#823 Poster 10
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How to Choose the best Empirical Model for Optimum Energy Yield Predictions

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0) GLOSSARY (see also IEC 61724)

POA	= Plane of array
G_I	= POA instantaneous irradiance (kW/m²)
T_{AMB}	= Ambient temperature (C)
T_{MOD}	= Module temperature (C)
WS	= Wind speed ($m\ s^{-1}$)
AM	= Air Mass (nominal is AM 1.5)
STC	= G_I=1kW/m², T_{MOD}=25C, Direct only AM1.5, WS=$0ms^{-1}$
YF	= AC Energy yield (kWh/kWp)
H_I	= POA sum insolation (kWh/m²/year)
LLEC	= "Low light efficiency coefficient" = ($Eff_{0.2kW/m^2}/Eff_{1kW/m^2}$)
NOCT	= T_{MOD} @ (G_I=0.8kW/m², T_{AMB}=20C, AM1.5, $1ms^{-1}$)
I^2Rs	= % Loss due to series resistance = $I_{MAX}^2 * R_{SERIES}/P_{MAX.STC}$
dT_{MOD}	= T_{MOD} – 25C
γ	= Gamma = $1/P_{MAX} * dP_{MAX}/dT_{MOD}$
RATING	= $P_{ACTUAL}/P_{NAMEPLATE}$
PR_{DC}	= DC Performance Ratio = $P_{MAX.MEASURED} / P_{MAX.NAMEPLATE} / G_I$

(1) INTRODUCTION

Many empirical performance models (EPM) have been used in the PV industry to characterize module measurements and to predict kWh/kWp.

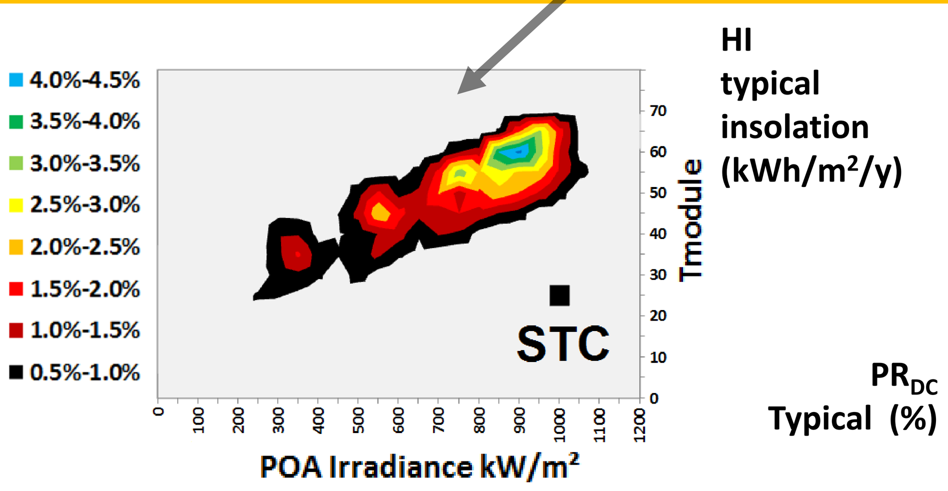
11 existing models have been studied (anonymised as models A to N but not in this order)
CREST, HEYDENRICH, IEC60891, LFM2013, MOTHERPV, 4th ORDER POLYNOMIAL, PVCOMPARE, PVGIS, PVUSA, PVUSA+, SRCL2014.

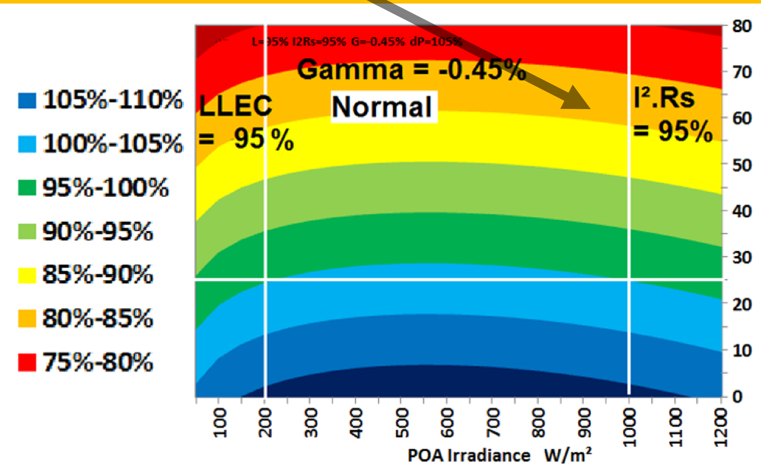
Measured PV data was for both c-Si and Thin Films from
a) Gantner Instruments OTF data in Tempe, AZ
b) 3rd party "IEC 61853 Matrix" indoor measurements including ASU, JRC ESTI, Sandia and TUV Rheinland.

(2) PREDICTING ENERGY YIELD (YA or YF) FROM INSOLATION (H_I) AND PR_{DC}

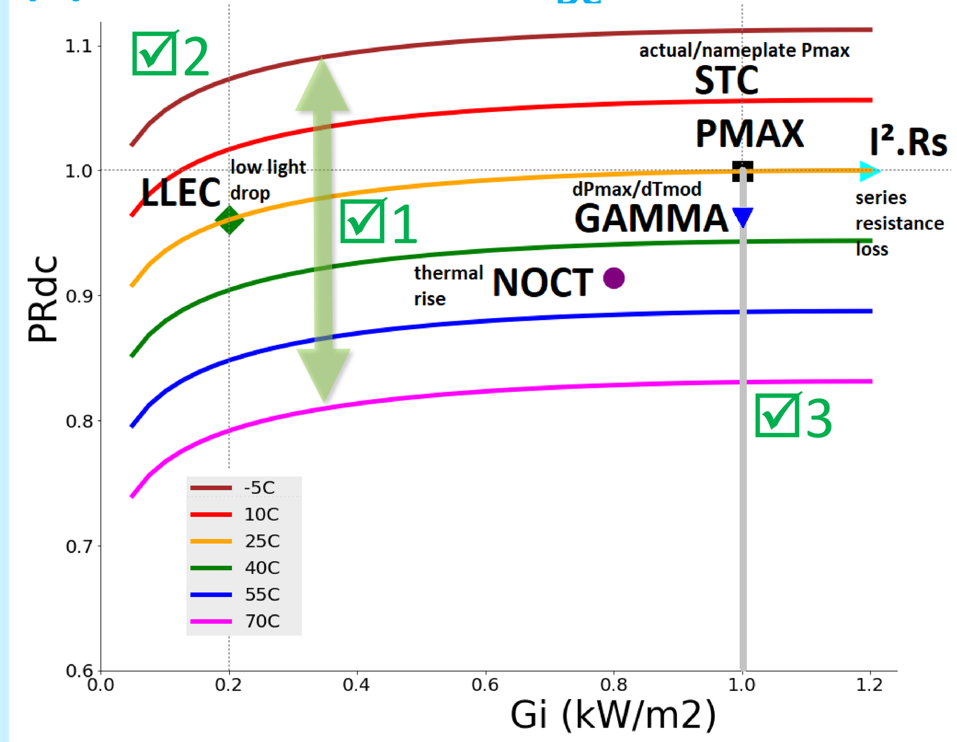
Sum "Insolation * PR_{DC}" over all irradiance and module temperatures

$$YA\ or\ YF \propto \sum_{G_I, T_{MOD}} H_I(G_I, T_{MOD}) \times PR_{DC}(G_I, T_{MOD}) \quad (1)$$





(3) THE SHAPE OF PR_{DC} IS CHARACTERISED BY 5 PARAMETERS



Illustrating good PV Performance

Uniform vertical ☑1 separation means gamma = constant

Smooth behaviour at lowest ☑2 and highest ☑3 light levels

(4) TYPICAL EMPIRICAL PERFORMANCE MODEL (EPM) FORMULA

$$PR_{DC} = \{C_1 * fn_1(G_I, T_{MOD}...) + C_2 * fn_2(G_I, T_{MOD}...) + ... \} \quad (2)$$

Empirical fit coefficients C_i — input dependencies — sum terms 1..n

How to fit : Optimise C_{1-n} to minimise RMS ($P_{MEASURED} - P_{PREDICTED}$)

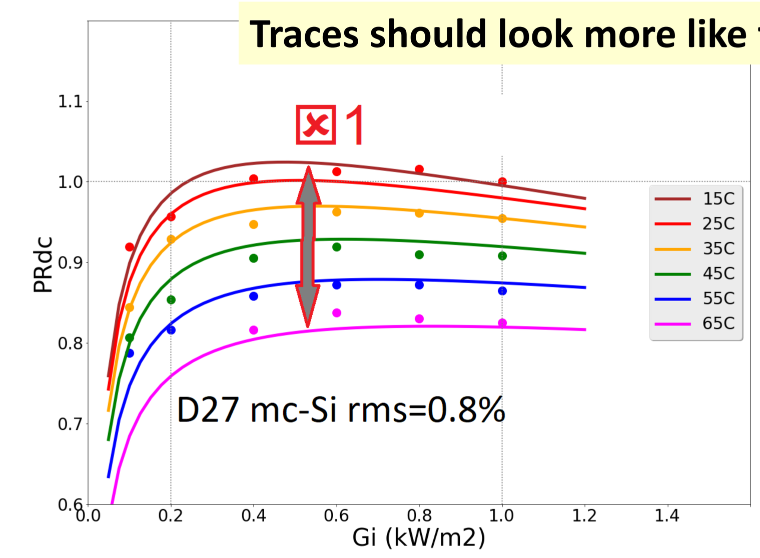
The 11 empirical models use different selections of **input dependencies** including **G_I, log(G_I), T_{MOD}, G_I*T_{MOD}, G_I^2, T_{MOD}^2**, etc. …

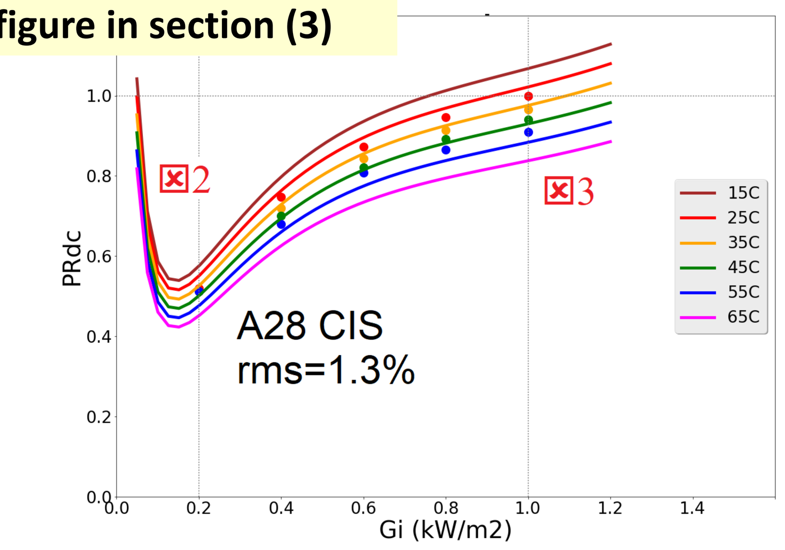
(5) SOME EMPIRICAL MODELS GIVE UNPHYSICAL FITS ☒

Model D : Temperature coefficient (line separation vertically) wrongly depends on module temperature ☒1

Model A : PR_{DC} diverges away from sensible values at lowest ☒2 and curves up at highest ☒3 irradiances

Traces should look more like figure in section (3)





(6) CREATE A "MECHANISTIC PERFORMANCE MODEL" (MPM) TO MINIMISE FITTING ERRORS

	Present empirical models	New Model MPM
Are coefficients normalised ? (are they Independent of area?)	☒ No	☑ Yes
Are there only physically significant input dependencies?	☒ No	☑ Yes
Is it easy to compare different modules ?	☒ No	☑ Yes

(7) NEW MECHANISTIC PERFORMANCE MODEL (MPM) FORMULA

$$PR_{DC} = C_1 + C_2 * dT_{MOD} + C_3 * Log_{10}(G_I) + C_4 * G_I + C_5 * WS + C_6 / G_I \quad (3)$$

Quality — Gamma — LogGi — Gi — Windspeed* — 1/Gi**

	Quality C_1	Gamma C_2	LogGi C_3	Gi C_4	WS C_5	1/Gi C_6	rms err
2) ASU_cSi	111.7%	-0.52%	21.2%	-11.9%	0.0%	0.0%	0.5%
27) ESTI_mcSi	115.5%	-0.45%	23.9%	-15.4%	0.0%	0.0%	0.3%
32) TUV cSi	105.2%	-0.42%	10.1%	-5.2%	0.0%	0.0%	0.2%
10) CFV_cSi	103.3%	-0.37%	9.4%	-3.4%	0.0%	0.0%	0.2%
23) SAPM_cSi	98.5%	-0.41%	9.4%	-2.6%	0.0%	0.0%	0.1%
24) PVSYST_CdTe	112.3%	-0.26%	19.2%	-12.0%	0.0%	0.0%	0.2%

Example MPM coefficient values for fits in section (8)

Note : Quality C_1 ~ 100%; C_2 to C_6 are correction factors
* indoor measurements wind=0 so here C_5 → 0
** some datasets can get good results with C_6=0
G_I kW/m²; dTmod = T_{MOD}-25 ; WS ms^{-1}

(8) MPM FITS MEASURED AND MODELLED DATA RMS<=0.5%

TITLE = "MODEL LETTER + MODULE ID NUMBER" ; PV TECHNOLOGY ; RMS ERROR"

MPM fits to MATRIX DATA from ASU, JRC ESTI, TUV and CFV

NOTE : ASU's measurement temperatures are not evenly spaced

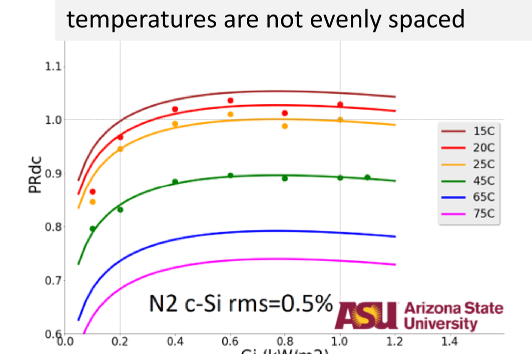


Fig. 7. MPM c-Si #2 ASU [13].

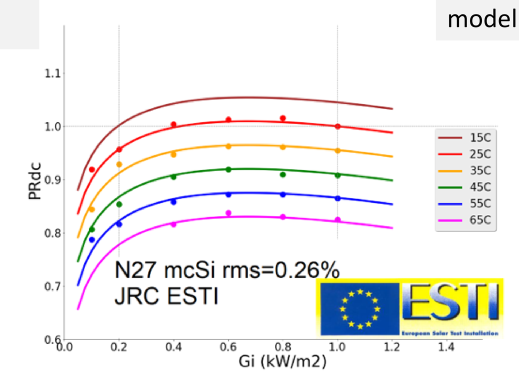


Fig. 8. MPM mc-Si #27 ESTI [16].

NOTE : This module falls faster at low light than the model predicts, will need to adjust MPM for better fit

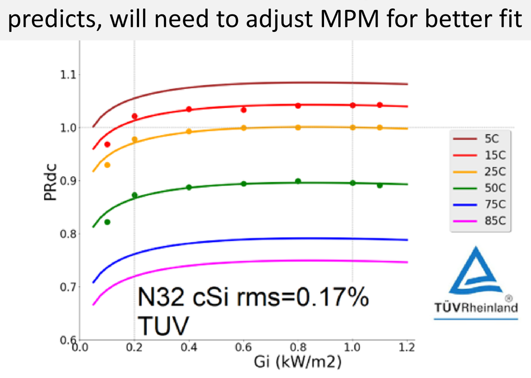


Fig. 9. MPM c-Si #32 TUV [19].

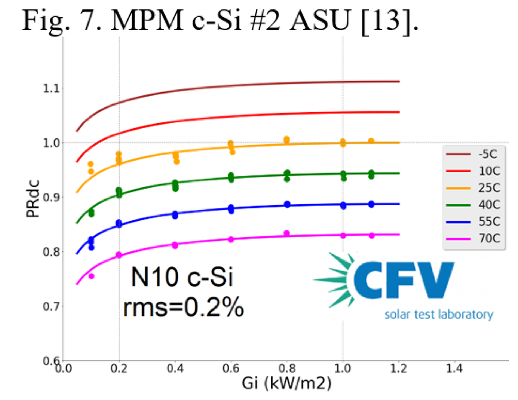


Fig. 10. MPM c-Si #10 CFV [18].

NOTE : This Module low light falls slower than N32 and MPM handles this well

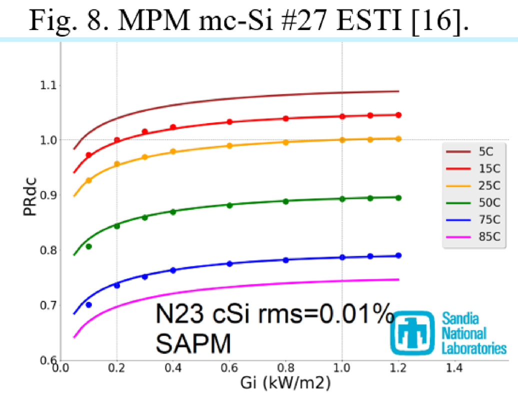


Fig. 11. MPM c-Si #23 SAPM [14].

Sandia Array Performance Model

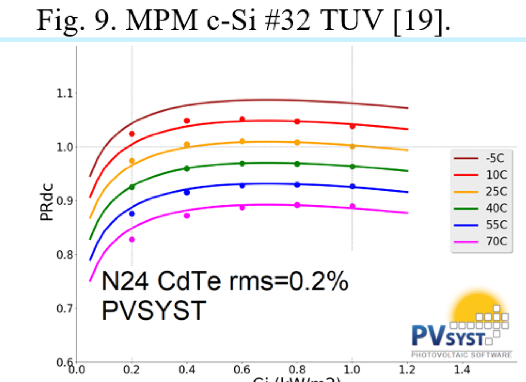


Fig. 12. MPM CdTe #24 PVSYST [15].

PVSYST's modified 1-diode Model

(9) CONCLUSIONS

- **Some empirical models give non constant temperature coefficients and/or poor fits at low or high light levels due to their unphysical coefficient dependencies**
- **An improved normalised "mechanistic performance model" (MPM) has been introduced which works well with all PV technologies tested both indoor and outdoor**
- **Gantner Instruments has added the MPM to their analysis software for both module and large power plant measurements**
- **The MPM fits IEC 61853 Matrix data (<=0.5% rms) reducing 23 measurements to 4-6 parameters. It could be used as a the standard interpolation method**

(10) ACKNOWLEDGEMENTS : Thanks to many staff at ASU, CREST, GI, JRC ESTI, PVGIS, SANDIA and TUV Rheinland for their help and discussions. Also CFV.

Next talk " 5CO.7.6 A Systematic Comparison of >7 Empirical Models Used for Energy Yield Predictions vs PV Technology" 33rd PVSEC Amsterdam Sep 2017