BUILDING A WORLD OF DIFFERENCE

May 1, 2013

# 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 on 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 | | |
|---|---|---|---|---|
| $W \cdot m^{-2}$ | 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

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

**Measure of flash test equipment accuracy at low light levels**

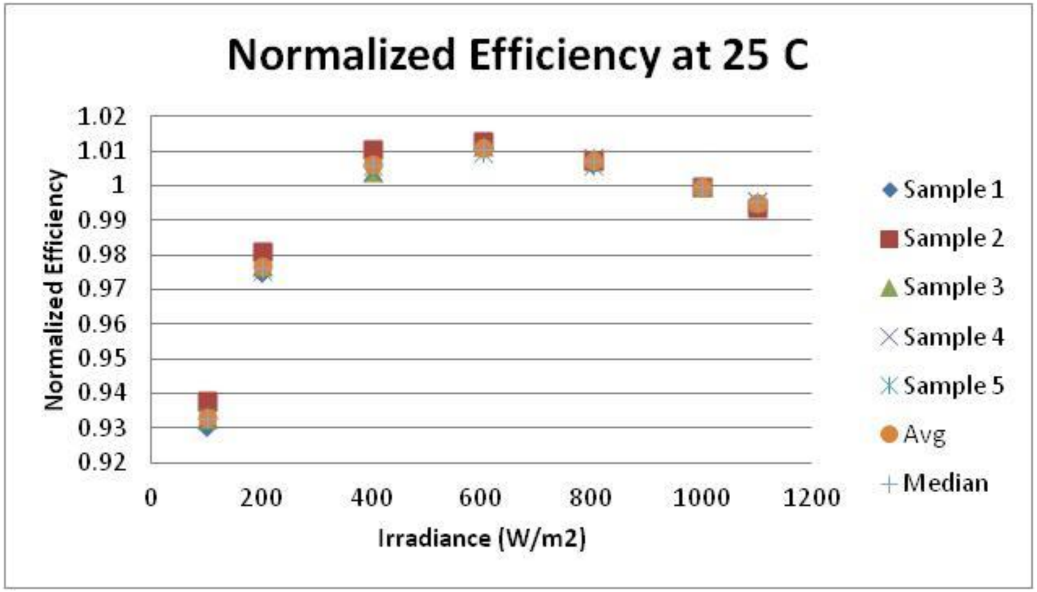
**Data quality checks implemented for measurement accuracy and sample outliers**

# 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**

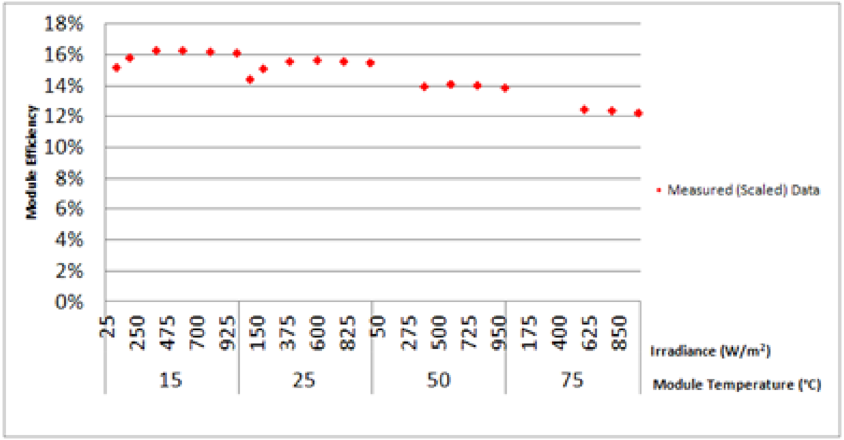
# MODULE PERFORMANCE CHARACTERIZATION—DATA VALIDATION & NORMALIZATION

**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 | | |




**Average expected Pmp/Efficiency curves are used as the target efficiency curves for PAN file optimization**

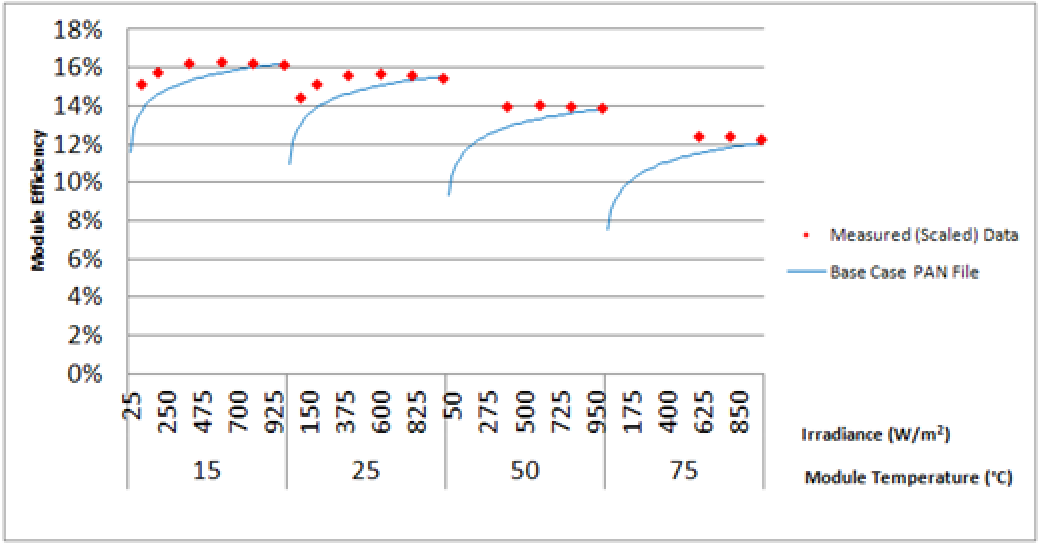
# PAN FILE OPTIMIZATION – BASE CASE

**Utilize Datasheet IV curve characteristics at STC**

**Model Base Case PAN file using PVsyst default values**

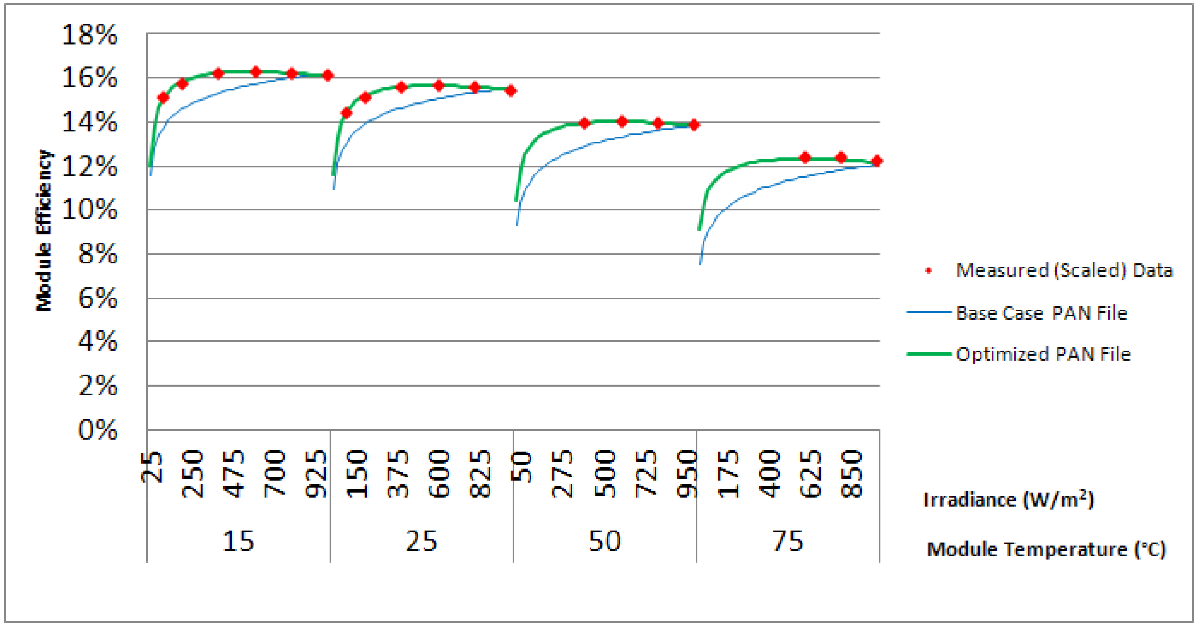
- **Shunt Resistance (Rsh)**
- **Shunt Resistance at $G_{inc}$ = 0* (Rsh, G =0)**
- **Series Resistance (Rs)**
- **Exponential Parameter* (Exp)**

*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

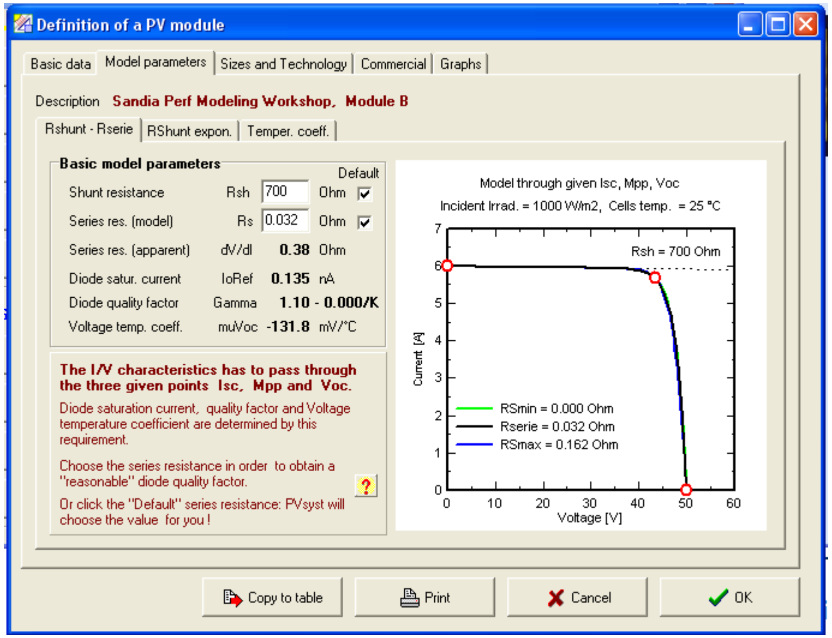
- **Default PAN files typically underestimate performance in low- and intermediate-light conditions**
- **Optimized PAN Files result in 0.1-0.3% RSS (Default PAN file RSS: 2-4%)**
- **Estimated impact to production estimates: 2-5% gain in energy vs using default PAN files, depending on location**

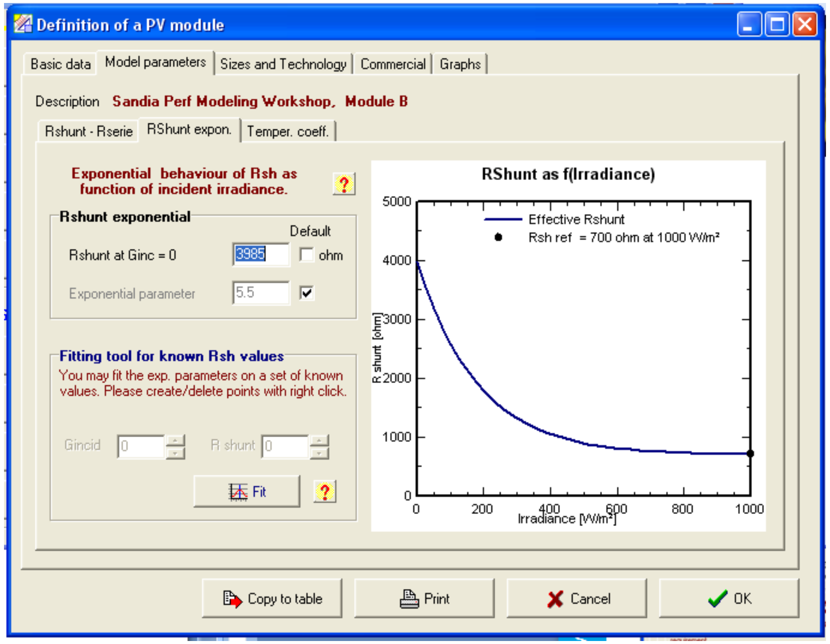
**Improvement in accuracy of optimized PAN files results in higher forecasted yield**

# 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

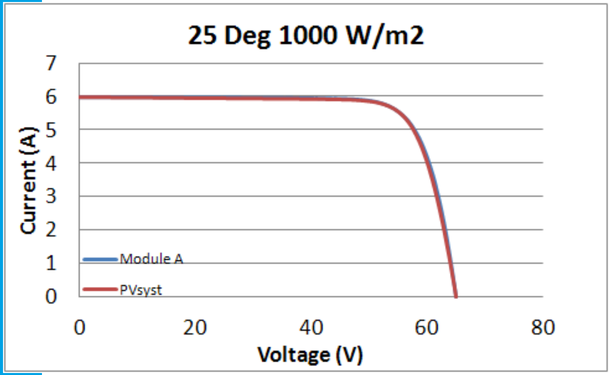
PVsyst calculates 3 points from each non-STC IV curve [(0, Isc), (Vmp, Imp), and (Voc, 0)] using input resistance values

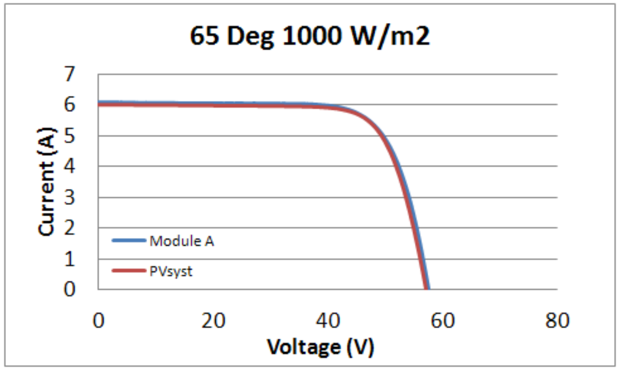
While the temperature coefficient Isc specified, the temperature coefficient of Voc is product of the model

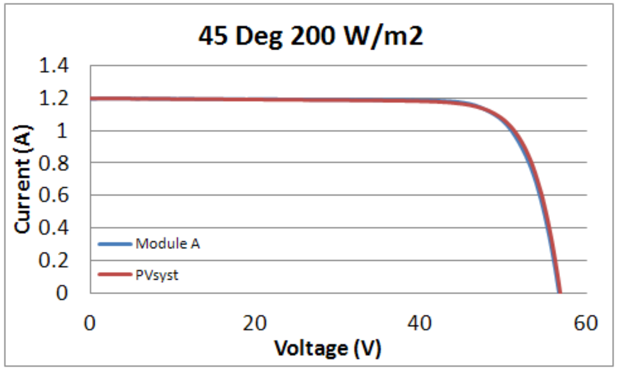
However we can force the model to match the measured product of Imp*Vmp

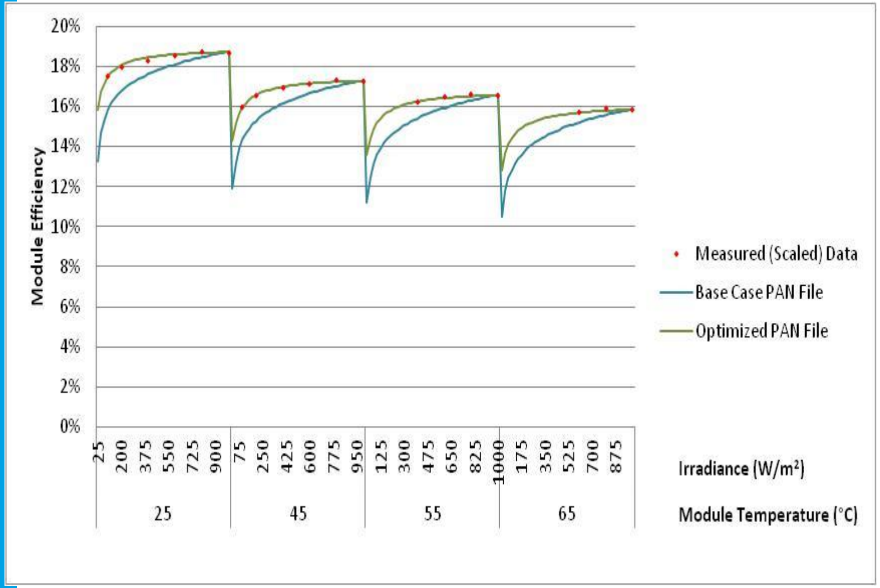
**Due to interdependencies, B&V optimizes with respect to measured efficiencies**

# RESULTS FROM MODULE A ANALYSIS




| Temperature (°C) | Irradiance (W/m2) | Error in Isc | Error in Voc | Error in Pmp |
|---|---|---|---|---|
| 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 Pmp is treated as a fitting parameter**
  - → **coupled with ideality factor, gamma**
  - → **Impacts calculation of IV curves at non-STC conditions**



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

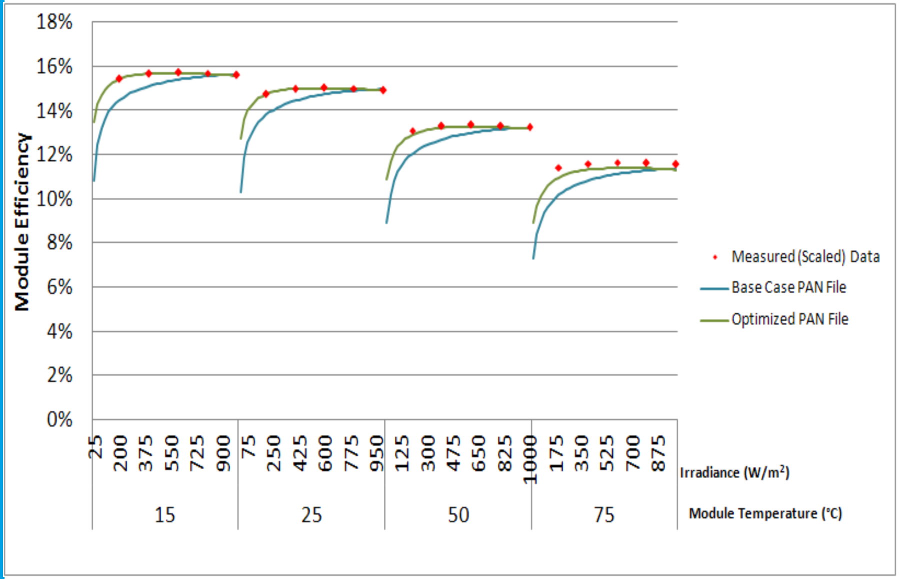
# CHALLENGES/LIMITATIONS

μPmp = -0.451%

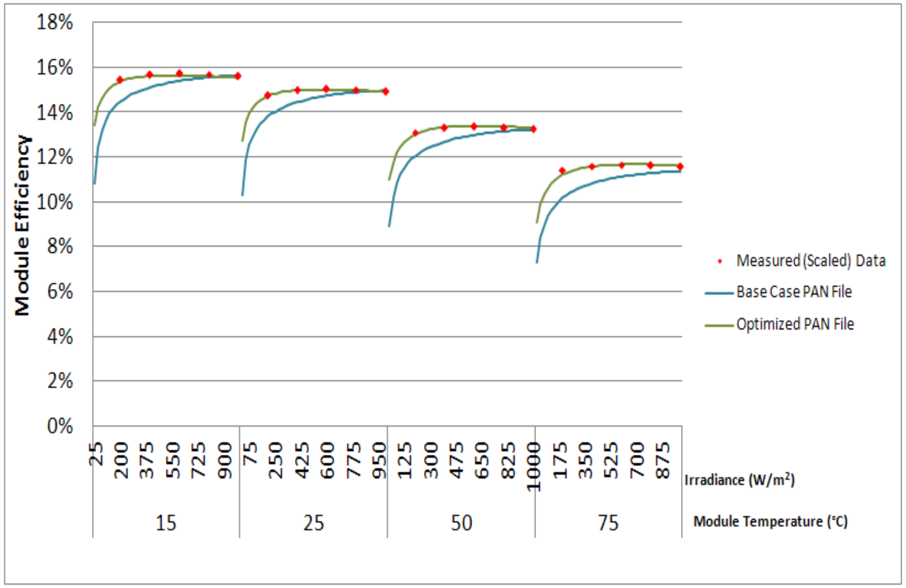
| Irradiance (W/m2) | Temperature (degC) 1 | 15 | 25 | 50 | 75 |
|---|---|---|---|---|---|
| 1000 | | 303.08 | 290.00 | 257.30 | 224.61 |
| 800 | | 243.92 | 233.40 | 207.08 | 180.77 |
| 600 | | 183.36 | 175.45 | 155.67 | 135.89 |
| 400 | | 121.70 | 116.45 | 103.32 | 90.19 |
| 200 | | 59.94 | 57.35 | 50.89 | 44.42 |

## Example:

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




Fit using datasheet Pmp temp. coeff:
μPmp = -0.451%  RSS = 0.74%

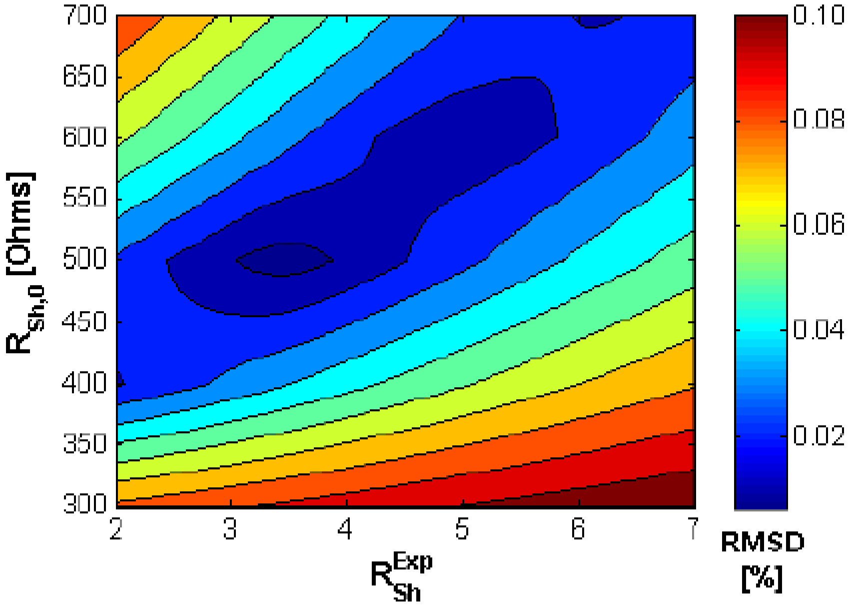



Fit using optimized Pmp temp. coeff:
μPmp = -0.419%  RSS =0.29%

**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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