SRCL
Steve Ransome Consulting Limited

Poster #211 Area 7
15:30 – 17:00, Tues 7 Jun
PVSC 49, Philadelphia USA

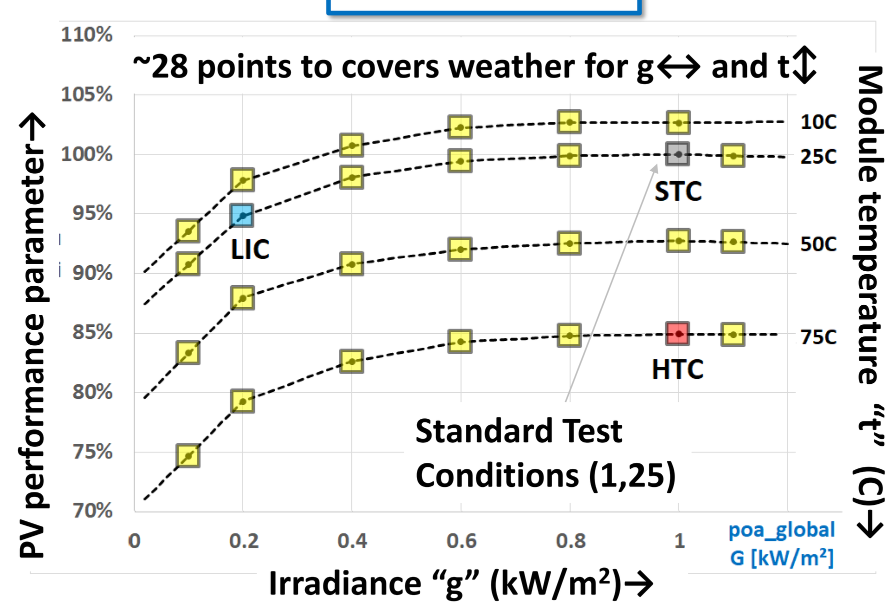
Benchmarking PV performance models with high quality IEC 61853 Matrix measurements (Bilinear interpolation, SAPM, PVGIS, MLFM and 1-diode)

Steve Ransome (SRCL) : steve@steveransome.com : www.steveransome.com

INTRODUCTION

- Many performance models give reasonably good fits to measurement data with existing finite scatter.
- More accurate matrices can now enable model fit benchmarking
- Residual fit analysis shows which model coefficients are needed for best fits with meaningful outputs
- An improved method for temperature coefficient extraction is given

IEC 61853 Matrix



Model fits are used to calculate energy yields vs. climate and validate measured performance

DEFINITIONS:

(Coefficients shaded)

Empirical Model :
non-physical coefficients, not useful values

Mechanistic Model :
physically meaningful, useful values

```
MLFM4: mechanistic performance model, 4 meaningful, normalised coefficients
    param  = c_1 +c_2*t +c_3*log10(g) +c_4*g # not for v_oc # c_4*g to fit r_series loss
    * v_oc = c_1 +c_2*t +c_3*log10(g)*t_K/t_stc_K +c_4*g # v_oc only
SAPM: "partly mechanistic" dimensioned
    v_mp   = vmpo +c2*s*d*ln(g) +c3*s*(d*ln(g))^2 + bvmpo*t # no term by g for r_series
    i_mp   = impo *(c0*g+c1*(g)^2)*(1+aimp*t)
    pr_dc  = v_mp * i_mp / p_mp_stc / g ; d=N *kb *(T+273.15)/q
    v_oc   = voco +c8*s*d*ln(g) +bvoco*t
PVGIS: 6-7 mostly empirical coefficients, no g term for r_series
    param  = k_0 +k_1*ln(g) +k_2*ln(g)² +k_3*t +k_4*t*ln(g) +k_5*t*ln(g)² +k_6*t²
Bi-lin: just linear interpolation and extrapolation to any matrix
```

AVG, STDEV RMSE (9 Si MODULES)

Parameters	A) MLFM4	B) SAPM	C) PVGIS
norm_i_sc	0.16%	0.42%	0.36%
norm_v_oc *	0.08%	0.07%	0.12%
norm_i_mp	0.23%	0.29%	0.32%
norm_v_mp	0.20%	0.25%	0.27%
norm_ff	0.31%	0.56%	0.23%
pr_dc	0.17%	0.40%	0.32%
Avg all params	0.19%	0.33%	0.27%

Average RMSE fits by model

Parameters	A) MLFM4	B) SAPM	C) PVGIS
norm_i_sc	0.05%	0.08%	0.11%
norm_v_oc *	0.01%	0.03%	0.06%
norm_i_mp	0.05%	0.08%	0.14%
norm_v_mp	0.05%	0.06%	0.07%
norm_ff	0.07%	0.11%	0.05%
pr_dc	0.05%	0.09%	0.09%
Avg all params	0.04%	0.06%	0.07%

Stdev RMSE fits by model

The pvgis pr_dc equation used for all parameters.

1-DIODE MODELS

1-diode models (PVSYST, CEC, de Soto etc.) define their intrinsic parameter dependencies differently e.g. r_series(g, t), r_shunt(g, t), I_o(g, t) but aren't measured by matrices

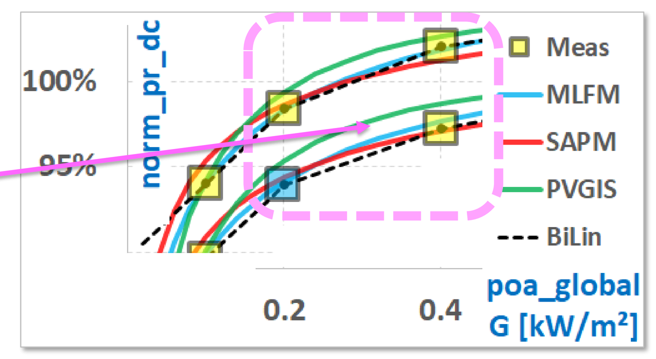
1-diode has not yet been able to analysed

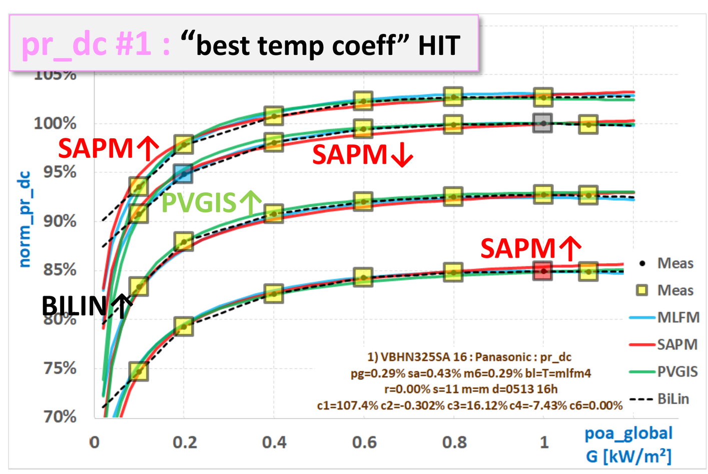
FITTING pr_dc FOR DIFFERENT MODULES

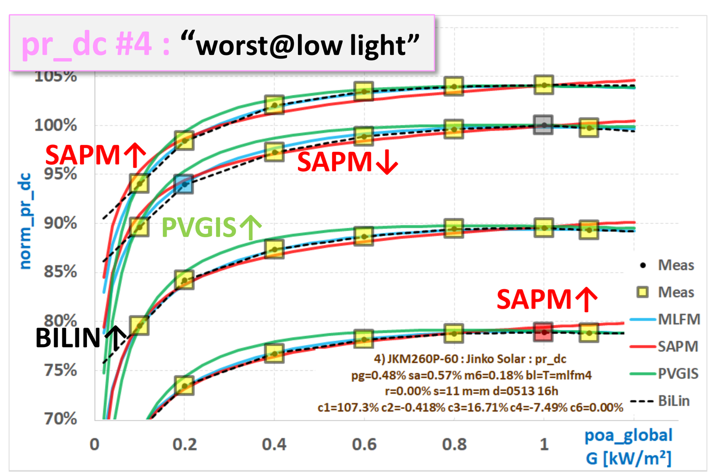
"normalised efficiency pr_dc"
= meas_eta_mod / stc_eta_mod
= meas_p_mp / stc_p_mp / g

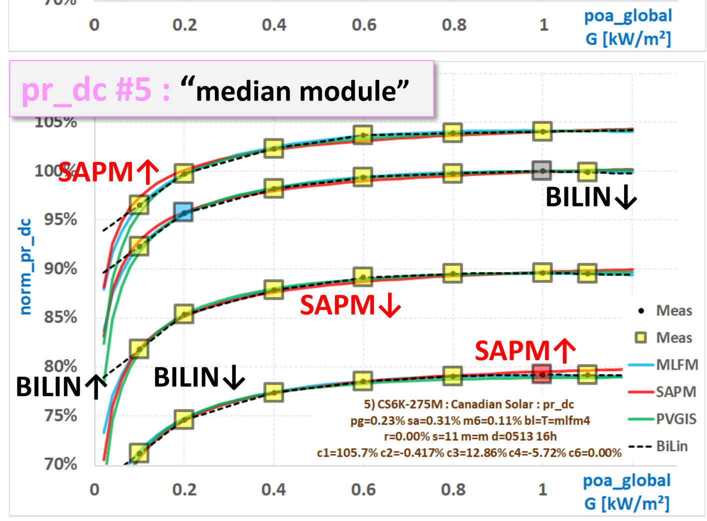
Fit models to data to minimize RMSE.

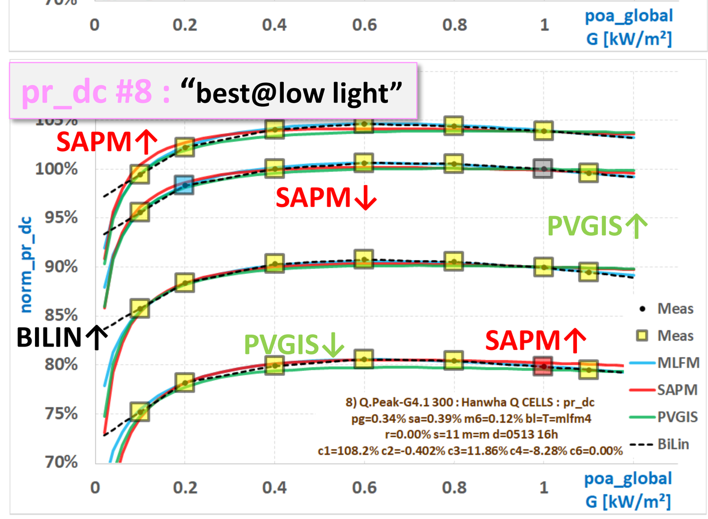
Analyse any discrepancies between models(lines) and measurements (dots) vs. irradiance→, temperature↓, and module









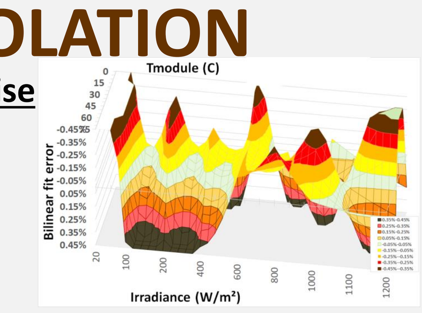


Some systematic residuals can be seen by model vs. irradiance e.g. "↑↓↑"

BILIN-INTERPOLATION

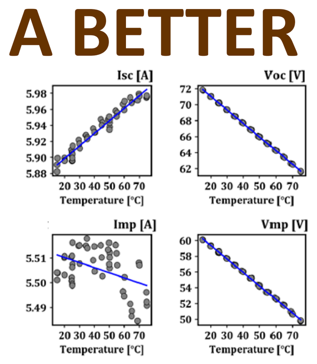
pr_dc(g,t) small random noise

If there's any curvature, noise or extrapolations then fits are inaccurate



BILIN is affected by noise and extrapolations

A BETTER METHOD TO FIND TEMP. COEFFS.



IEC 61853 values and linear trend fits

Temperature coefficients can be simply and accurately calculated from good model fits without needing extra measurements and trend fits

e.g. temp. coeff. = fit(g=1, t=26C) / fit(g=1, t=25C) - 1 (unit 1/K)

PVGIS has non-linear temp. coeffs., measured data are usually linear.

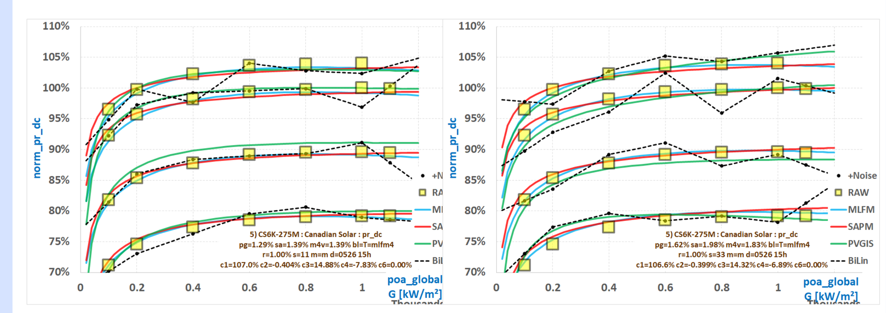
Trend fits vs. predicted model temp. coeffs.

IEC trend temp. coeffs.	Parameters	A) MLFM4	B) SAPM	C) PVGIS	Common
0.03%	norm_i_sc	0.00%	0.00%	0.03%	alpha
-0.24%	norm_v_oc *	-0.01%	0.00%	0.02%	beta
0.00%	norm_i_mp	0.00%	0.00%	0.05%	
-0.29%	norm_v_mp	-0.01%	0.00%	0.04%	
-0.08%	norm_ff	-0.01%	0.00%	0.05%	
-0.30%	pr_dc	-0.01%	0.00%	0.05%	gamma
1/K	Residual error	(1) < +/- 0.01%	(1) < +/- 0.01%	(2) ~ +0.02-5%	

Improved procedure : Fit matrix with MLFM4 then use c_2 as temperature coefficient.

FITS TO NOISY DATA

Matrices with 1% rmse added to v and i points separately, 2 random seeds shown, Yellow = noiseless. Fit to noisy points



MLFM4 and SAPM are mechanistic, with linear temp. coeffs. and sensible behaviour vs. irradiance.
PVGIS has non-linear empirical terms which fit noise with unphysical non linear temp. coeffs.
BILIN just interpolates/extrapolates the noise.

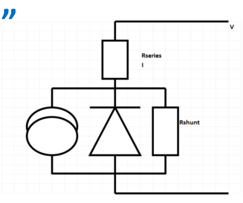
PVGIS + BILIN : poor fits when noisy
MLFM4 + SAPM : best at coping with noisy data

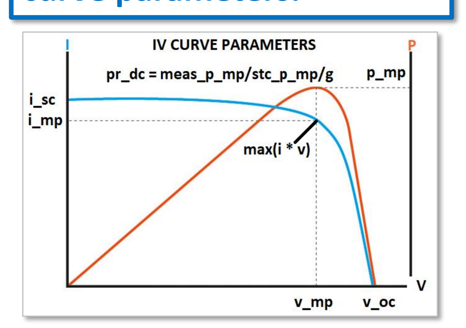
FITTING IV CURVE PARAMETERS (MODULE #5)

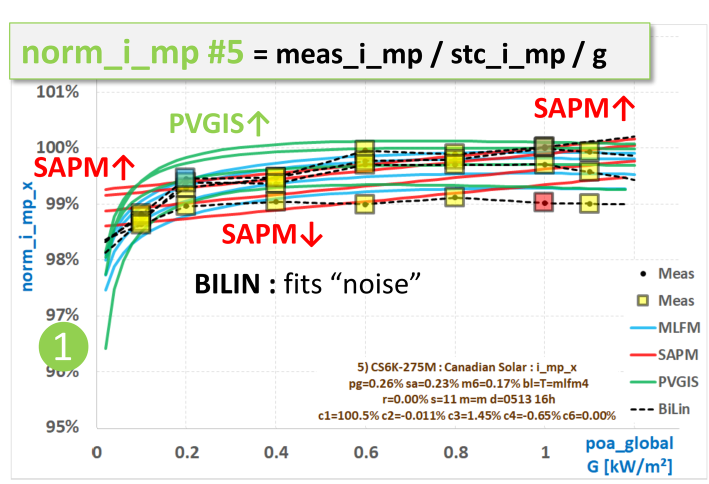
Now analyse any discrepancies for other IV curve parameters.

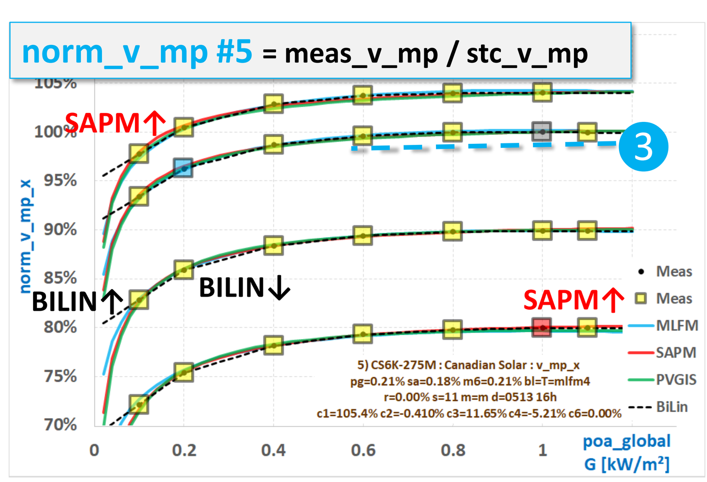
① i_mp only varies ~1% so has little effect on pr_dc (=norm_i_mp*norm_v_mp) discrepancies are almost irrelevant

The "Slope at high irradiance" v_mp and pr_dc is lowered by any i².r_series loss as i~g
v_oc has no r_series loss as i=0





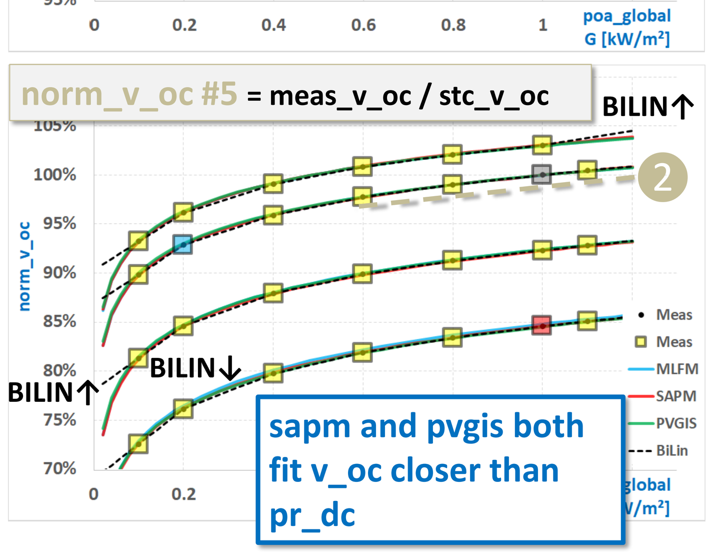




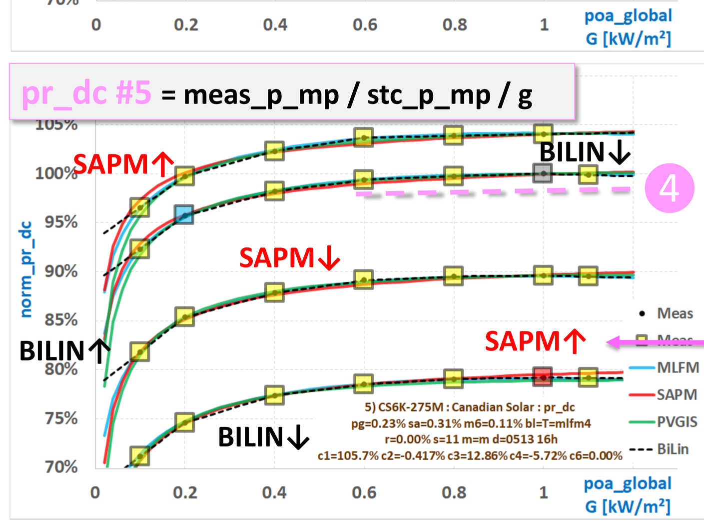
③ v_mp has an "i_mp².r_series loss" which flattens curves at high g

② v_oc i=0 so "i².r_series loss"=0, curves are rising at high irradiance.

④ pr_dc curve shape is dominated by shape of v_mp



sapm and pvgis both fit v_oc closer than pr_dc



Overpredictions at high irradiance from SAPM and PVGIS are caused by them not modelling the r_series loss correctly.

MLFM models it OK

SUMMARY OF DATA FITTING BY MODELS

MODEL RESIDUALS vs. IRRADIANCE AND FIT PARAMETER (=fit, ↑overestimate, ↓underestimate)

Model name	A) MLFM4+			B) SAPM			C) PVGIS			D) Bi-Linear		E)
Irradiance range g (kW/m2)	<0.2	0.2 - 0.6	>0.6	<0.2	0.2 - 0.6	>0.6	<0.2	0.2 - 0.6	>0.6	<0.2	0.2 - 0.6	>0.6
pr_dc (r_series loss)	=	=	=	↑	↓	↑	=	↑	↕	↑	=	↓
v_mp (r_series loss)	=	=	=	=↑	=	=↑	=	↑	=↓	↑	↓	=
imp (smaller so noisier)	=	=	=	↑	↓	↑	=	↑	=	fits noise		
voc (no r_series loss)	=	=	=	=	=	=	=	=	=	↑	↓	↑

AVERAGE RESIDUAL FIT ERROR (pr_dc FOR 9 MODULES)

	A) MLFM4+	B) SAPM	C) PVGIS	D) Bi-Linear
Avg nRMSE pr_dc	0.17%	0.40%	0.32%	n/a
Std nRMSE pr_dc	0.05%	0.09%	0.09%	n/a

SUMMARY OF MODEL PERFORMANCE

A) MLFM4+	B) SAPM	C) PVGIS	D) Bi-Linear
Voc fit now improved	Residuals depend on g	Residuals depend on g	No coefficients
Useful orthogonal coeffs	Overestimates high g	Residuals vary by module	Poor fit to noisy data
Good temp coeffs	Good temp coeffs	Unphysical fits	Poor with extrapolated
Best model overall	Physical fits	Non-linear temp coeffs	Can't fit very dense matrix

- Models need an i^2.r_series term for best fits to pr_dc and v_mp
- Accurate temperature coefficients can be found just by fitting matrix data
- MLFM4 has about 50% of RMSE of other models tested

References : www.steveransome.com email : steve@steveransome.com
https://pvpmc.sandia.gov/ https://github.com/pvlib/pvlib-python