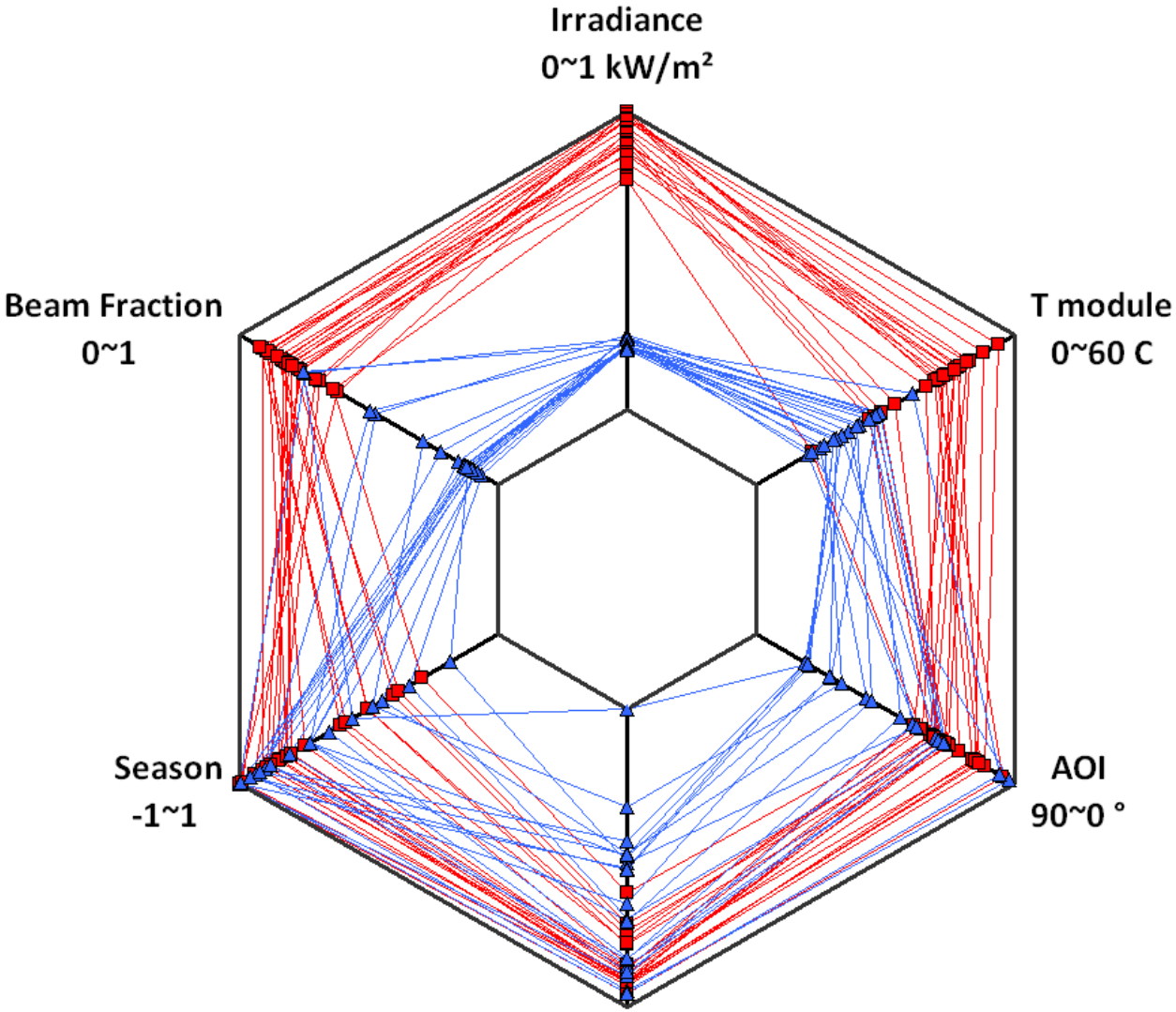
Comparing Low Light efficiency values

Simulation programs vs Manufacturer data



Correlation of meteorological parameters

High vs. Low Irradiance

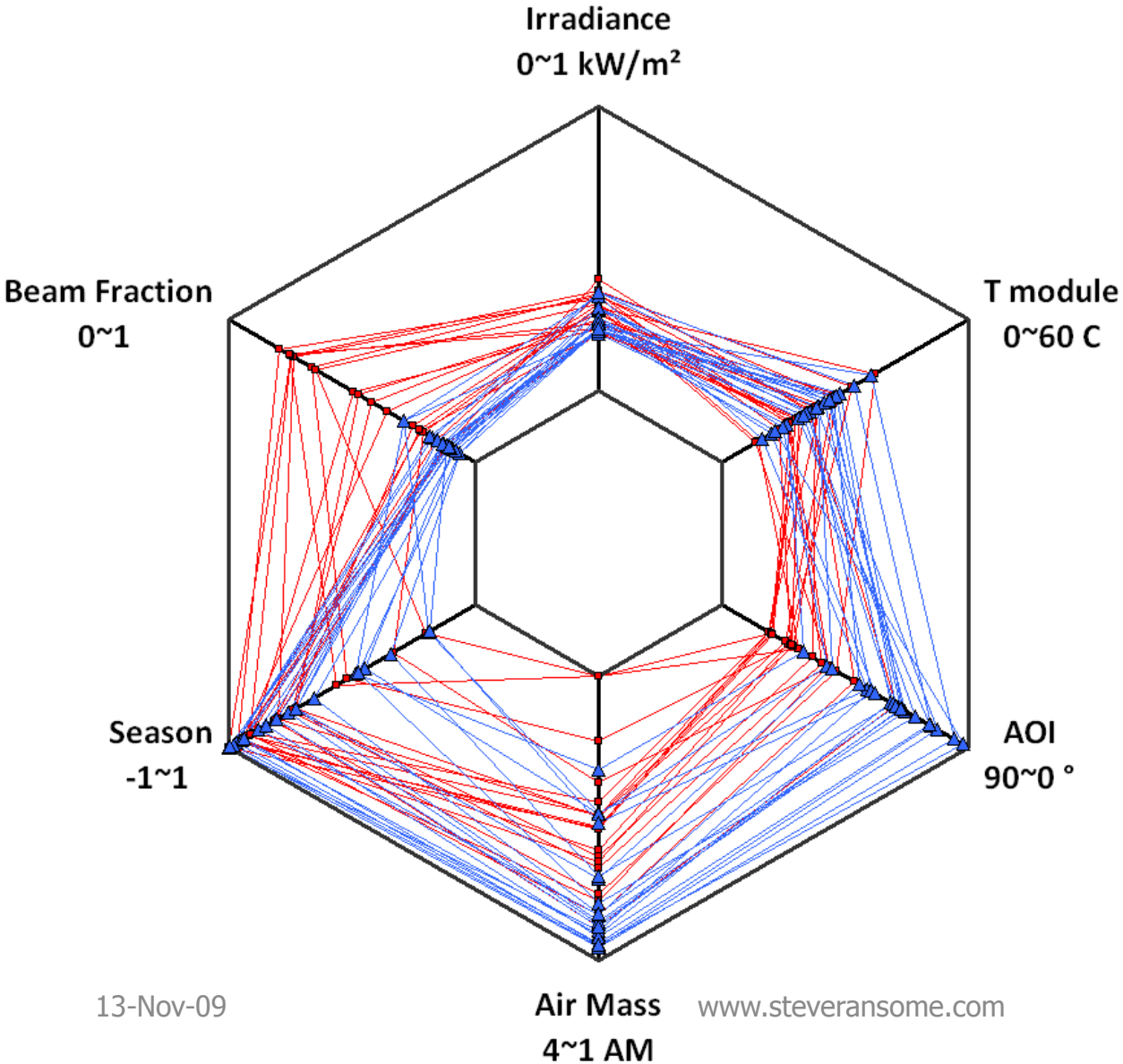


High Irradiance correlates with

- 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



Both are low Temperature

High Clearness

correlates with

- **High AOI**
- **High Air Mass**
- **High beam fraction**

→clear morning/evening

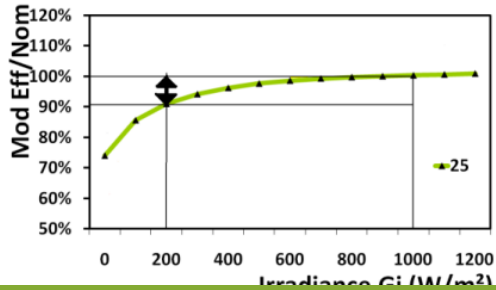
Low Clearness

correlates with

- **Low AOI**
- **Low Air Mass**
- **Low Beam Fraction**

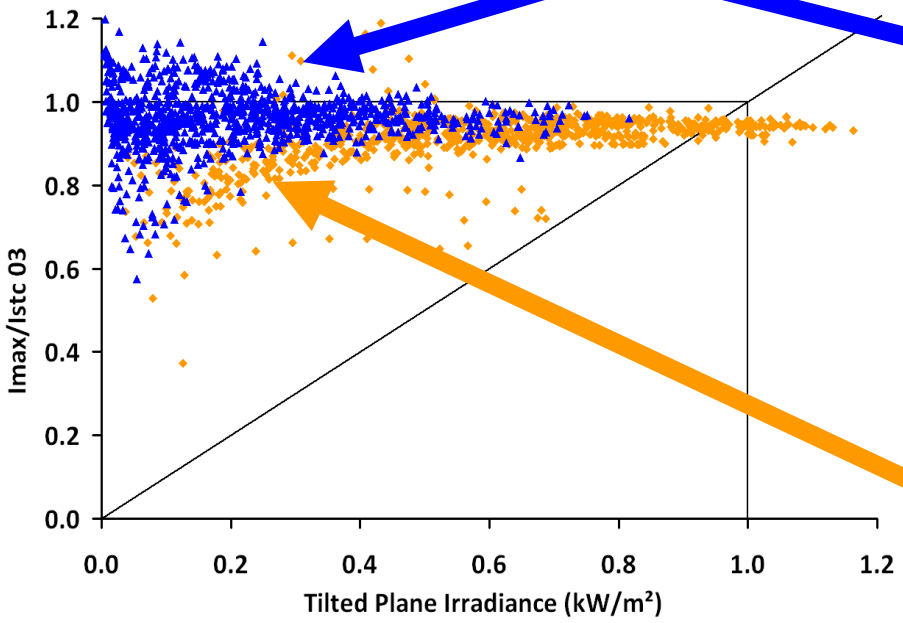
→dull daytime

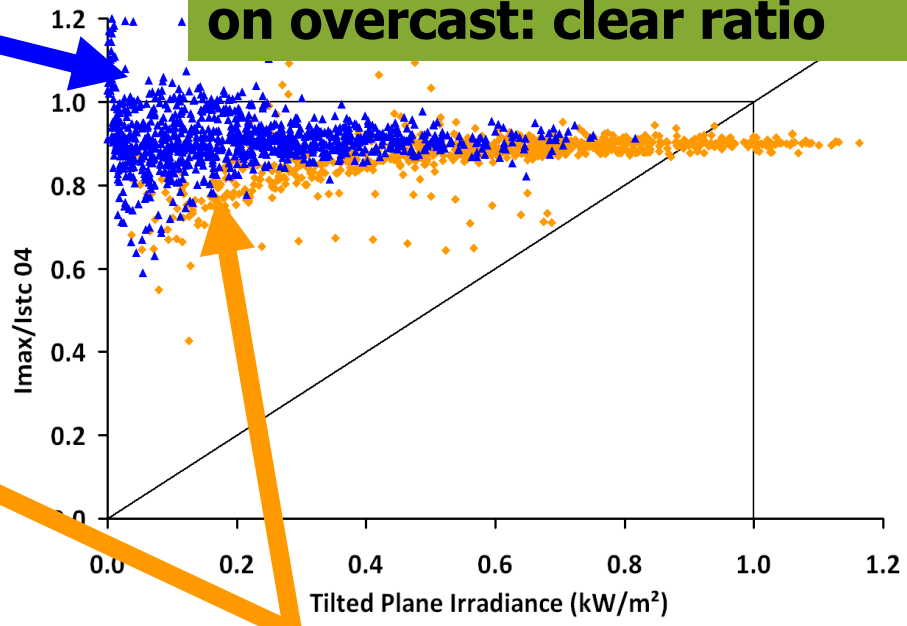
Measured low light current,efficiency differ under Overcast and Clear conditions



Scatter and rise in efficiency (dull daytime)

Averaged value depends on overcast: clear ratio



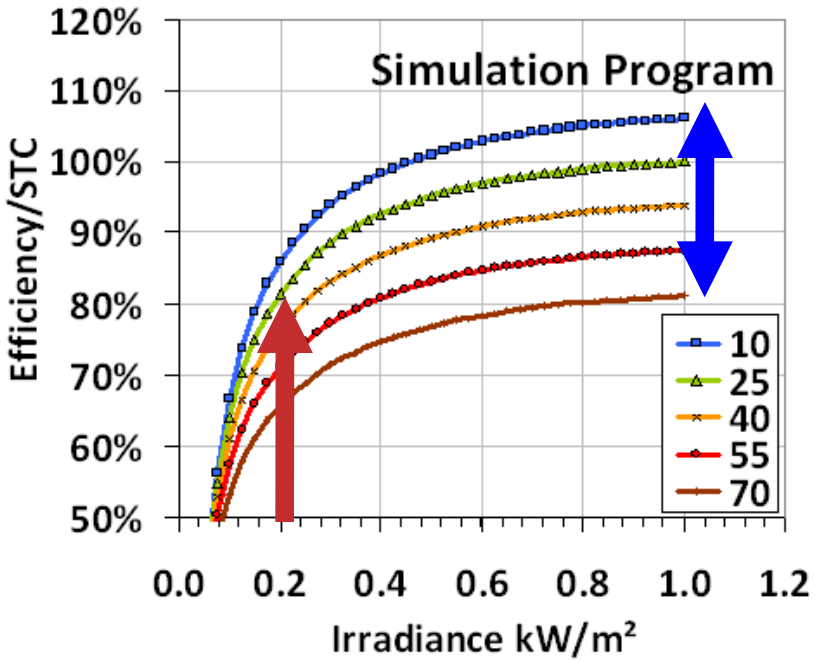


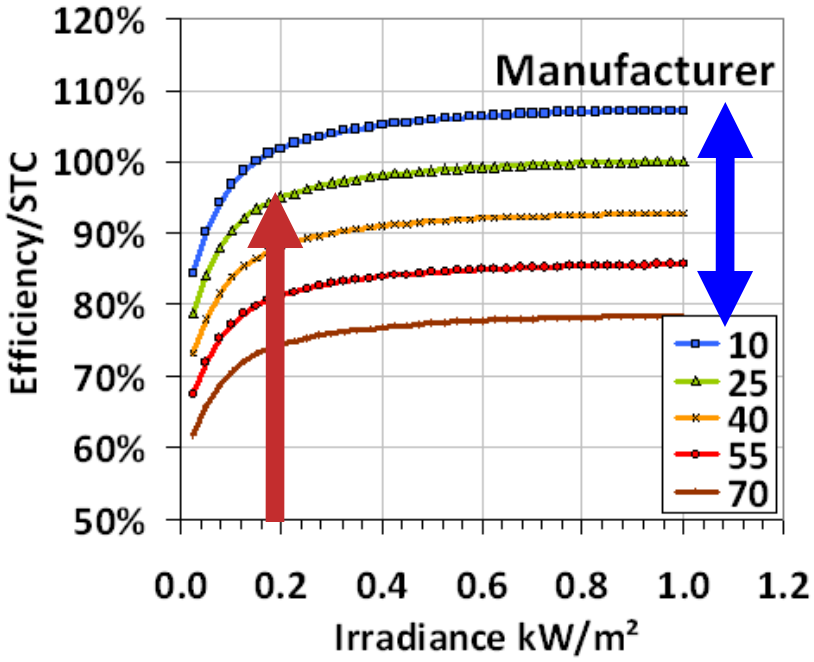
Low light depends on sensor type

Fall in efficiency ~ high AOI, Air mass (clear mornings/evenings)

Correcting efficiency vs irradiance and temperature Module #3

Gamma (dPmax/dTemperature)
-0.42%/K → -0.48%/K



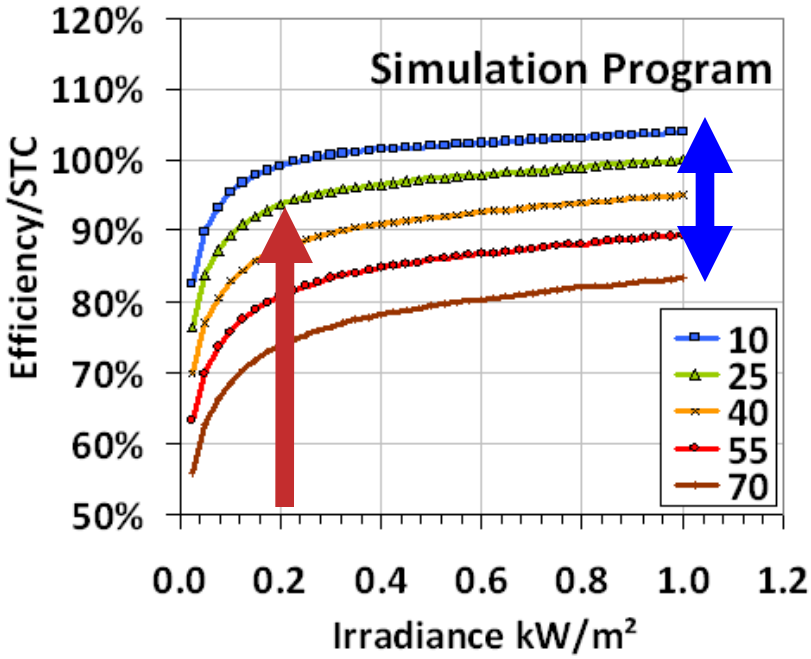


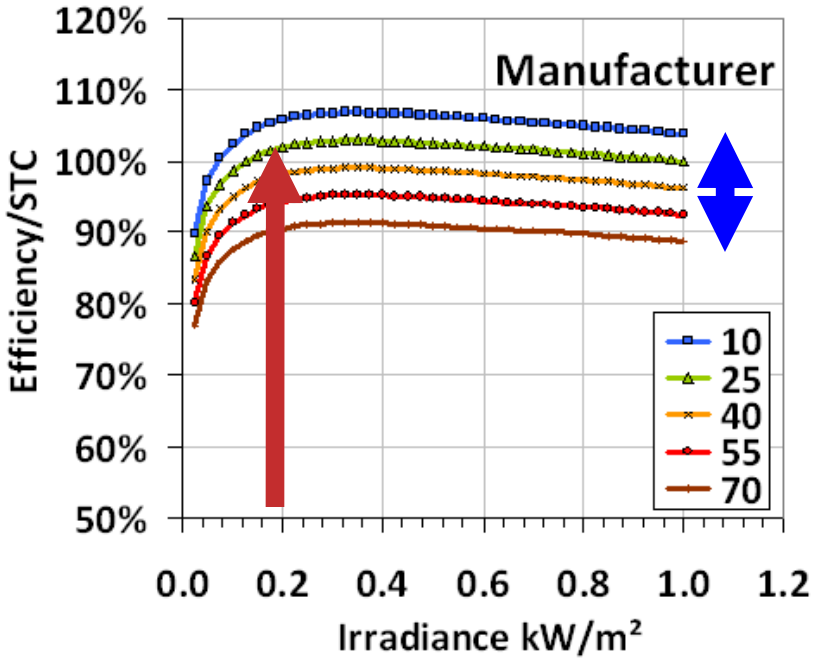
Low light efficiency change
82% → 95%

High Rshunt gives high efficiency down to low light levels

Correcting efficiency vs irradiance and temperature Module #9

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





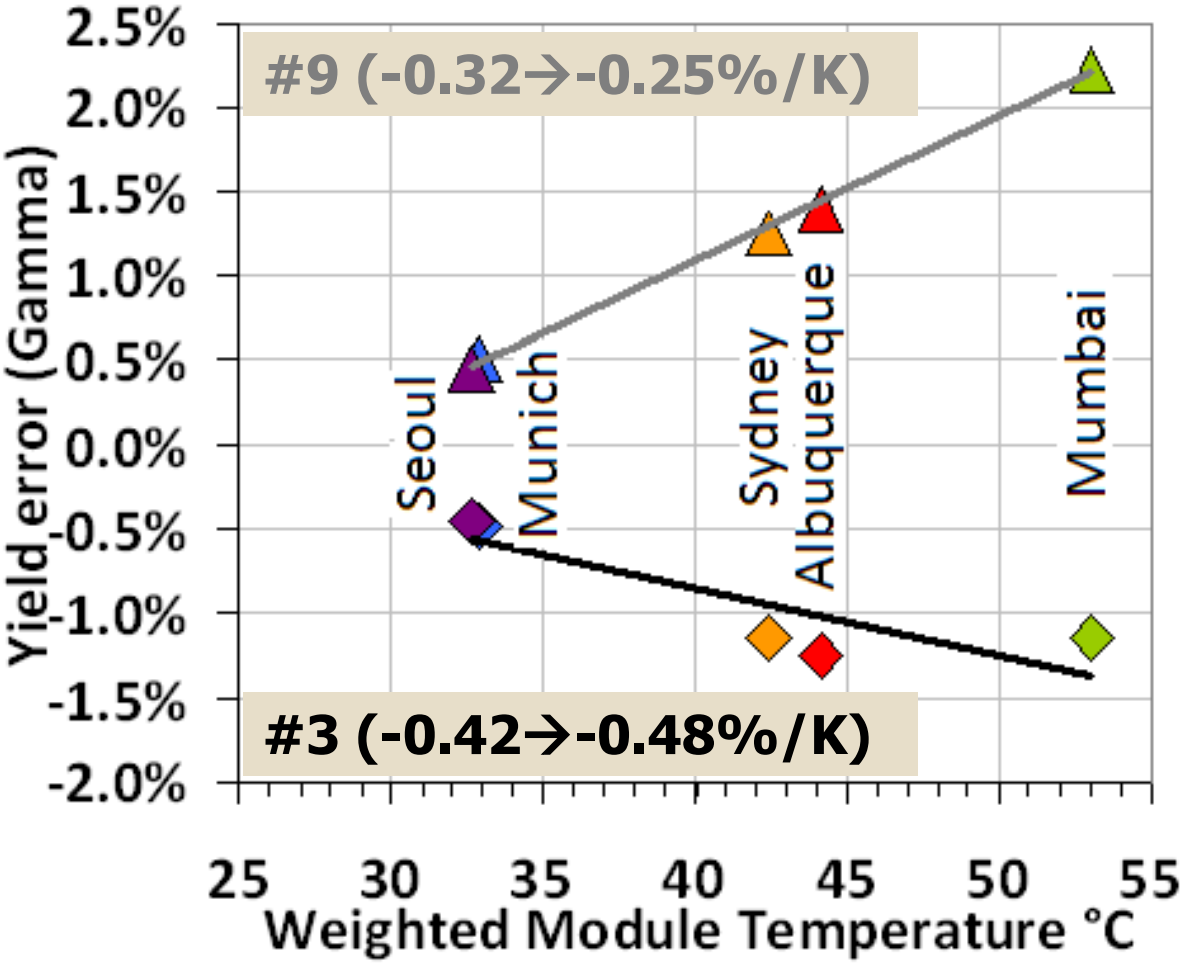
Low light efficiency change
94% → 102%

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

Check simulation errors for two modules five met sites chosen worldwide

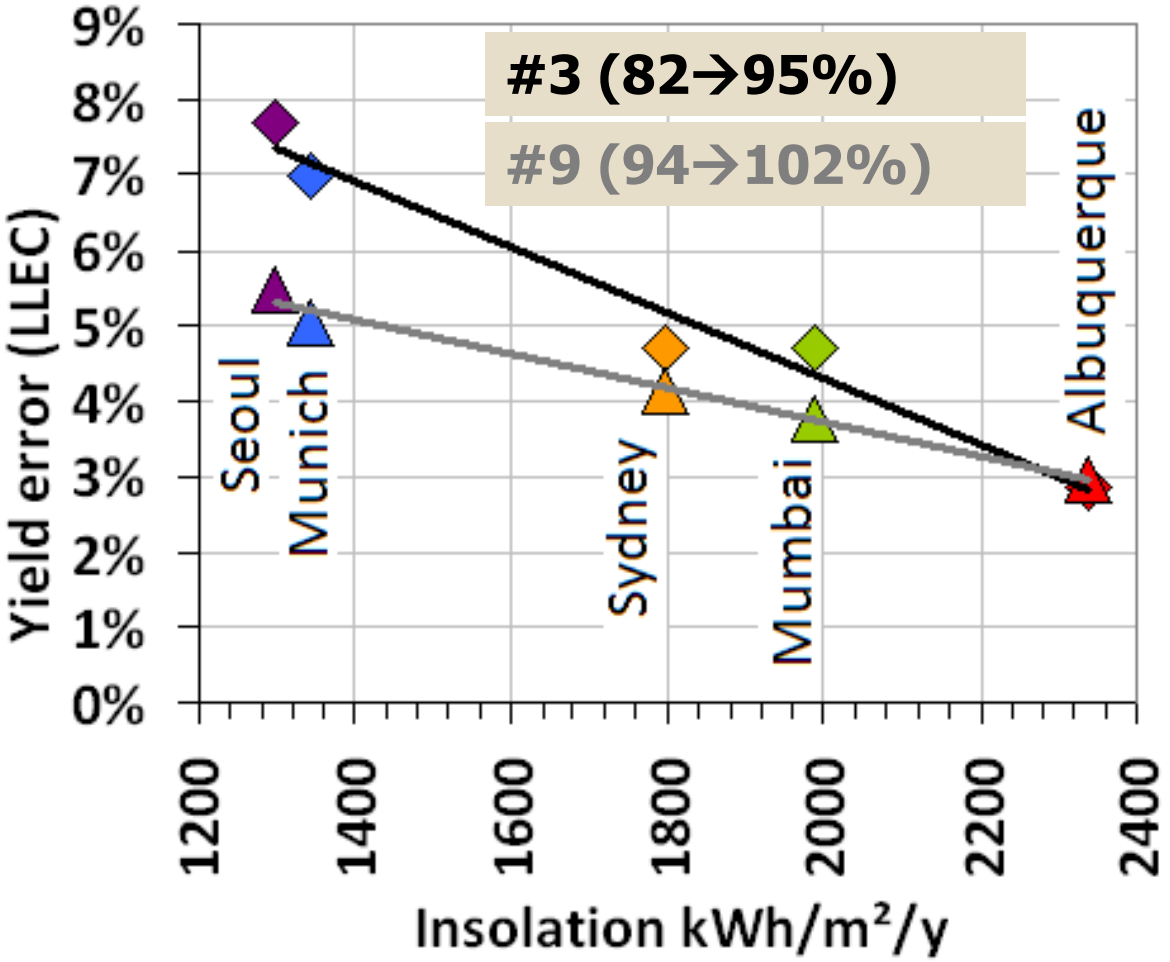
	Site name, Country Insolation, temperature	Latitude °	POA Insolation kWh/m²	Weighted Tmodule °C
1	Munich, DE Dull, cool	48°N	1345 *	14.3 *
2	Albuquerque NM, USA Very bright, warm	35°N	2336 ***	18.7 **
3	Mumbai, IN Bright, Hot	19°N	1988 **	30.3 ***
4	Seoul, KO Dull, cool	38°N	1299 *	15.4 *
5	Sydney, AU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

Correcting gamma error modelled kWh/kWp change vs. weighted module temperature



- **#3 had a smaller correction than #9 so a lesser effect (%/C)**
- **#9 rises with temperature as manufacturers claim better than simulation, #3 opposite**
- **Coolest sites (Seoul, Munich) have least difference should be 0% at 25C site**

Correcting low light efficiency error modelled kWh/kWp change vs. plane of array insolation



- **#3 had larger correction than #9 (13 vs 8%) so greater effect**
- **Both rise as light level falls as more time at low light – higher change than Gamma error**
- **Sunniest site (Albuquerque) has little 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**
- **Correct low light efficiency - biggest gain in cloudy conditions**
- **Correct Pmax temp. coefficient - biggest change in hot conditions**
- **Corrections values vary by manufacturers and technologies**
- **c-Si has been modelled more pessimistically than thin film**
- **Corrections should bring modelled kWh/kWp closer together by technology to match real measurements better**

Thank you for your attention !

Acknowledgements :

ISET for German data

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All SRCL papers :

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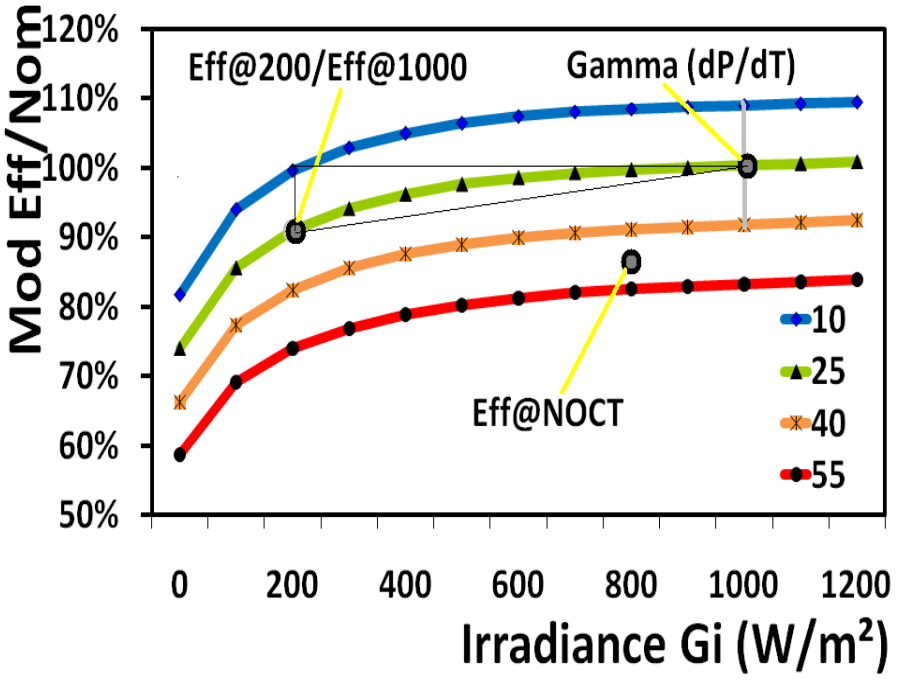

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