

BUILDING A WORLD OF DIFFERENCE

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BLACK & VEATCH PAN FILE CREATION SERVICE

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AGENDA

- 1) Introduction: B&V PAN File Creation Service
- 2) Module Performance Characterization
 - Data Validation
 - Data Normalization
- 3) PAN File Optimization
 - Base Case
 - Curve-Fitting
 - Evaluation
- 4) Impact on Energy Production Estimates
- 5) Challenges/Limitations

INTRODUCTION

PAN files created using PVsyst default values often result in misrepresentation of expected module performance

Industry needs 3rd party development/validation to help ensure performance modeled within PVsyst represents expected performance

B&V launched custom PAN file creation service with the goal of more accurately representing measured module performance within PVsyst

Two step process:

- 1) Module Performance Characterization
- 2) PAN file parametric optimization to match measurements

Developers and Financiers need custom PAN files from independent 3rd parties for energy forecasts that don't leave any kWh off the table



MODULE PERFORMANCE CHARACTERIZATION—PERFORMANCE CURVES

Characterize photovoltaic (PV) module electrical performance as a function of irradiance and temperature

According to IEC 61853: PV Module Performance Testing and Energy Rating

IRRADIANCE	Module temperature			
$\text{W}\cdot\text{m}^{-2}$	15 °C	25 °C	50 °C	75 °C
1 100	NA			
1 000				
800				
600				
400				NA
200			NA	NA
100			NA	NA

- 5 samples
- Exposed to outdoor light soak until power output stabilized
- 22 temperature/irradiance conditions
- Indoor measurements, AM 1.5

Process begins with indoor IV-curve measurement of stabilized modules

MODULE PERFORMANCE CHARACTERIZATION—DATA VALIDATION & NORMALIZATION

Measured IV curve data is used to generate normalized efficiency/power output coefficients for each sample

Pmp/Efficiency most relevant, controllable parameter within PVsyst (discussed later)

Sample 1: Normalized Efficiency				
	15	25	50	75
1100	0.000	0.994	0.892	0.783
1000	1.042	1.000	0.896	0.789
800	1.049	1.006	0.904	0.795
600	1.052	1.011	0.908	0.799
400	1.050	1.005	0.900	0.000
200	1.018	0.975	0.000	0.000
100	0.977	0.930	0.000	0.000

Sample 2: Normalized Efficiency				
	15	25	50	75
1100	0.000	0.994	0.891	0.788
1000	1.041	1.000	0.896	0.793
800	1.049	1.008	0.904	0.801
600	1.056	1.013	0.909	0.805
400	1.053	1.011	0.904	0.000
200	1.025	0.981	0.000	0.000
100	0.986	0.938	0.000	0.000

Sample 3: Normalized Efficiency				
	15	25	50	75
1100	0.000	0.997	0.891	0.784
1000	1.041	1.000	0.896	0.790
800	1.050	1.008	0.904	0.797
600	1.055	1.011	0.910	0.801
400	1.051	1.006	0.904	0.000
200	1.018	0.976	0.000	0.000
100	0.977	0.932	0.000	0.000

Sample 4: Normalized Efficiency				
	15	25	50	75
1100	0.000	0.996	0.895	0.792
1000	1.044	1.000	0.900	0.796
800	1.051	1.008	0.905	0.804
600	1.055	1.011	0.909	0.806
400	1.051	1.004	0.904	0.000
200	1.021	0.977	0.000	0.000
100	0.982	0.933	0.000	0.000

Sample 5: Normalized Efficiency				
	15	25	50	75
1100	0.000	0.996	0.892	0.790
1000	1.041	1.000	0.896	0.795
800	1.047	1.006	0.903	0.801
600	1.050	1.010	0.907	0.804
400	1.047	1.006	0.899	0.000
200	1.017	0.976	0.000	0.000
100	0.977	0.934	0.000	0.000

Measured performance is represented as coefficients with respect to nominal (STC) rating

MODULE PERFORMANCE CHARACTERIZATION—DATA VALIDATION & NORMALIZATION

Data validation steps:

Isc linearity

$$\widehat{I_{sc}}(G) = \left(\frac{G_0}{G}\right) \cdot \frac{I_{sc}(G)}{I_{sc}(G_0)} \quad , \quad G_0 = 1000 \left[\frac{W}{m^2}\right]$$

Measure of flash test equipment accuracy at low light levels

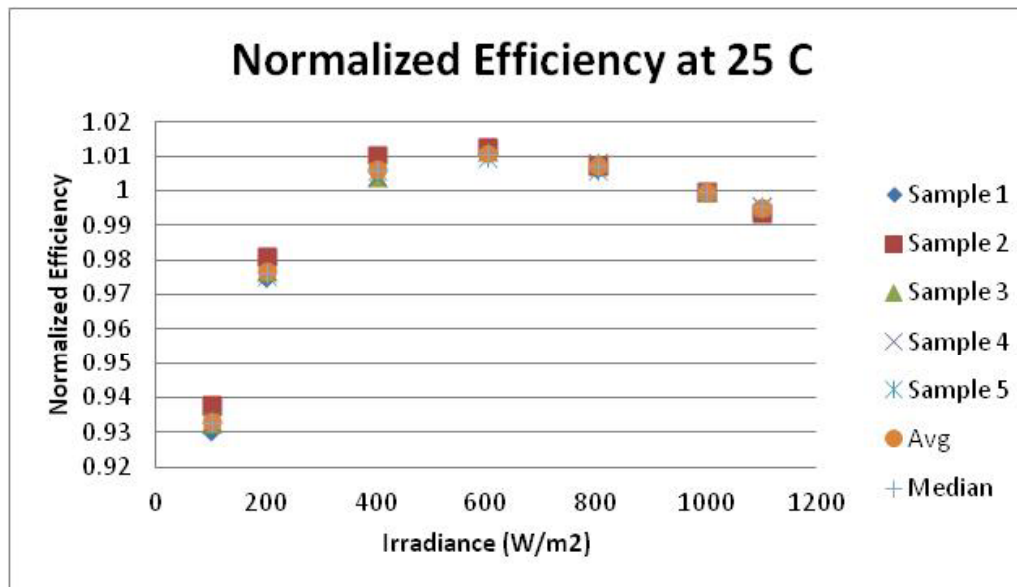
Data quality checks implemented for measurement accuracy and sample outliers

MODULE PERFORMANCE CHARACTERIZATION—DATA VALIDATION & NORMALIZATION

Data validation steps:

Isc linearity

Sample uniformity



Variation for all samples at all temperatures and irradiance conditions falls within the measurement tolerance of flash tester

Data quality checks implemented for measurement accuracy and sample outliers

MODULE PERFORMANCE CHARACTERIZATION—DATA VALIDATION & NORMALIZATION

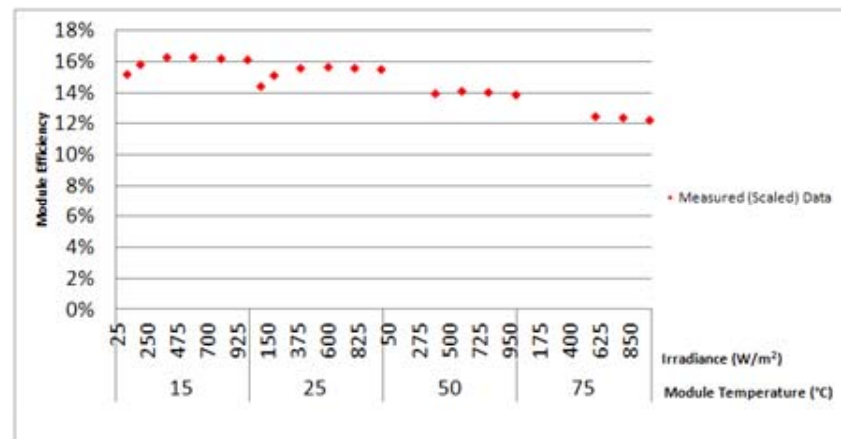
Data validation steps:

Isc linearity

Sample uniformity

Coefficients are averaged and used to produce “Expected IEC 61853 Pmp” dataset for a module with nominal output

EXPECTED POWER OUTPUT BASED ON NAMEPLATE				
	15	25	50	75
1100		328.44	294.42	259.89
1000	312.51	300.00	269.01	237.73
800	251.82	241.74	217.00	191.96
600	189.65	182.00	163.52	144.53
400	126.03	120.76	108.24	
200	61.18	58.62		
100	29.40	28.00		



PAN FILE OPTIMIZATION – BASE CASE

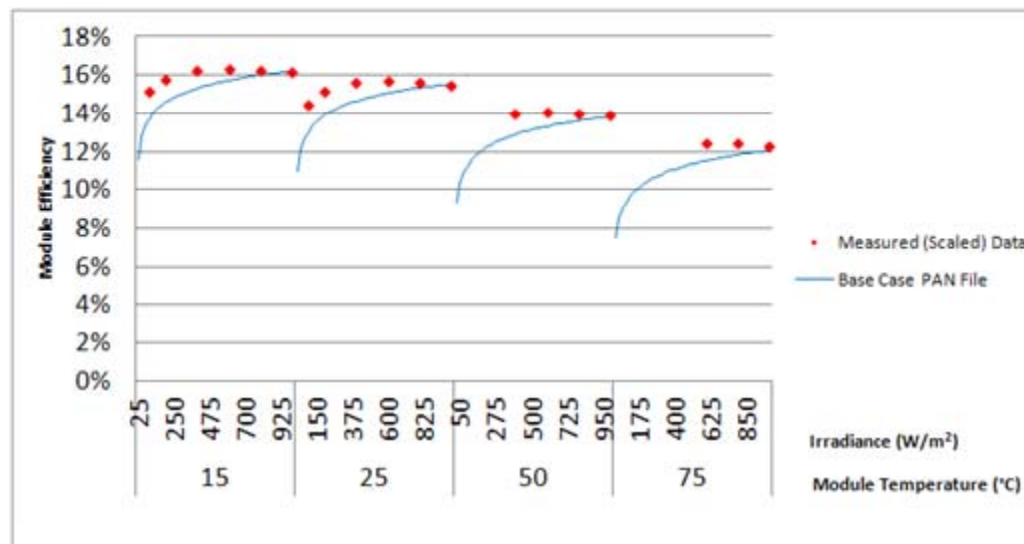
Utilize Datasheet IV curve characteristics at STC

Model Base Case PAN file using PVsyst default values

Shunt Resistance (Rsh) Shunt Resistance at $G_{inc} = 0^*$ (Rsh, G = 0)

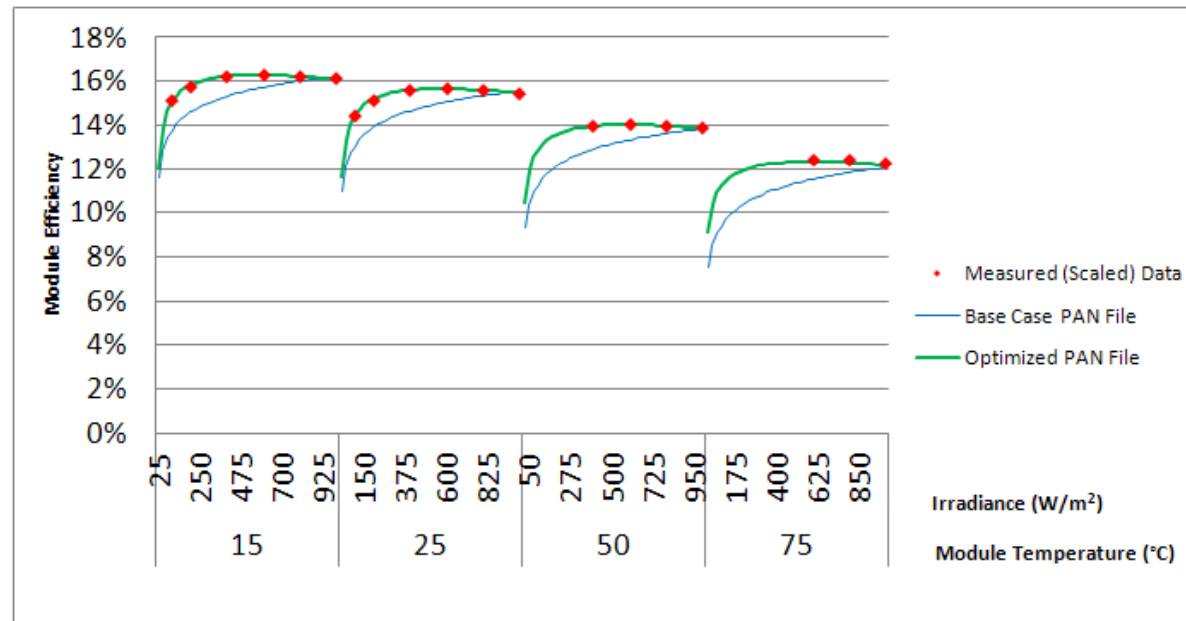
Series Resistance (Rs) Exponential Parameter* (Exp)

*Describes exponential behavior of Rsh as a function of incident irradiance



Datasheet electrical parameters + PVsyst defaults are starting point of optimization analysis

PAN FILE OPTIMIZATION – CURVE-FITTING



Algorithmically vary PAN file parameters until residuals minimized

Systematic order of operations based on sensitivity analysis

Weighted toward typical operational temperature, 50 °C curves
(secondary consideration)

**Parametric optimization to minimize residuals
with respect to measured efficiency curves**

IMPACT ON ENERGY PRODUCTION ESTIMATES

- Default PAN files typically underestimate performance in low- and intermediate-light conditions
- Optimized PAN Files result in 0.1-0.3% RSS (Default PAN file RSS: 2-4%)
- Estimated impact to production estimates: 2-5% gain in energy vs using default PAN files, depending on location

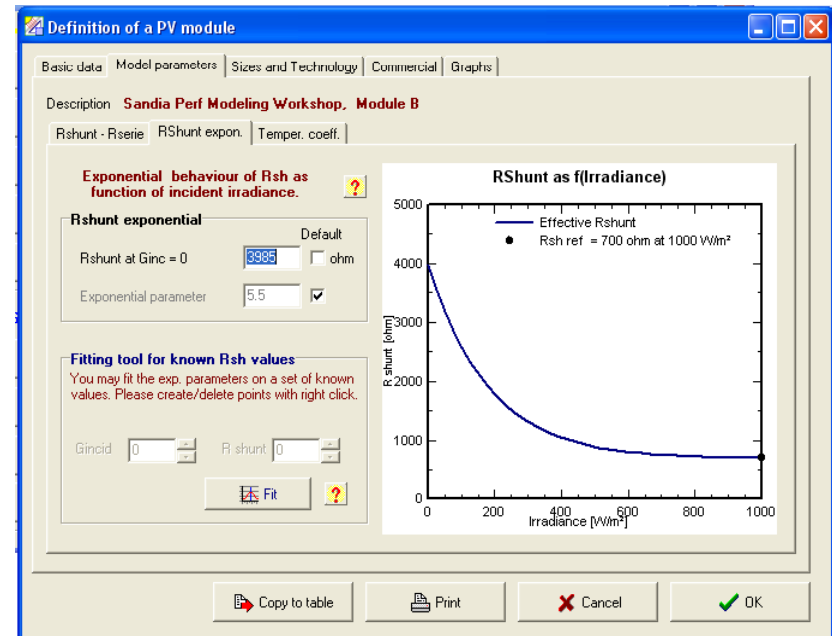
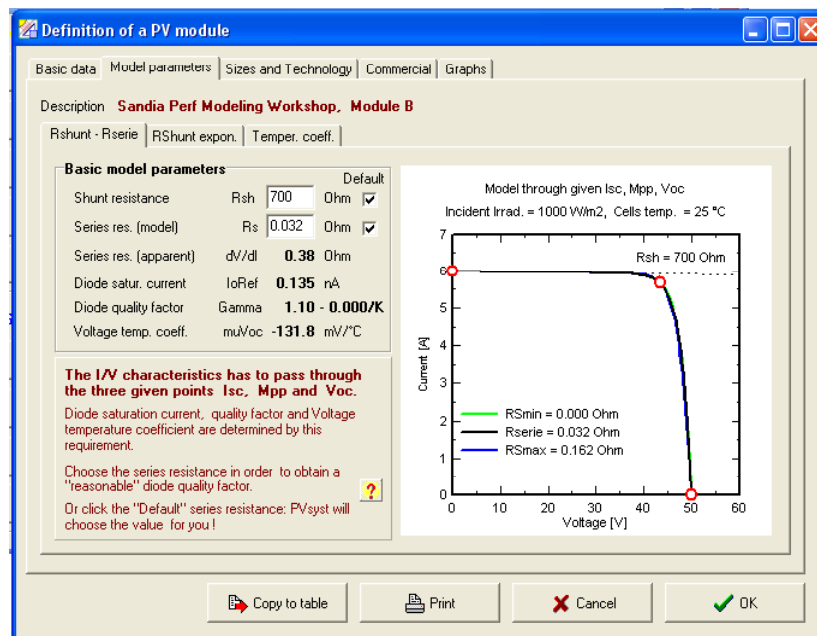
Improvement in accuracy of optimized PAN files results in higher forecasted yield



CHALLENGES/LIMITATIONS

Module resistances are selected to best fit measured data

Parameters do not represent the typical physical meaning



Module resistances are treated as non-physical curve-fitting parameters

CHALLENGES/LIMITATIONS

Singl-diode model has interdependencies, thus optimized PAN file values are non-physical

- Temperature coefficient of Voc is tied to selected Rs value
 - not always possible to match manufacturer's specification
 - Impacts calculation of IV curves at non-STC conditions

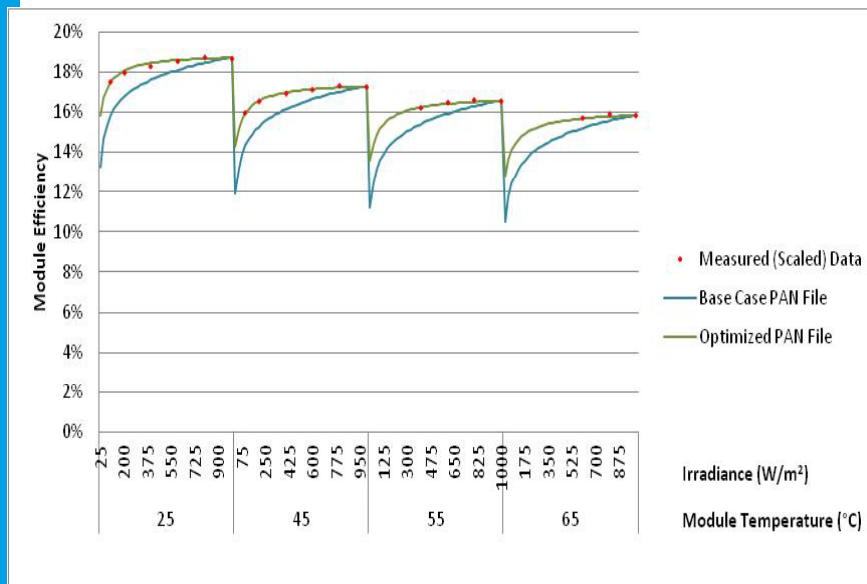
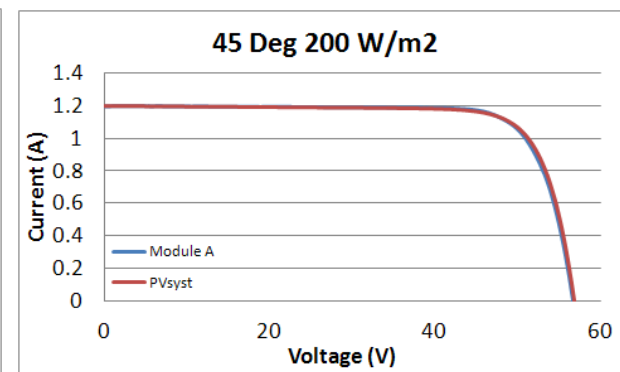
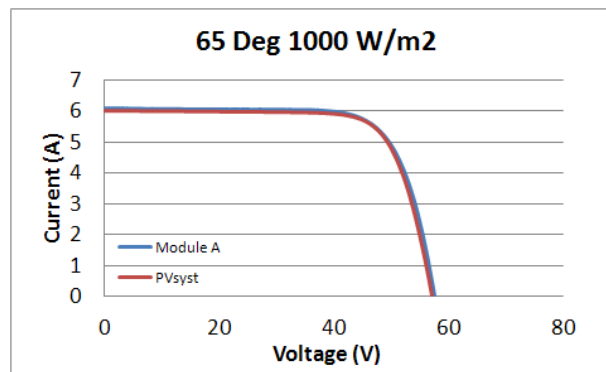
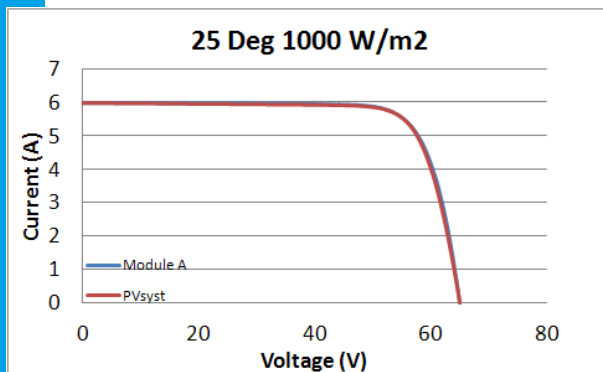
PVsyst calculates 3 points from each non-STC IV curve [(0, Isc), (Vmp, Imp), and (Voc, 0)] using input resistance values

While the temperature coefficient Isc specified, the temperature coefficient of Voc is product of the model

However we can force the model to match the measured product of $Imp \cdot Vmp$

Due to interdependencies, B&V optimizes with respect to measured efficiencies

RESULTS FROM MODULE A ANALYSIS



Temperature (°C)	Irradiance (W/m ²)	Error in I _{sc}	Error in V _{oc}	Error in P _{mp}
25	1000	0.003%	0.015%	0.029%
	600	0.025%	-0.233%	-0.250%
	200	-0.267%	-0.261%	-0.320%
45	1000	0.854%	0.155%	0.115%
	600	0.255%	0.094%	-0.140%
	200	-0.035%	-0.115%	0.104%
65	1000	1.279%	0.656%	0.365%
	600	0.750%	0.602%	0.439%

CHALLENGES/LIMITATIONS

Single-diode model has interdependencies, thus optimized PAN file values are non-physical

- Temperature coefficient of P_{mp} is treated as a fitting parameter
 - coupled with ideality factor, gamma
 - Impacts calculation of IV curves at non-STC conditions

Temperature coefficient of P_{mp} behaves as a non-physical fitting parameter

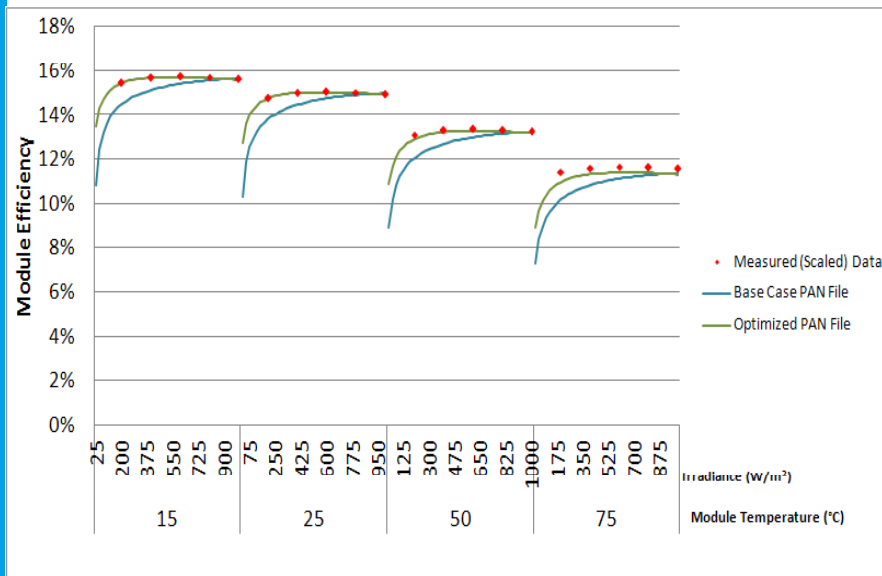
CHALLENGES/LIMITATIONS

Example:

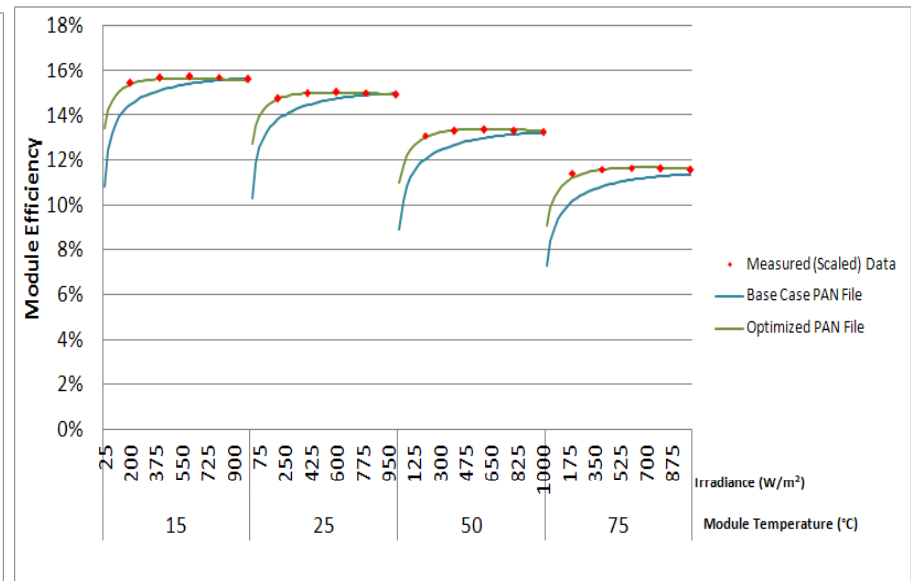
Synthetic dataset was created using measured Pmp data at 25°C which was extrapolated to other temperatures using datasheet temperature coefficient of Pmp

$$\mu_{Pmp} = -0.451\%$$

Irradiance (W/m ²)	Temperature (degC)				
	1	15	25	50	75
1000		303.08	290.00	257.30	224.61
800		243.92	233.40	207.08	180.77
600		183.36	175.45	155.67	135.89
400		121.70	116.45	103.32	90.19
200		59.94	57.35	50.89	44.42



Fit using datasheet Pmp temp. coeff:
 $\mu_{Pmp} = -0.451\%$ RSS = 0.74%

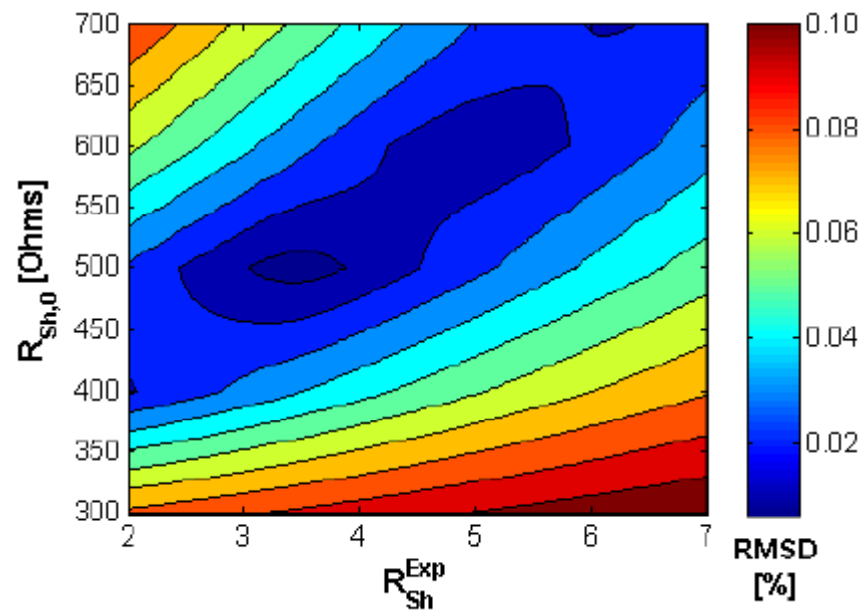


Fit using optimized Pmp temp. coeff:
 $\mu_{Pmp} = -0.419\%$ RSS = 0.29%

Temperature coefficient of Pmp behaves as a non-physical fitting parameter

CHALLENGES/LIMITATIONS

Non-unique solution to single-diode model



K. Sauer, T. Roessler, "Systematic Approaches to Ensure Correct Representation of Measured Multi-Irradiance Module Performance in PV System Energy Production Forecasting, Software Programs", 38th IEEE Photovoltaic Specialists Conference (PVSC), 2012

Residual- minimization is the critical metric

SUMMARY/ FUTURE WORK

- B&V PAN file creation service provides PAN files more closely matched to measured module behavior
- Represent expected efficiency curves of nameplate-rated modules operating in a stabilized condition
- PAN file parametric optimization performed to minimize residuals between modeled and measured data
 - PAN file parameters are treated as non-physical
 - Fit is weighted toward typical operational temperature
- 2-5% gain in forecasted energy expected, compared to default PAN files
- Future work: PVsyst 6 evaluation, IAM modifier, LID characterization

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