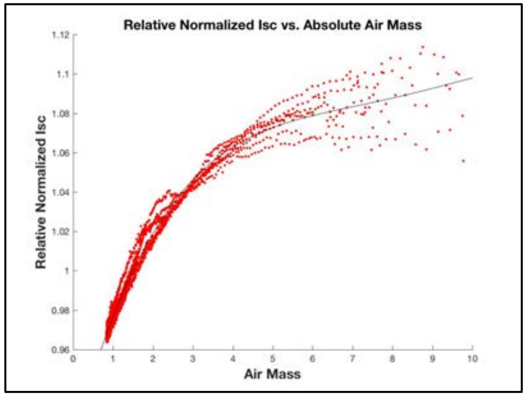

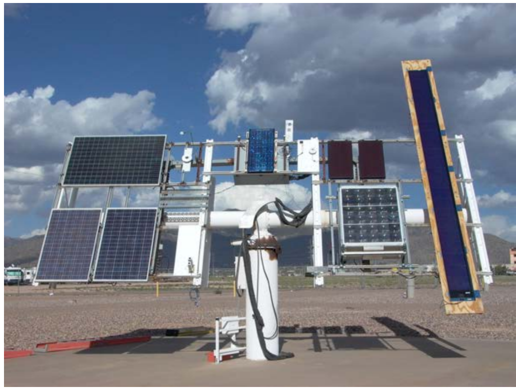

Assessment of the Accuracy of PV Performance Models for Predicting Multi-Year Field Performance of CIGS Systems.

Bruce King

9th PV Performance Modeling Workshop
6 December, 2017
SAND2017-12884C

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Goals

- Characterize degradation/stability across a range of CIGS products & technology
- Fielded systems
- Common operating environment
- Assess performance model accuracy

System Descriptions

Sandia National Laboratories

System	Cell	Package	Size (kW)	Installation	Age, months	Status
CIGS-1	discrete	Polymer/Flex	3.36	1/12	18	Inactive
CIGS-2	discrete	Glass-glass	2.2	1/12	45	Active
CIGS-3	discrete	Glass-glass	2.32	6/12	41	Active
CIGS-4	monolithic	Glass-glass	4.8	6/13	20	Inactive
CIGS-5	monolithic	Glass-glass	6	4/15	22	Active
CIGS-6	monolithic	Glass-glass	6	4/15	23	Active

- Grid-tied, 600VDC Central Inverters
- Independent DC monitoring (Voltage, Current), module temperature
- Local POA Irradiance, co-located weather platform
- 5-second sampling => 1 minute averages for analysis
- Nightly automated data screening (PECOS)

System Descriptions

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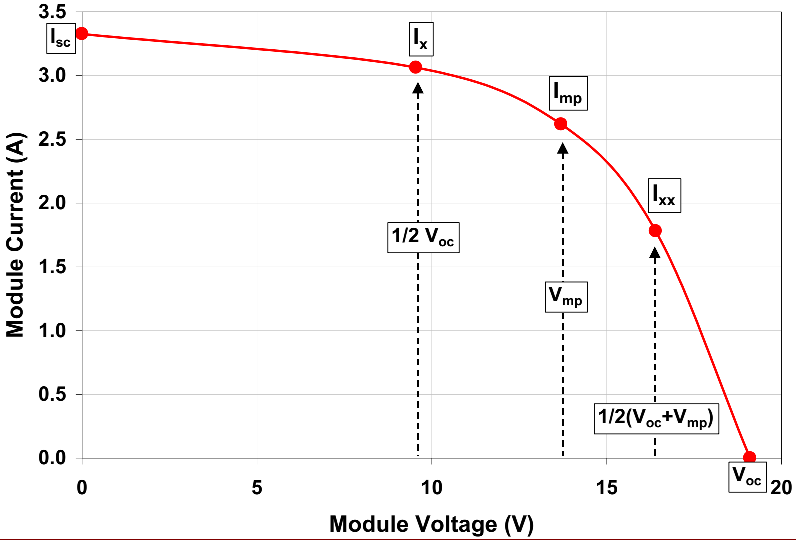
CIGS-5	monolithic	Glass-glass	6	4/15	22	Active
CIGS-6	monolithic	Glass-glass	6	4/15	23	Active

For this presentation, will focus only on the two oldest, active systems

Characterization Methods



Individual modules characterized before and after deployment

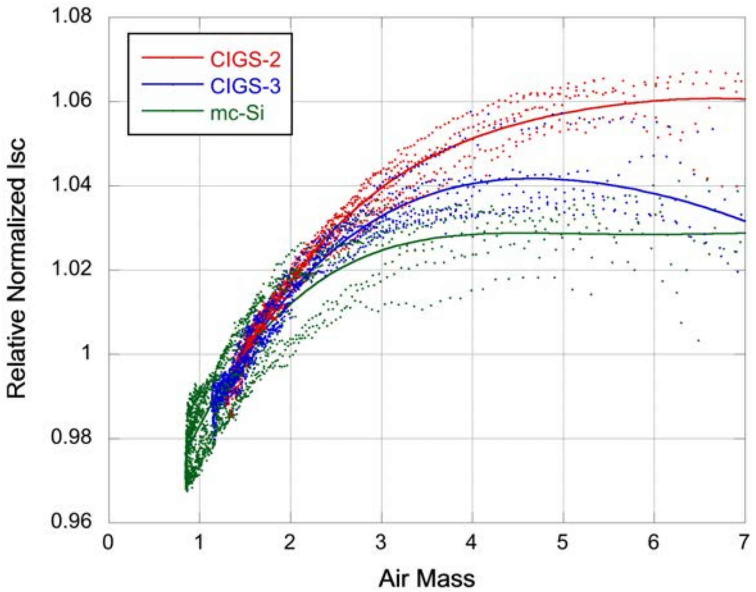
Outdoor Tracker Testing

- Two-axis solar tracker, modules held normal to sun, 2-4 weeks.
- Tracker held on sun from sunrise to sunset, multiple days, clear and cloudy conditions
- IV curves measured at 2 minute intervals
- Approximately 1000 IV curves minimum

Model Calibration

- Sandia Array Performance Model
- Semi-empirical model that defines five points on the IV curve
- Sub-components affecting performance
  - Air mass, f_1(AM) – proxy for spectral response
  - Diode Ideality factor , n

Air Mass(Spectral Response)

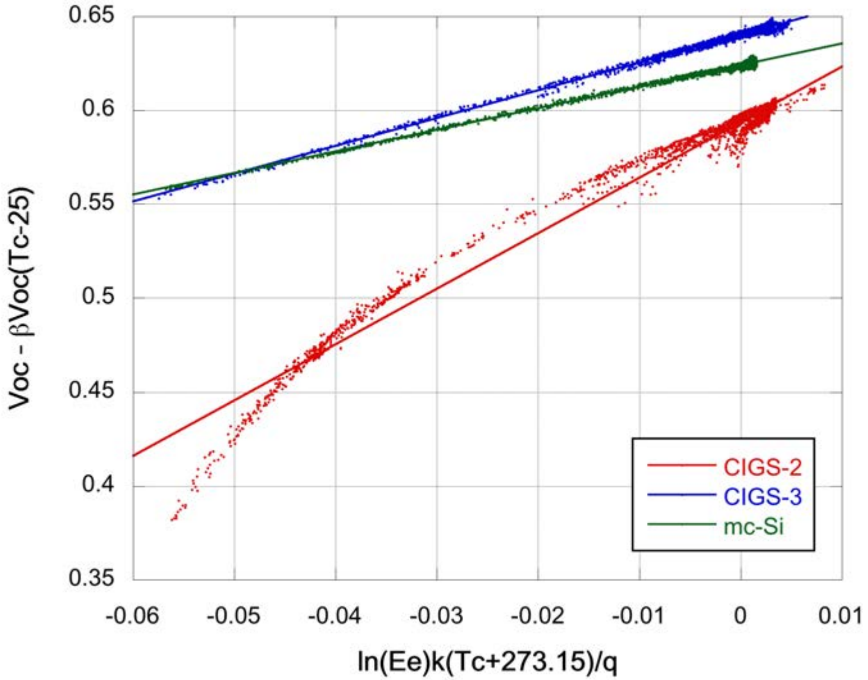


$$f_1(AM) = a_0 + a_1(AM) + a_2(AM)^2 + a_3(AM)^3 + a_4(AM)^4$$

System ID	$\Delta f_1(3), \%$	$\Delta \int_1^5 f_1(Am), \%$
CIGS-2	0.38%	0.50%
CIGS-3	-0.15%	-0.10%

- Proxy for solar spectral influence on I_{sc}. Dimensionless, defined to be 1 at AM1.5.
- CIGS typically displays pronounced response
  - f_1(AM) rises monotonically with increasing air mass
  - Peak values as high as 1.12 observed (typical c-Si peak ~1.02)
- Air mass response and by extension, spectral response, observed to be stable over multiple years

Diode Ideality Factor



$$V_{oc} = V_{oco} + N_s \delta(T_c) \ln(E_e) + \beta_{Voc}[T_c - T_0]$$

$$\delta(T_c) = \frac{nk[T_c + 273.15]}{q}$$

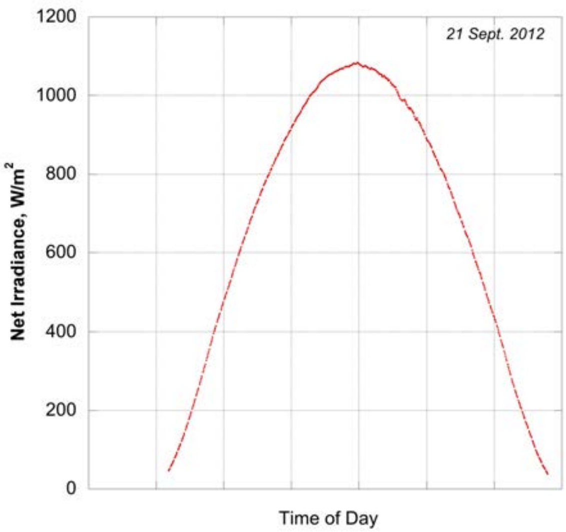
System	New	Aged	% Δ
CIGS-2	2.96	4.60	-55%
CIGS-3	1.48	1.51	-1.9%

- In both SAPM and CEC models, diode ideality factor (n) is expected to be constant
- Typical for “good” CIGS ~1.5-1.6 (c-Si ~1.1)
- CIGS-2 display non-linear behavior at low Irradiance/low cell temp
  - Non-linearity impacts the calculated value and prediction accuracy for voltage
- Pronounced change observed with age for CIGS-2

System Performance Modeling

- SAPM – use model coefficients calibrated from outdoor tracker testing
- Inputs – local weather, irradiance
  - 1-minute weather files from onsite weather station
  - Spans period of system operation, 2012-2017
  - Apply filters to remove night-time, low irradiance conditions, bad data
- Calculate Net plane of array irradiance, corrected for angle of incidence

$$E_{net} = E_{POA} - E_{DNI}\cos(AOI)[1 - f_2(AOI)]$$



System Performance Modeling

- Calculate effective cell temperature from net POA irradiance, ambient temperature and wind speed

$$T_c = E_{net}\left[e^{a+b*WS}\right] + \frac{E_{net}}{1000}\,\Delta T + T_a$$

- Calculate effective irradiance from air mass, net POA irradiance

$$E_e = f_1(AM)E_{net}$$

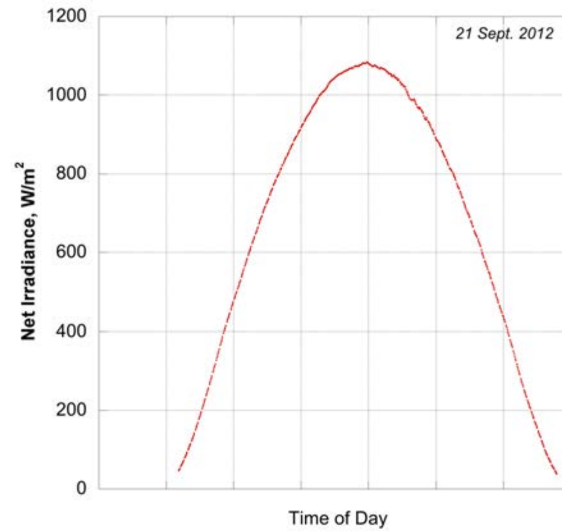
- Calculate current and voltage at max power

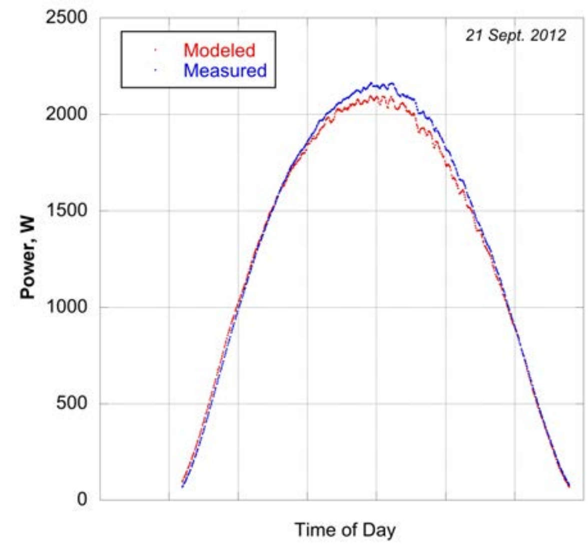
$$I_{mp} = I_{mpo}\left[C_0E_e + C_1E_e^2\right]\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right]$$

$$V_{mp} = V_{mpo} + C_2N_s\delta(T_c)\ln(E_e) + C_2N_s[\delta(T_c)\ln(E_e)]^2 + \beta_{Vmp}[T_c - T_0]$$

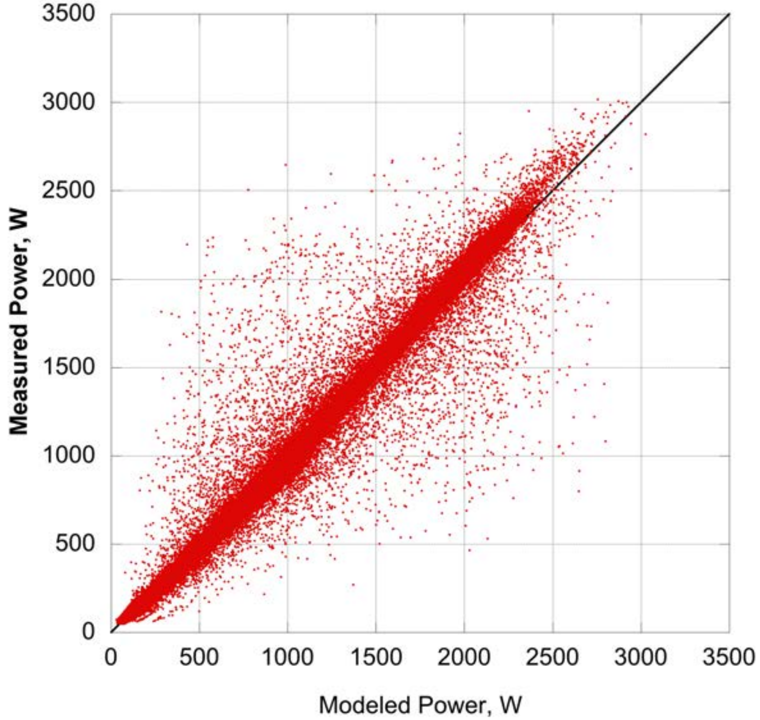
$$P_{mp} = I_{mp}V_{mp}$$

- Compare Measured vs Modeled for period of operation (2012-2017)

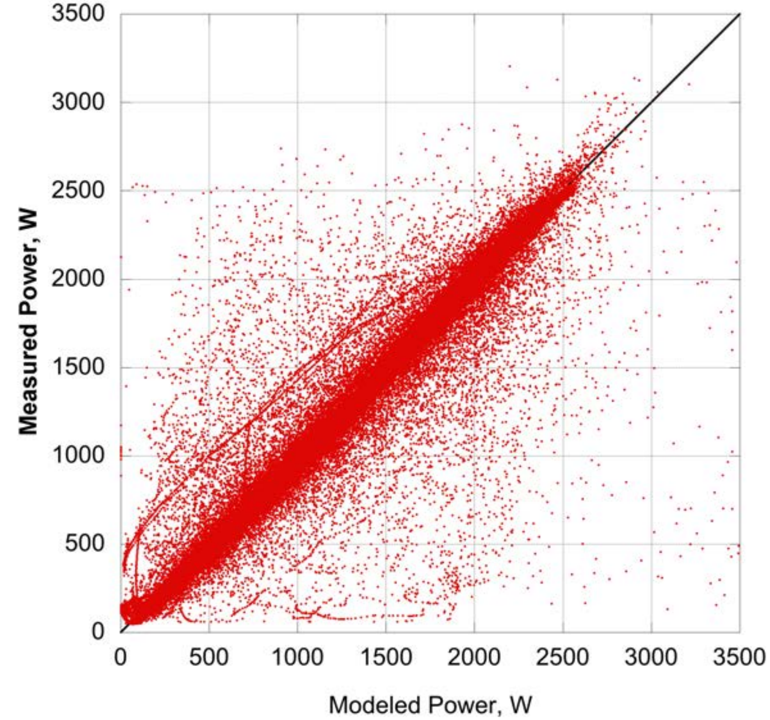




Results – CIGS-3: All Conditions



2012

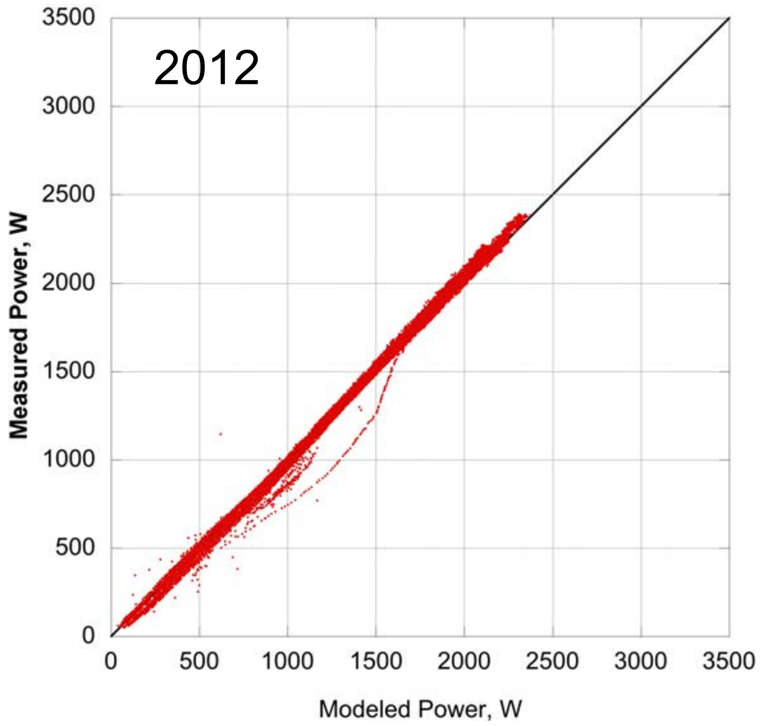


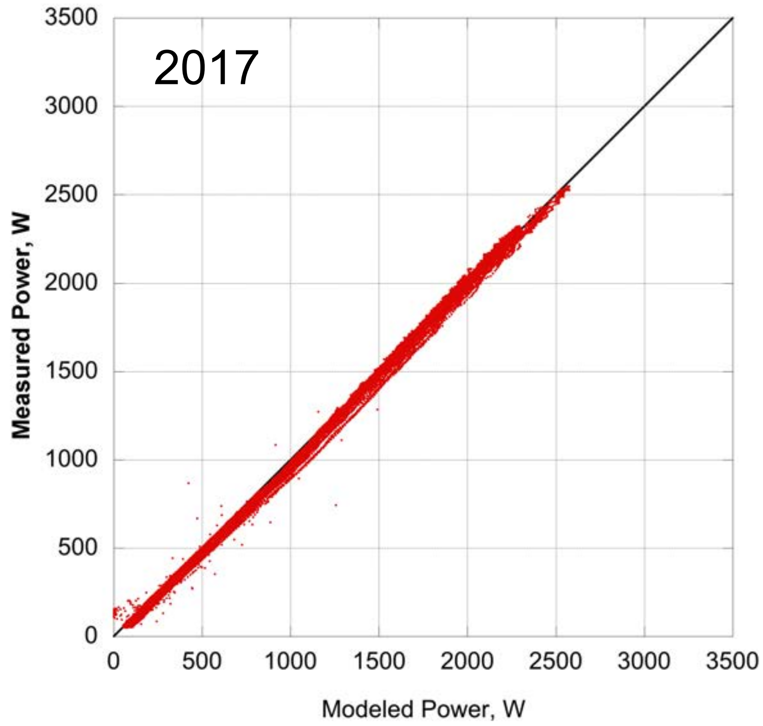
2017

- 6 months of operation
- Mean Bias Error = -10.5W

- 9 months of operation
- Mean Bias Error = 24W

CIGS-3: Clear Conditions

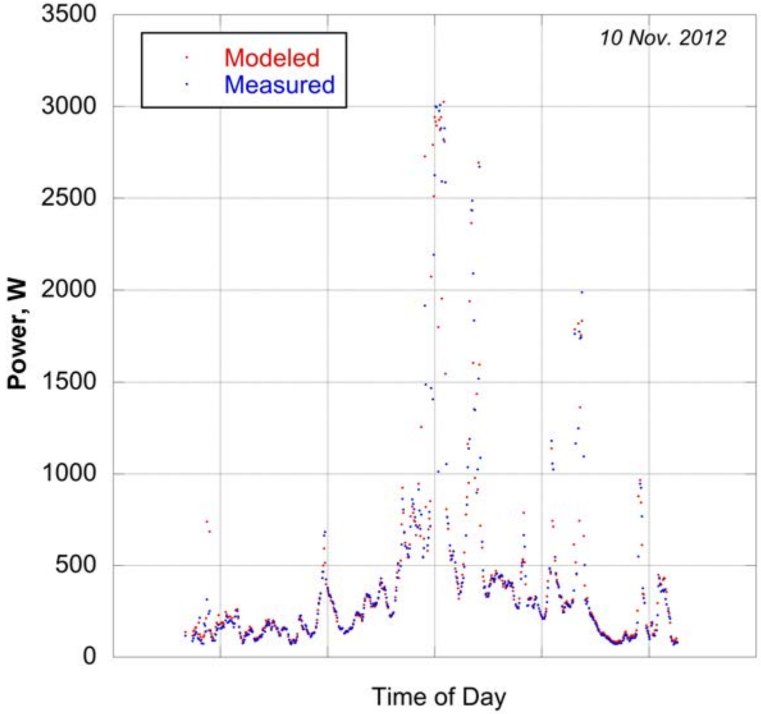


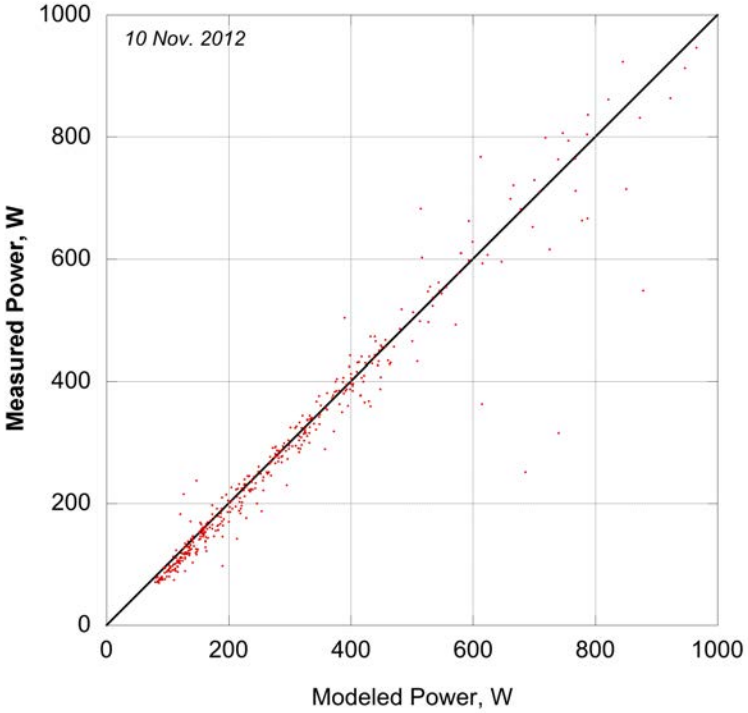


- Apply a Clear Sky filter* to remove cloudy and highly variable days
- Mean Bias Error = -14.7W/2012, 15W/2017.
- Slight change in Mean Bias error between measured and modeled power across multiple years supports observation from individual module testing degradation rate is low for this system (< 0.25%/year)

*PV_LIB Version 1_32/pvl_detect_clear_times

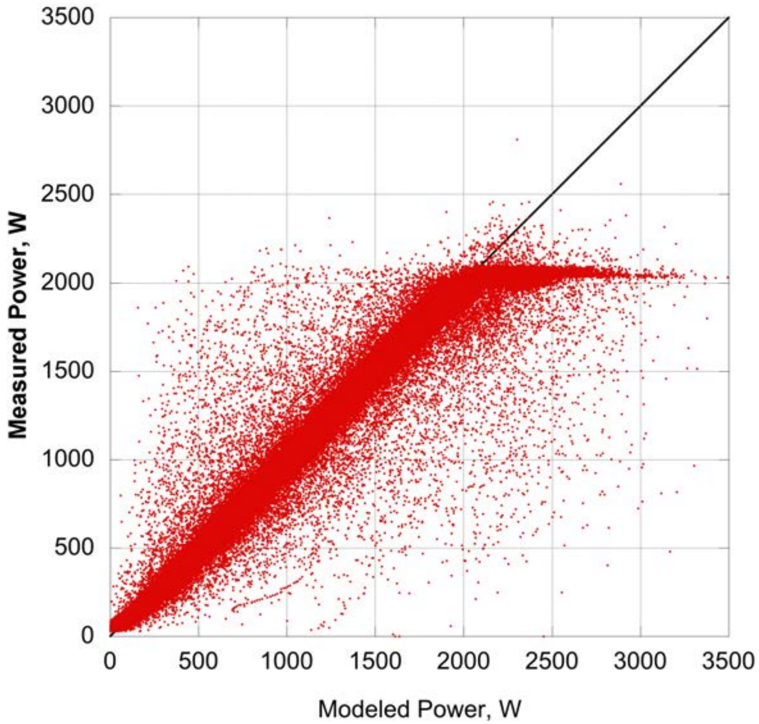
CIGS-3: Cloudy Conditions

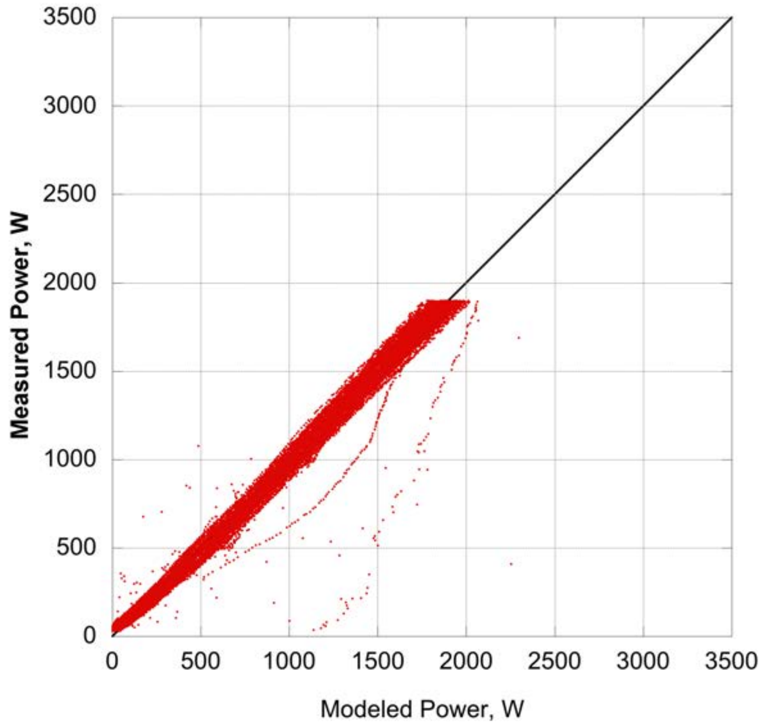




- Investigation of stable, overcast days (i.e. low irradiance, low variability) also reveals a "better" fit at low irradiance
- Mean Bias Error = 5W
- Reflects current calibration practices for SAPM; cloudy conditions are intentionally introduced to represent low irradiance behavior

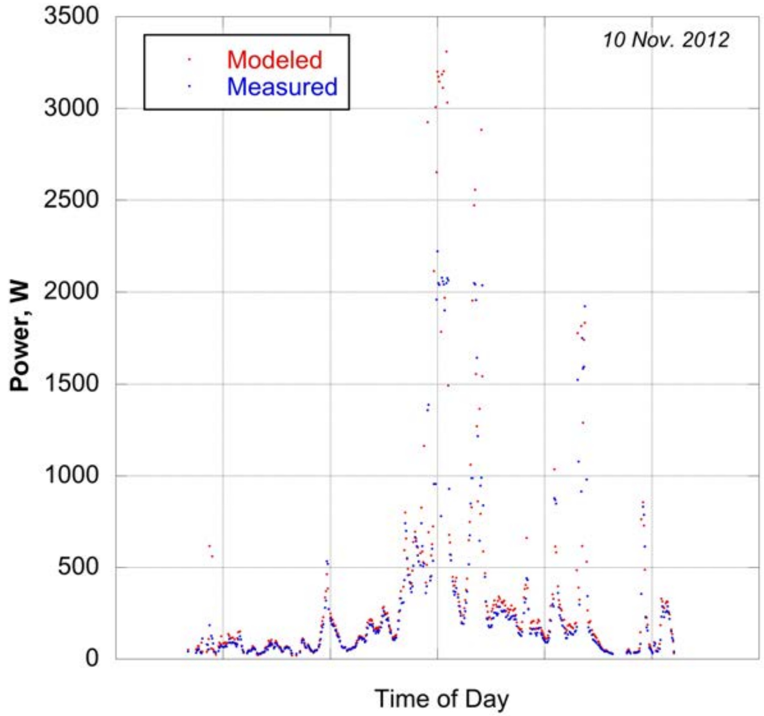
CIGS-2: More Complicated

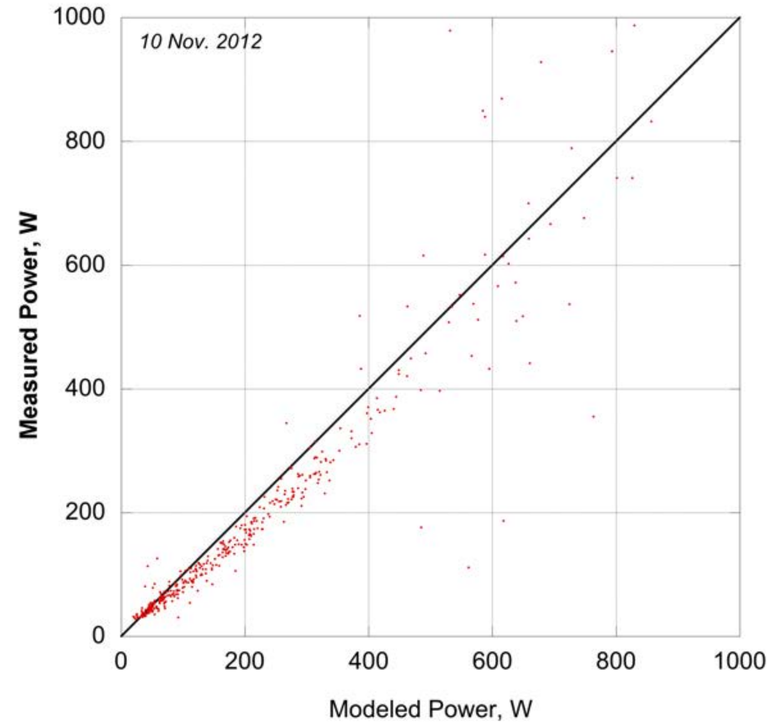




- In addition to cloudy and variable conditions, CIGS-2 displayed significant inverter clipping
- Mean Bias Error = 53W/all conditions, 14W/clear
- Results from 2012 only, 2017 results not ready for this presentation

CIGS-2: Cloudy Conditions





- Investigation of stable, overcast days (i.e. low irradiance, low variability) had a worse fit at low irradiance than observed for CIGS-3
- Likely reflects non-linear diode behavior, particularly at low irradiance/ low temperature

Summary

- Two CIGS systems of approximately the same age/generation were investigated to assess multi-year model prediction accuracy
- Performance predictions were made using onsite measured weather and model calibrations from outdoor tracker testing
- Model predictions closely matched measured performance data for one system, CIGS-3. A very low degradation rate of < 0.25%/year could be inferred from these results.
- Prediction accuracy for CIGS-3 was generally good for both clear and stable cloudy conditions. Transient conditions proved to be more difficult.
- Measured data from CIGS-2 was problematic and revealed significant inverter clipping when compared to model predictions.
- When clipping was accounted for, model prediction CIGS-2 for clear sky conditions was good (only 1 year analyzed).
- Prediction accuracy for CIGS-2 was not as good for cloudy conditions, likely due to non-linear diode behavior.
- A more accurate, low irradiance model for CIGS-2 will likely require a non-linear/variable diode factor.