Choosing the best Empirical Model for predicting energy yield

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7th PVPMC SUPSI Canobbio Switzerland 30-31 Mar 2017

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Mechanistic
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Contents of talk

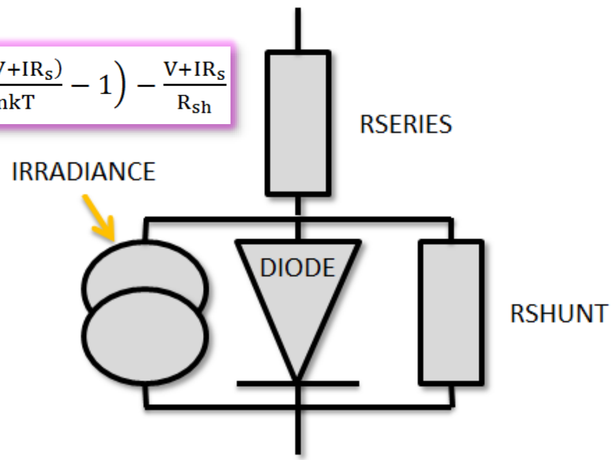
- Summarise the status of common PV models
- Explain empirical models, when can they be useful?
- Compare 10 existing models with Gantner Instruments outdoor measurements data for 3 PV technologies
- Use the models’ best points to propose a new “mechanistic model”
- Analyse how it improves on existing models
- Propose further optimisation and additions such as spectral effects

Standard models

Curve fits e.g. 1 diode (fit equivalent circuit to IV curve)

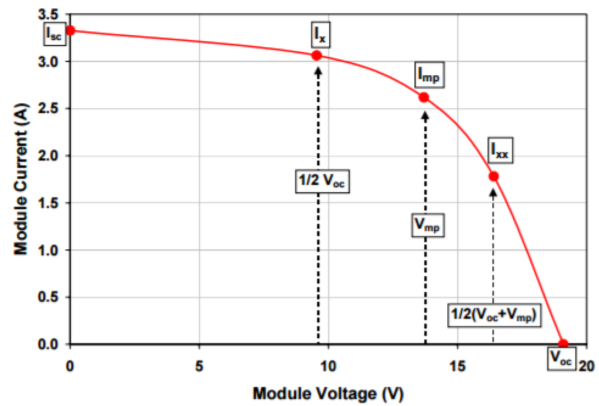
- Imperfect traces (e.g. cell mismatch) cause curve fit difficulties
- R_{SHUNT}, R_{SERIES} etc. vary with G_I , T_{MOD} (not defined in model) so can predict incorrect Low light efficiency and gamma

$$I = I_L - Io_1 . \exp\left(\frac{q(V+IR_S)}{nkT} - 1\right) - \frac{V+IR_S}{R_{sh}}$$



Point modelling e.g. SAPM (I_{SC}, P_{MP}, V_{OC} …)

- Hard to understand – 29 coefficients including for AOI and SR
- Difficult to get a unique fit
- No modelled R_{SERIES} or R_{SHUNT}



- **Neither model is normalised, their coefficients are area dependent and make it difficult to study module variability and degradation.**
- **Both models predict much more than just P_{MAX}**

What is an empirical model?

- It's a **simple mathematical** model for calculating P_{MAX} as a function of weather inputs

$$P_{MAX} = G_I * \{ \underbrace{C_1}_{\text{Constant}} * fn_1 (\underbrace{G_I}_{\text{Irradiance}} , \underbrace{T_{MOD}}_{\text{Module\_Temp}} \dots) + C_2 * fn_2 (G_I , T_{MOD} \dots) + \dots \}$$

Empirical Fit Coefficients

Sum or product of terms 1..n

Input Dependencies

What is an empirical model?

- It's a **simple mathematical** model for calculating P_{MAX} as a function of weather inputs

$$P_{MAX} = G_I * \{ \underbrace{C_1}_{\text{Constant}} * fn_1(\underbrace{G_I}_{\text{Irradiance}}, \underbrace{T_{MOD}}_{\text{Module\_Temp}} \ldots) + C_2 * fn_2(G_I, T_{MOD} \ldots) + \ldots \}$$

Empirical Fit Coefficients

Sum or product of terms 1..n

Input Dependencies

- It **<u>doesn't</u>** need any physical understanding
  ☑ it's simple ☒ values aren't useful

- It should be able to be fitted by **any simple software** e.g. **Excel solver (**rather than specialised fitting software)

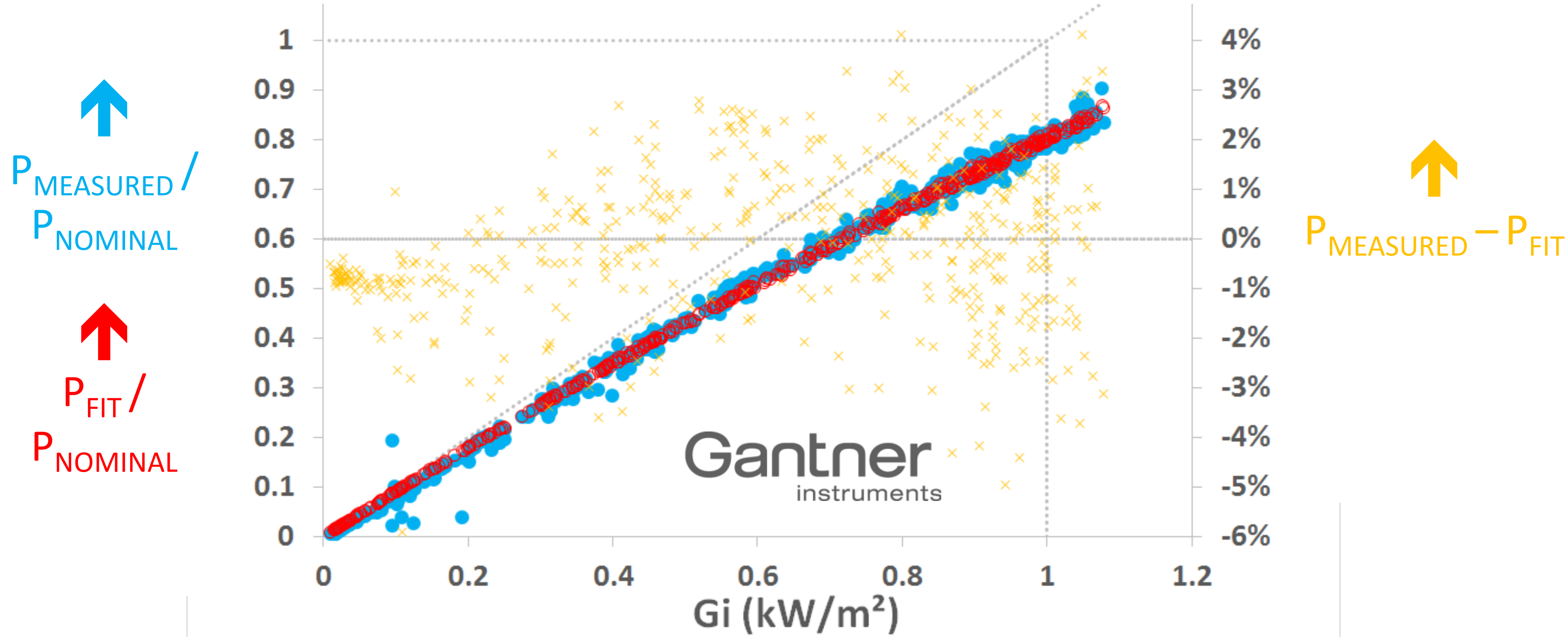
Simplest empirical model PVUSA with 4-coefficients

(modified: normalised and uses T_{MOD} not T_{AMB} to get a simpler temperature coefficient)

$$P = G_I * \{C_1 + C_2 * G_I + C_3 * T_{MOD} + C_4 * Wind\}$$

Pmax Irradiance Irradiance^2 Module_temp Wind_speed

(Usually it's only used at >0.7kW/m² due to its known poor fit at low light)



How is an empirical model used?

- Determining **bad measurement data** (out of usual range)
- **Interpolation** of missing P_{MAX} values
- Instantaneous performance **validation**
- Predicting performance at **given conditions** e.g. STC
- **Simple energy yield** estimation
  Summing predicted P_{MAX} vs. climate data (G_I, T_{MOD} …)

10 existing models have been studied

Anonymised as Models A .. K (but in a different random order)

- HEYDENRICH
- IEC60891
- LFM2013
- MOTHERPV
- POLYNOMIAL
- PVCOMPARE
- PVGIS
- PVUSA
- PVUSA+
- SRCL2014

- please send any I have missed ....

10 existing models have been studied

Anonymised as Models A .. K (but in a different random order)

- **HEYDENRICH** = `Gi*(C1 * C2*Gi*LN(Gi+1) + C3*(LN(Gi+e))²/(Gi+1)-1))`
- **IEC60891** = `IV curve translation (used but equations too complicated to show)`
- **LFM2013** = `Gi*(C1 +C2*LN(Gi)+C_3*Gi²)*(C4+C5*LN(Gi)+C6*Gi²)` simplified LFM
- **MOTHERPV** = `Gi*(C1 + C2*Gi + C3*Gi^2 + C4*LN(Gi) + C5*LN(Gi)^2)`
- **POLYNOMIAL** = `Gi*(C1 + C2*Gi + C3*Gi² + C4*Gi³ + C5*Gi⁴)`
- **PVCOMPARE** = `Gi*(C1+C2*Tmod+C3*Tamb+C4*SolAlt+C5*Tmod*Tamb+C6*Tamb²+C7*Tmod²)`
- **PVGIS** = `Gi*(1+C1*LN(Gi)+C2*(LN(Gi))²+Tmod*(C3+C4*LN(Gi)+C5*LN(Gi)²)+ C6*Tmod²)`
- **PVUSA** = `Gi*(C1 + C2*Gi + C3*dTmod + C4*WS)` poor fit low light
- **PVUSA+** = `Gi*(C1 + C2*Gi + C3*dTmod + C4*WS) - C_5` improved low light fit
- **SRCL2014** = `Gi*(C1*LN(Gi)+C2)*(1-(1-C3)*Gi²)*C4` LLEC, γ, NOCT, P_{MAX}, R_S

- please send any I have missed ....

Some dependencies used by models A…K

$$P = G_I * \sum_{i=1\ldots n} C_i * fn_i(G_I, T_{MOD} \ldots)$$

- G_I , G_I^2, G_I^{-1}
- $\ln(G_I)$, $\ln(G_I)^2$
- T_{MOD}, T_{MOD}^2
- T_{AMB}, T_{AMB}^2
- SolAlt

How many dependencies are mathematically and physically meaningful ?

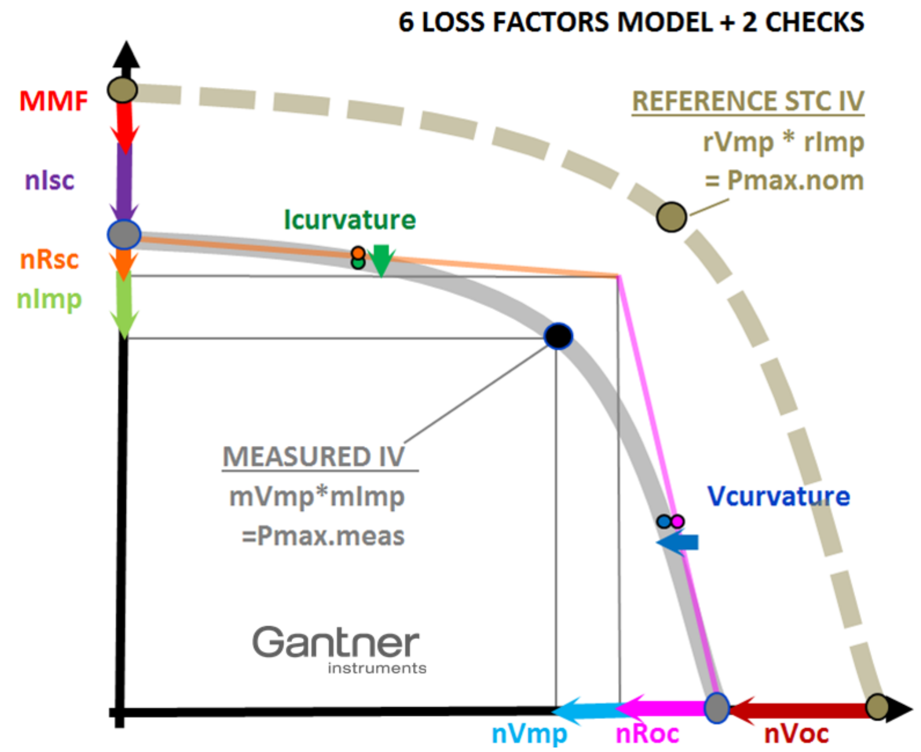
Also some combinations such as

- $[T_{MOD} * \ln(G_I)]$
- $[T_{MOD} * T_{AMB}]$

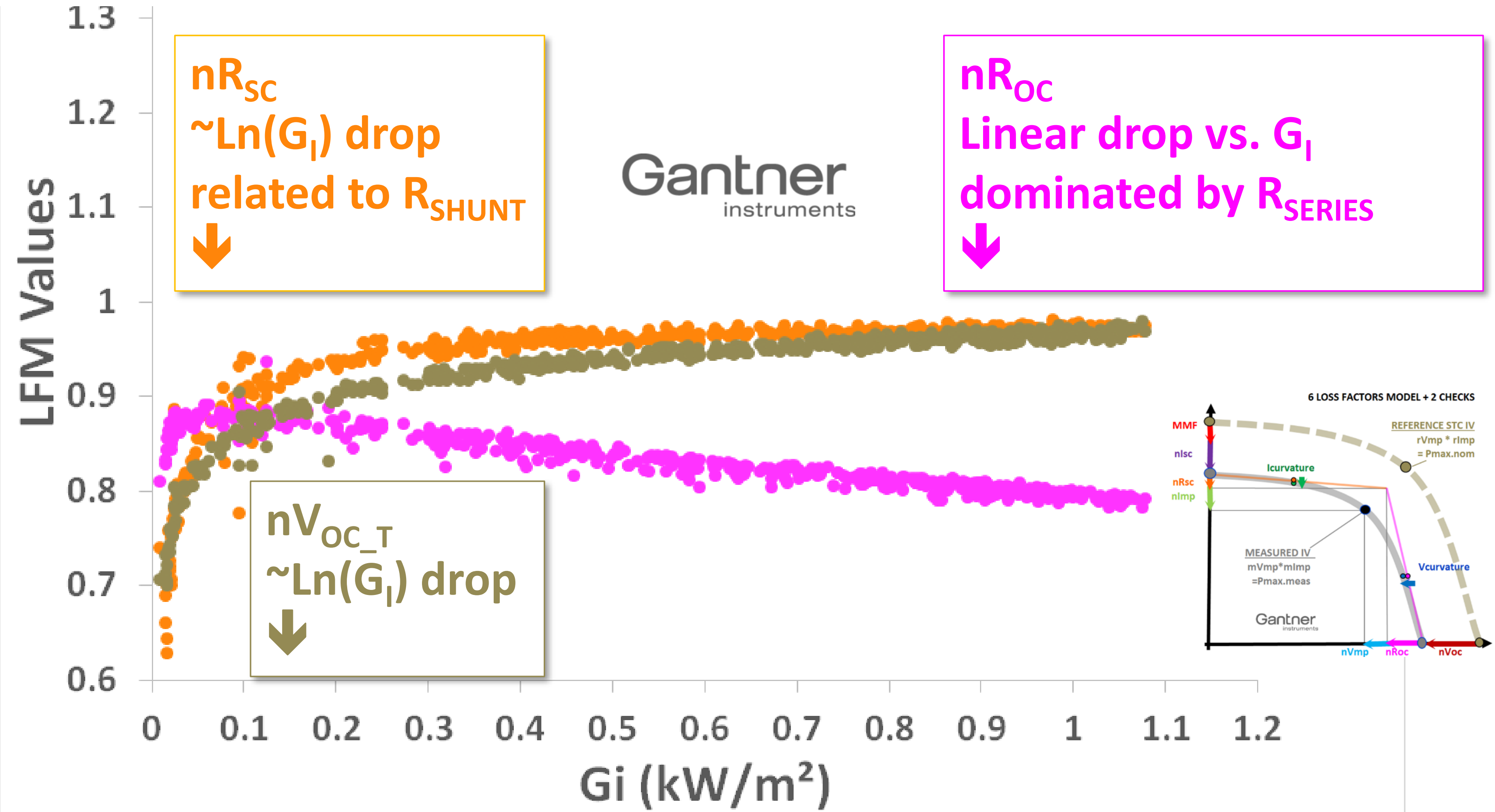
Choosing the optimum coefficients for models

- How do PV modules really behave i.e. efficiency as a function of Irradiance and T_{MODULE}?

- Use the **Loss Factors Model** (6 normalised orthogonal coefficients fitting the IV curve) to find out so we know how and what to model



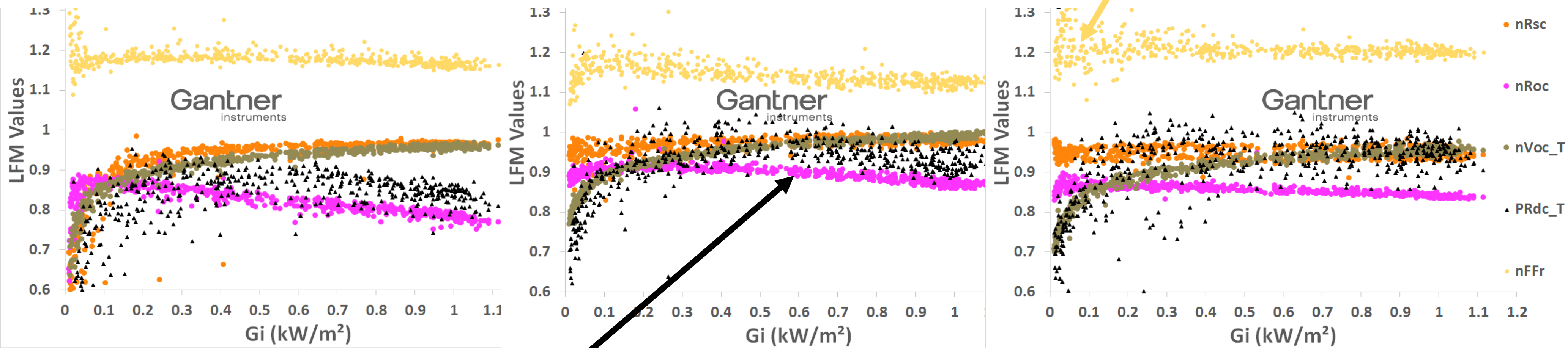
Three LFM coefficients nR_{SC}, nR_{OC}, nV_{OC} cause PR_{DC} vs. G_I
nI_{SC}, nI_{MP} and nV_{MP} are “almost constant” with G_I



How do nR_{SC}, nR_{OC}, nV_{OC} behave for different technologies?

nFF_R is the product of terms "constant vs. G_I" so can ignore

Note: $PR_{DC} \propto nR_{SC} * nR_{OC} * nV_{OC}$

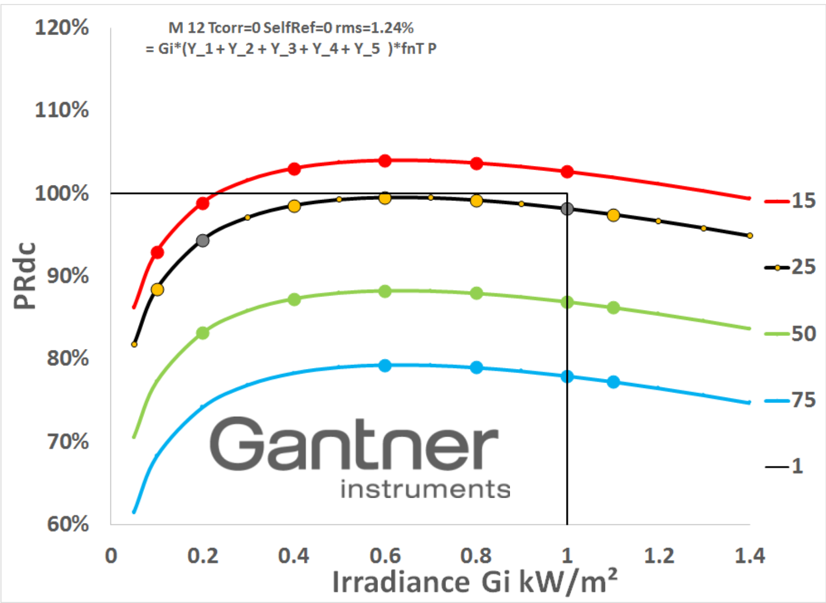


PR_{DC} vs. G_I is what the Empirical model needs to fit.

11) CdTe	12) c-Si	13) a-Si:uc-Si
Poor low light nR_{SC} Good nV_{OC} >0.1 sun Fast dropping nR_{OC}	Good low light nR_{SC} Steadily dropping nV_{OC} Best nR_{OC}	Good low light nR_{SC} Steadily dropping nV_{OC} Good nR_{OC}

Modules are characterised by "PR_{DC} vs. Irradiance and T_{MOD}" As used in simulation programs and matrix method IEC 61853

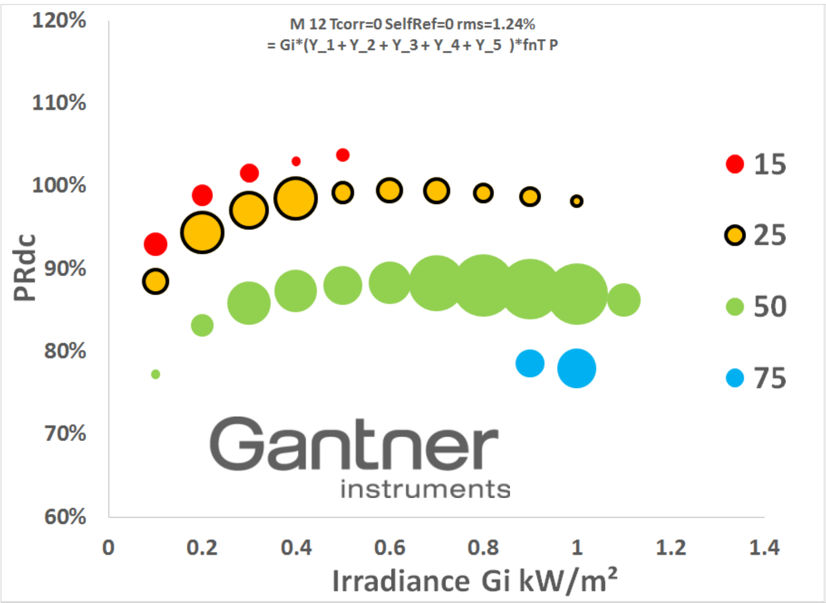
23 Matrix measurement points



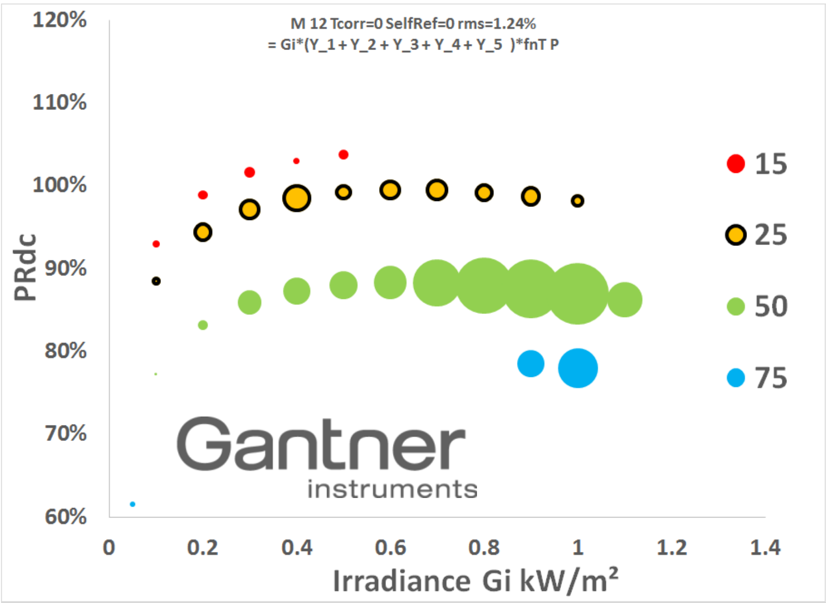
- 23 points are measured by the matrix method.
- Curves and coefficients are fitted to these

Modules are characterised by “PR_{DC} vs. Irradiance and T_{MOD}” As used in simulation programs and matrix method IEC 61853

% of points / year AZ



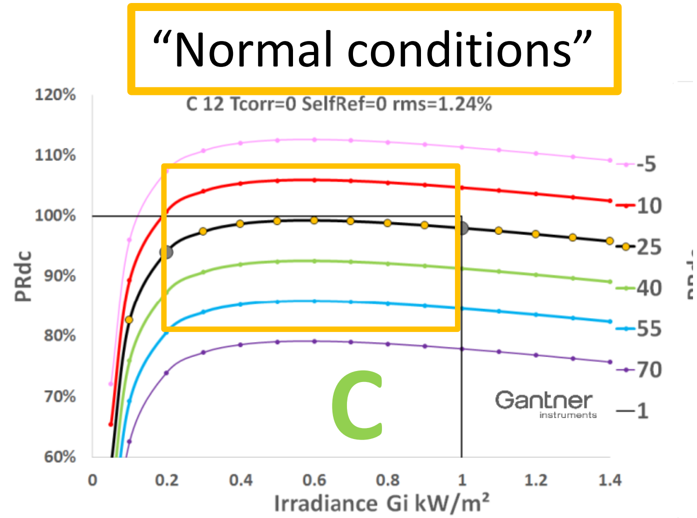
% of energy yield / year AZ



Fitting some of the models to

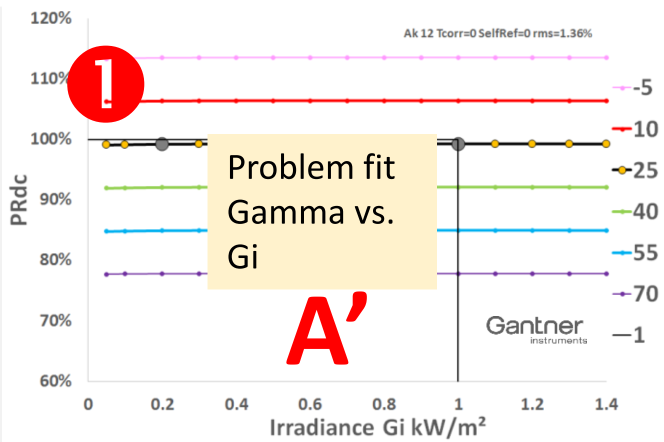
normalised efficiency PR_{DC} vs. Irradiance and T_{MODULE}

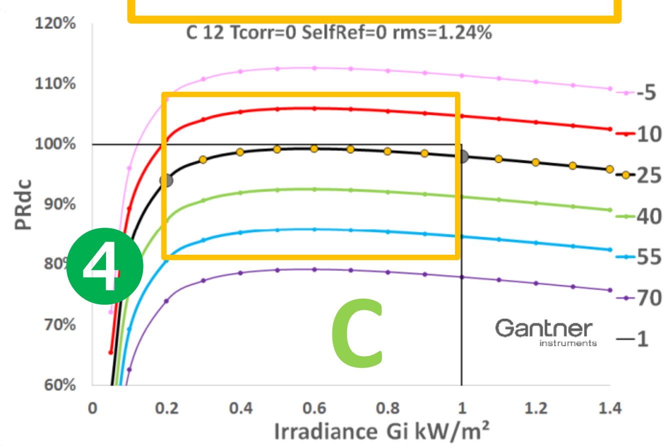
Best fits to PR_{DC} vs Gi c-Si model C (Gantner Instruments data)

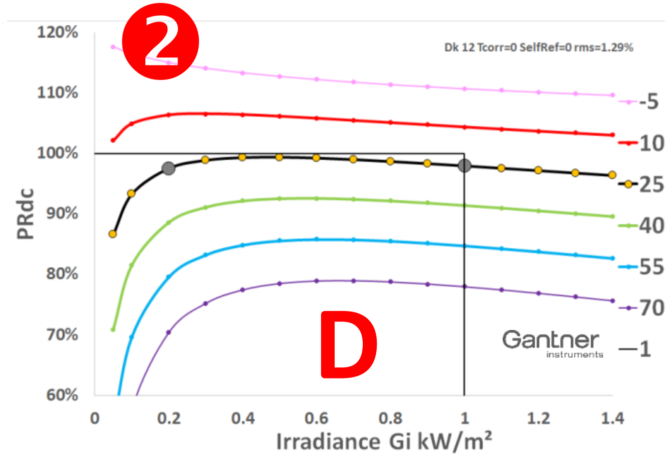


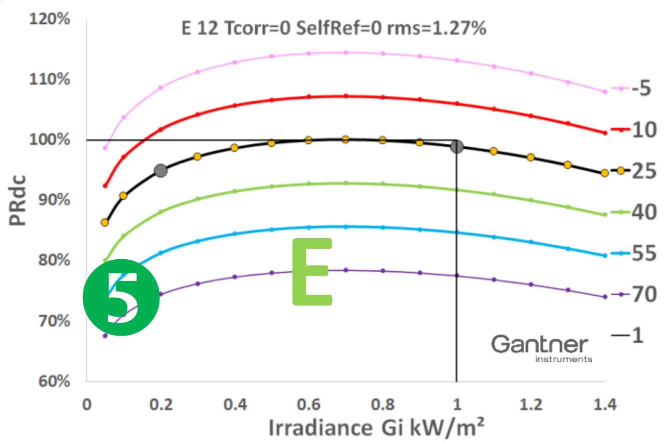
Best fits to PR_{DC} vs Gi c-Si "Easy to spot differences" for models A', C, D, E and J (Gantner Instruments data)

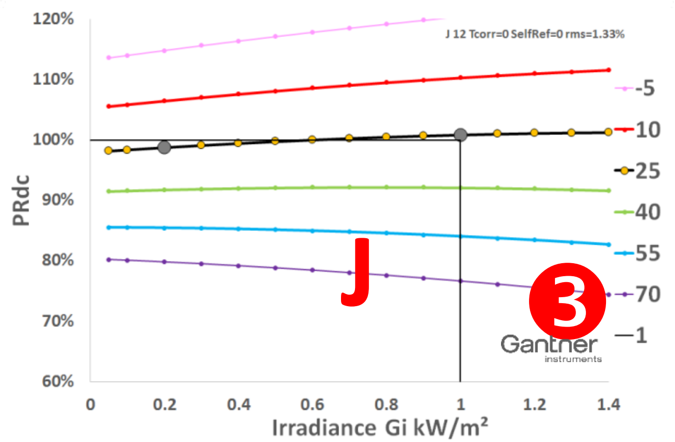
"Normal conditions"











120% L 12 Tcorr=0 SelfRef=0 rms=1.25%

Unphysical effects outside "normal conditions" e.g. $10<T_{MOD}<55$ and $0.2<G_I<1$

❶ Flat at low light

❷ Rising at low temp

❸ Gamma rise with GI

Differences

❹❺differ at low light

Existing models comparison

- Some have **trouble fitting simple data** e.g. A
- Most **aren't normalised**
- Some have **unphysical coefficients** e.g. T_{AMB}*T_{MOD}
- Many fit only PR_{DC} vs. G_I
  (need to correct for temperature * (1+Gamma*(T_{MOD}-25))

Suggest a **new model** using best features of existing ones

- **Optimise** the choice of coefficient dependencies
- **Test it** against PV technologies vs. other models

We can improve models by normalising them and making them more "Mechanistic"

Empirical Model

Not normalised. Coefficients scale with array size or module numbers

"Meaningless parameters" such as "$T_{AMB}*T_{MOD}$"

No idea what values mean good performance

e.g. $P_{MEAS} = G_I * \Sigma_{i=1..n} C_i * fn_i(G_I, T_{MOD}...)$

Mechanistic Model

Normalise coefficients by dividing by reference values e.g. $nV_{OC} = V_{OC.MEASURED}/V_{OC.REFERENCE}$

Now we can more easily compare modules and understand degradation changes

e.g. $PR_{DC} = (P_{MEAS}/P_{NOM}/G_I) = C_1 + C_2*Tmod + C_3*Ln(Gi) + C_4*Gi + C_5*WS + ?$

	P TOLERANCE	GAMMA	LLEC	RS	WIND
	%	%/K	%@LIC	%@STC	%/(ms-1)

A simple normalised 6 parameter mechanistic model (L)

PR_{DC} equation

- PR_{DC} =

$$
\begin{aligned}
&C_1 \\
&+ C_2 * dT_{MOD} \\
&+ C_3 * \ln(G_I) \\
&+ C_4 * G_I \\
&+ C_5 * WS \\
&+ C_6 / G_I \\
&+ \ldots
\end{aligned}
$$

- The **PR_{DC}** is the sum of each of these terms
- Plot on a stacked chart to determine the value of each term and its shape vs. irradiance
- Some terms may be redundant or insignificant e.g. C3 vs. C6

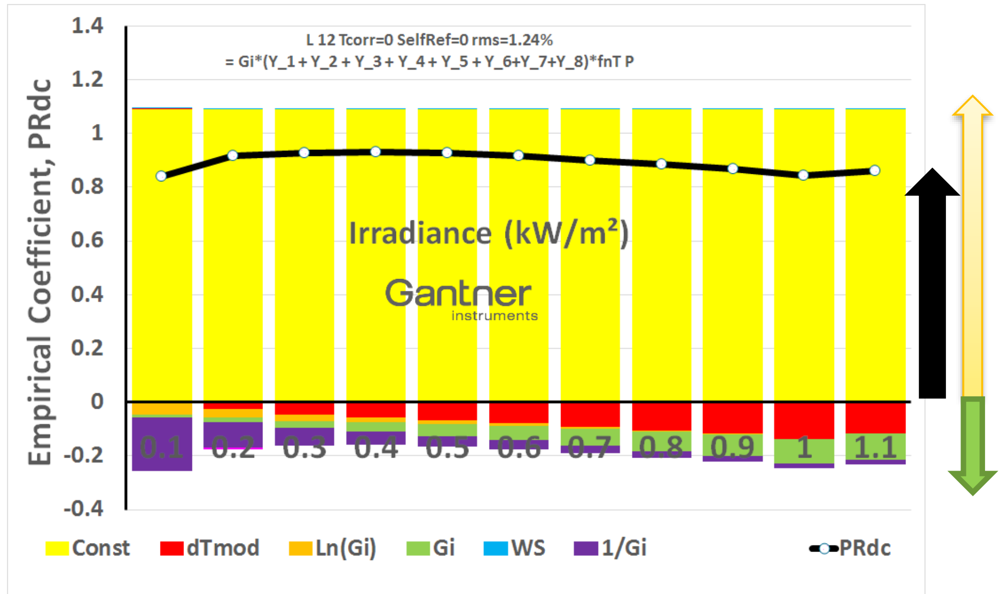
A simple normalised 6 parameter mechanistic model (L)

How many terms are independent?
How many are significant?

PR_{DC} equation

- PR_{DC} =
  - C_1
  - $+ C_2 * dT_{MOD}$
  - $+ C_3 * \ln(G_I)$
  - $+ C_4 * G_I$
  - $+ C_5 * WS$
  - $+ C_6 / G_I$
  - $+ \ldots$

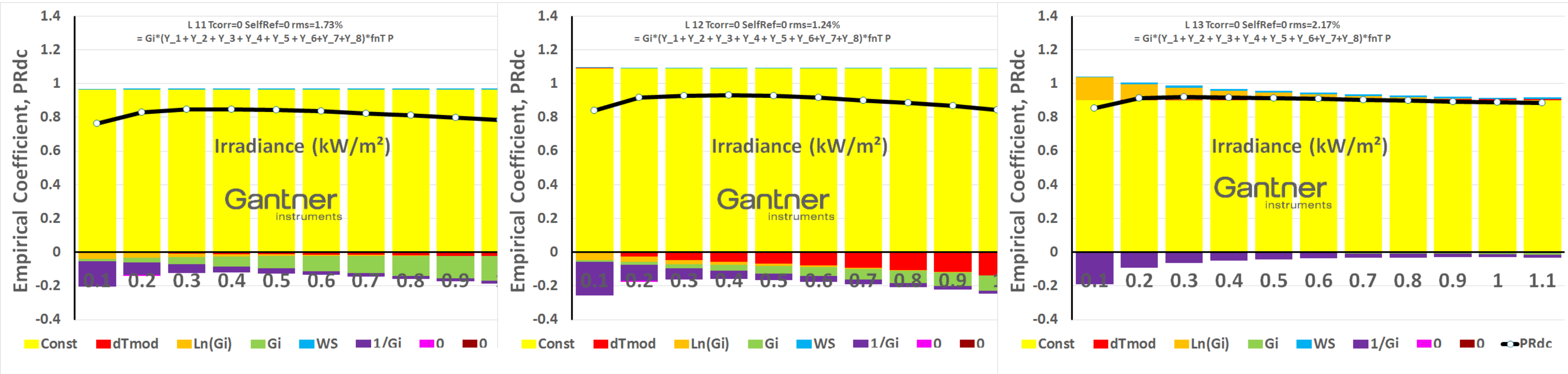
PR_{DC} vs. irradiance = Sum +ve and -ve coefficients



PR_{DC} vs. Irradiance for different technologies – Model L

$$PR_{DC} = C_1 + C_2*dT_{MOD} + C_3*\ln(G_I) + C_4*G_I + C_5*WS + C_6/G_I$$

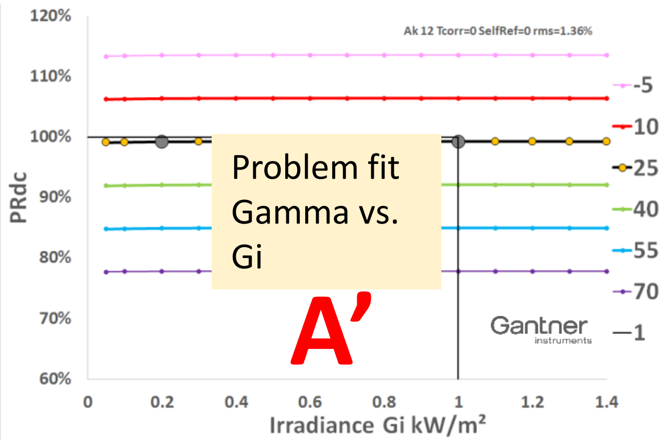
[CONST] [dTMOD] [ln(Gi)] [Gi] [WS] [1/GI]

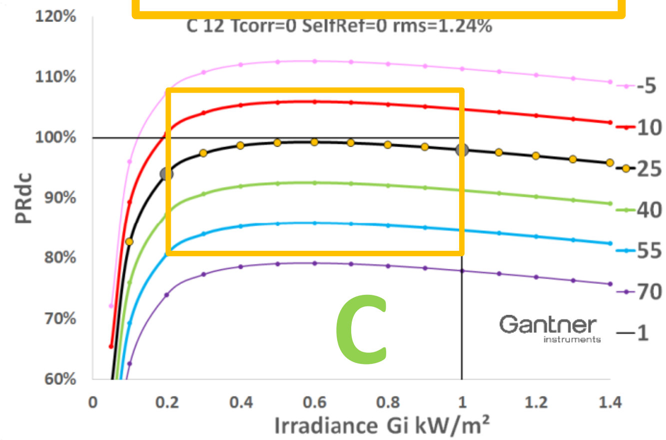


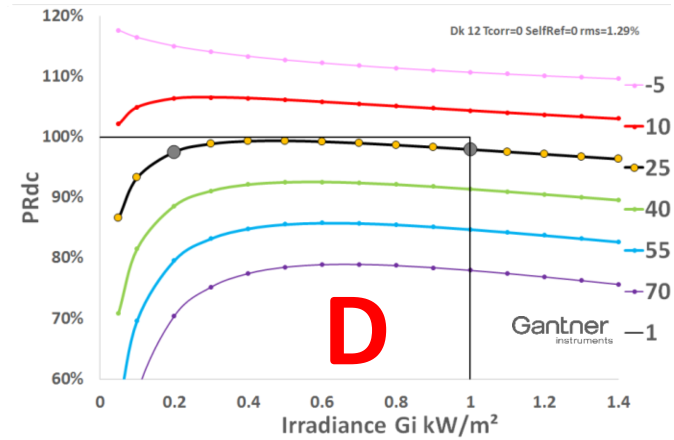
CdTe	c-Si	a-Si:uc-Si
Simple to fit	Worst **dTmod** coeff	Flattest PR_{DC} vs Irradiance

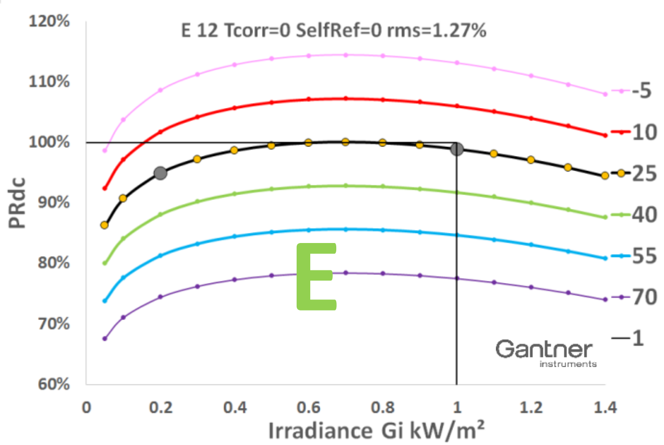
Best fits to PR_{DC} vs Gi c-Si for models A, C, D, E and J vs. New Model L (Gantner Instruments data)

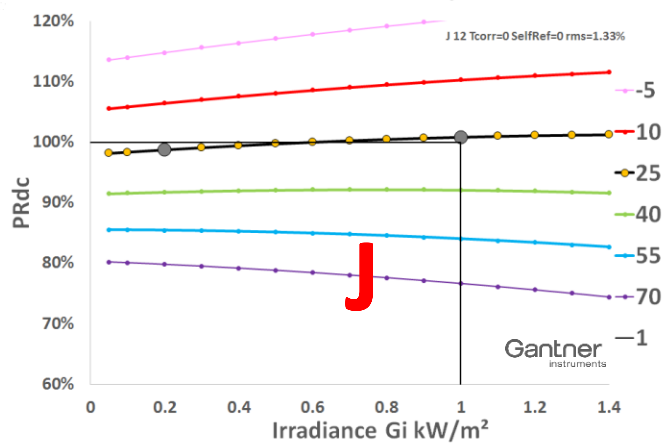
“Normal conditions”

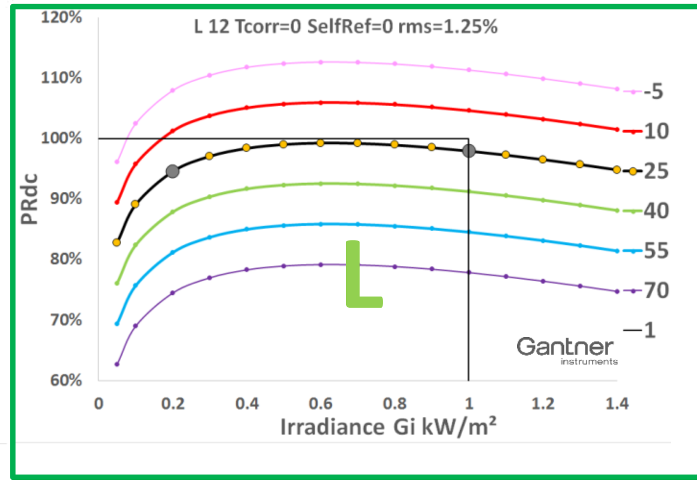






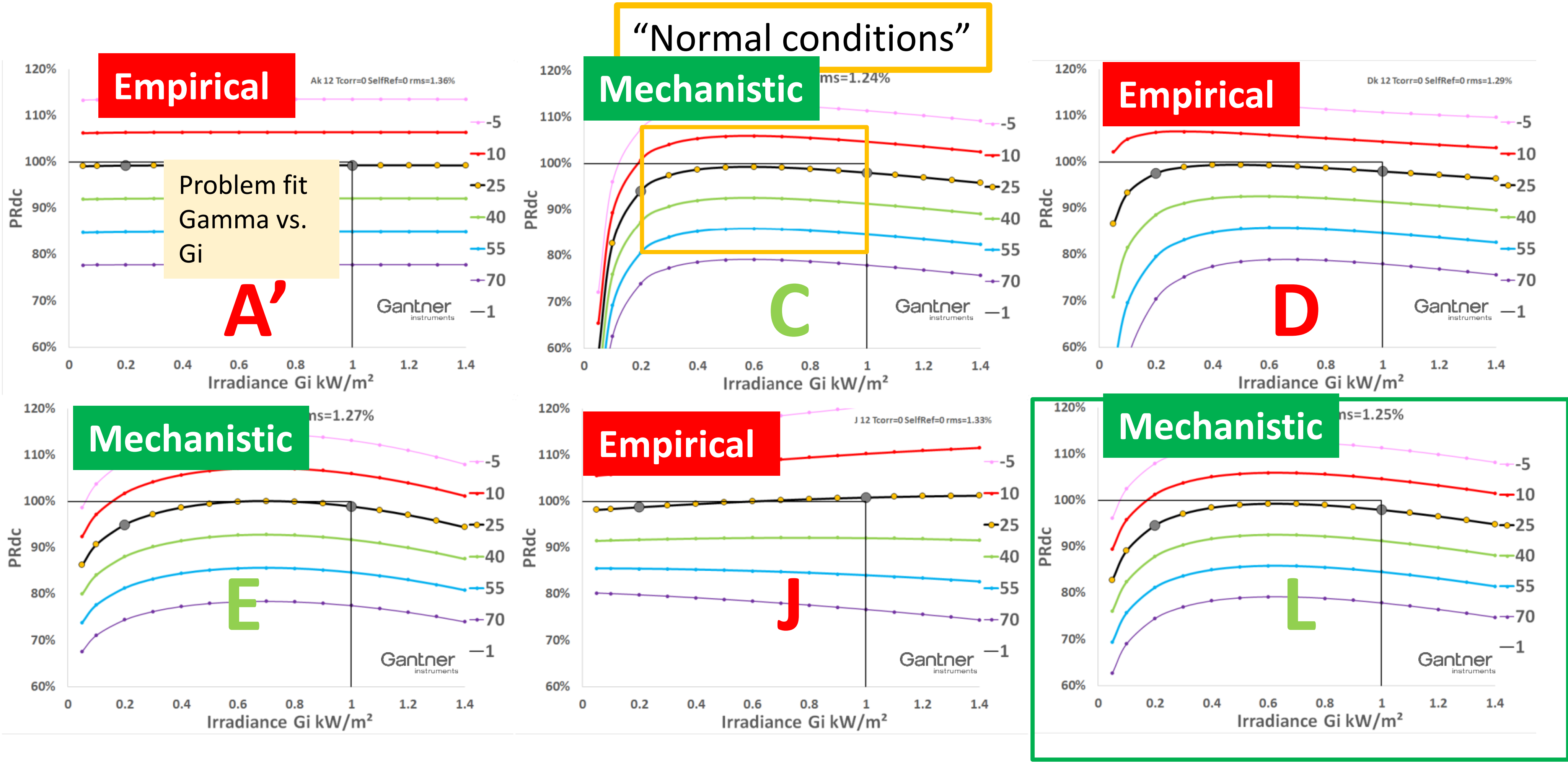






New model has sensible looking fit

Best fits to PR_{DC} vs Gi c-Si for models A, C, D, E and J vs. New Model L (Gantner Instruments data)



New model has sensible looking fit

Conclusions

- 10 Existing models have been tested
- Empirical models can be difficult to fit and may have meaningless coefficients
- LFM was used to determine optimum coefficients for a new Mechanistic Model (L) which works well

Next steps

- Further analysis- more modules, more sites
- Model spectral response, reflectivity and soiling, seasonal annealing
- Show reasons for any degradation

- If you wish to join in please send details of your model and any measurement data
- **Thanks for your attention and please get involved!**

Data required
Setup
Location : Lat, Lon, Alt
Orientation : Tilt and Azi
Module Details : Datasheet Values and Temp Coeffs

Essential :
Date+time
G_I Irradiance (by sensor type)
$T_{AMBIENT}$
T_{MODULE}
Windspeed
P_{DC}

Useful to have :
I_{DC} and V_{DC}
G_H, D_H
G_N
Spectrum, Rel Hum
I_{SC}, V_{OC}, R_{SC}, R_{OC}