SolarTech & San Jose State University PV Performance Assessment of Existing Systems Using SAM

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SolarTech Performance Committee Advisors:
- Joe Cunningham - CentroSolar
- Willard McDonald - Solmetric
- Laks Sampath - NeoZyte

Presenters

Joseph Cunningham
Director of Operations, CentroSolar

At CentroSolar, Joseph “Joe” Cunningham manages operations for North America overseeing three offices and warehouses, packaged system design and engineering as well as sourcing and project management for all projects.

Five years total in PV integration business, including Operations, Business Development, Sales and Marketing.

Active in SolarTech as a member of the PV Performance Committee, working on uniformity of PV performance modelling, measurement, troubleshooting and maintenance standards for this industry.

Prior to PV, over twenty years of entrepreneurial business experience in wireless telecommunications and cable TV.

Joe has a Bachelors of Science degree in Engineering from Cornell University. Lives in Carefree, Arizona, Married, 4 Children, enjoys competitive bicycling.

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Presenters

James Mokri, Adjunct Professor
Mechanical and Aerospace Engineering
San Jose State University

At SJSU, Mr. Mokri teaches:
•Solar Energy Engineering class
•Energy Conversion lab
•Advised more than 12 solar related student projects

Active on the performance committee at SolarTech for 2 years and consults for solar industry.

Prior to SJSU, Mr. Mokri worked for GE-Power Systems for 30 years in engineering and project management and was responsible for electrical equipment and systems at nuclear power plants.

Mr. Mokri has a BSME, BSEE, MS of E from Cal Poly University and lives in Los Gatos, CA, married, 2 sons (both employed).

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Topics To Discuss:

- Purpose of Project and background
- Summary of Metrics
- EPI (Energy Performance Index) Actual kWh/Expected kWh Using SAM
- Data quality issues
- Weather Data:
  - Irradiance: GHI, DNI, DHI, diffuse calc by model, POA
  - Cell temperature, averaging techniques
- Uncertainty analysis

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Purpose of Project

- Define Proper Use of Performance Metrics
- Help Define Maintenance Methods
- Financial Validation and Certainty
- Develop Tools for Anyone to Use

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Confusion Over Metric Calculation Method and Purpose:

METRIC	CALCULATION	REFERENCE
Yield	kWh / $kW_{DC\ STC}$	NREL/CP-520-37358
Performance Ratio	(kWh/ $kW_{DC\ STC}$) / (H/G_{STC})	IEC61724
Performance Ratio	kWh / (sunhours × area × efficiency)	SMA
Performance Ratio	(E_{Actual} / E_{Ideal}) * 100% E_{Ideal} is temp. and irrad. compensated	SolarPro, Taylor & Williams
Specific Production	MWh_{AC} / $MW_{DC\ STC}$	SolarPro, Taylor & Williams
Performance Ratio	(100 * Net production / total incident solar radiation) / rated PV module eff.	NREL/TP-550-38603
Performance Factor	$I_{SC,G}$*R_{SC}*FF_R*R_{OC}*$V_{OC,T}$	Sutterlueti
Performance Index	$kW_{measured}$ / $kW_{expected}$	SolarPro, Sun Light & Power
Performance Index	Actual Power / (Rated power * irrad adj. * temp adj * degradation adj * soiling adj * BOS adj)	Townsend
Output Power Ratio	$kW_{measured}$ / $kW_{predicted}$	SolarPro, Sun Light & Power
Output power	kW > CF-6R-PV Table	CEC Commissioning
Output power	kW > 95% expected	SRP Arizona Utility
Specific Production	MWh_{AC} / $MW_{DC\text{-}STC}$	SolarPro, Taylor & Williams
Acceptance Ratio	kW_{actual} / $kW_{expected}$	Literature
Inverter comparison	kWh of multiple similar inverters	Qualitative
String comparison	I_{mp}, V_{mp} of multiple parallel strings	Qualitative
Utility billing	Monthly comparison	Qualitative
Performance Ratio, temp. comp. (CPR)	(kWh/ kW_{DC} *K_{Temp}) / (H/ G_{STC})	Proposed in this project
Energy Performance Index (EPI)	kWh AC actual / SAM AC Expected using actual weather data	Proposed in this project

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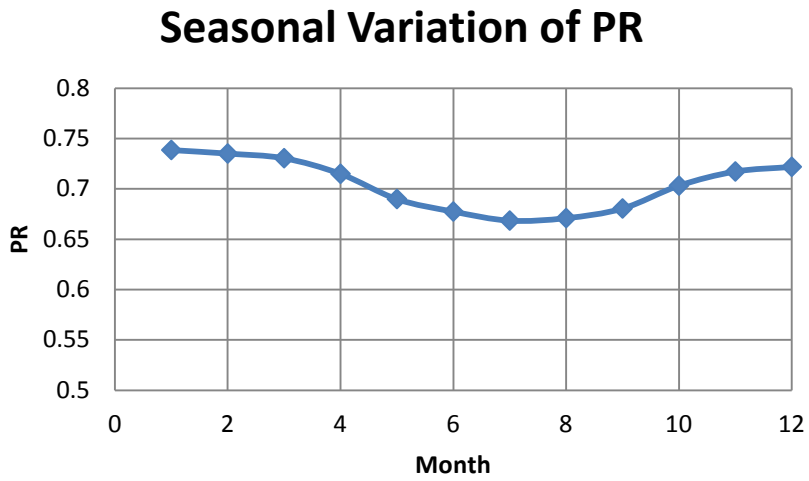
Issues With Commonly Used Metrics

Performance Ratio (uncorrected):



Note seasonal variation that can lead to interpreting as underperformance in spring

PERFORMANCE METRICS INVESTIGATED IN PROJECT

METRIC	USE	METHOD	UNCERTAINTY
kWh Production	Maintenance	Compare AC kWh over periods or inverters	High
Yield	Financial	kWh_{AC} / Rated DC Power	Low
PPI – Power Perf. Index	Commissioning	Measured kW_{AC} Output vs. Expected kW_{AC} Output	Moderate
PR-Performance Ratio	Maintenance	(kWh_{AC}/Rated kW_{DC}) / (kWh_{SUN}/1000)	High
CPR – Temp. Corrected PR	Maintenance	[kWh/(Rated kW_{DC}*Temp Corr.)] / [kWh_{SUN}/1000]	Moderate
EPI – Energy Perf. Index, EPI-SAM	Maintenance, Commissioning, Financial	Actual kWh_{AC} / Calc. kWh_{AC} Using SAM	Moderate
EPI – Energy Perf. Index, EPI-Regression	Maintenance & Commissioning, Financial	Actual kWh_{AC} / Calc. kWh_{AC} Using Regression Model	Low

Comments on Metrics:

- PPI - Used for commissioning and assessment of instantaneous power (versus energy)
- PR doesn't require a PV Model but has excessive seasonal variation.
- CPR reduces seasonal variation using a power-weighted daily average cell temperature.
- EPI-SAM depends on accurate PV Model to calculate expected performance using actual weather and assumed derate factors. Moderate uncertainty. Lower uncertainty if EPI value is trended.
- EPI-Regression applies operating data to "train" regression model using actual weather and AC kWh output. Matrix operation in Excel or Matlab to calculate equation coefficients. Low uncertainty.

EPI Metrics Uses

- EPI-SAM: Calculate actual kWh_{AC} /expected kWh_{AC} using SAM model with actual climate data in TMY3 format as input file
- Commissioning – A Six Month Commissioning Period to Catch Early Installation and Equipment Failures
- Maintenance - Is the system underperforming to the point where a root-cause-analysis and corrective maintenance is needed?
- Financial Analysis – Is the system performing as expected and Modeled?

Measurement Issues

- Radiation
  - –Pyranometer responsivity, sensor cleaning, calibration, angle of incidence, spectral content, sample rate (15 minute vs. hourly)
  - –Plane of Array (POA) irradiance calculated from GHI with existing NREL DISC (Direct Insolation Solar Code) program for DNI and model for diffuse, such as Perez.
  - –Use Satellite Data Such As Solar Anywhere?
- Temperature - Module temp, cell temp, from ambient
- Wind speed, Direction - Effect on cell temperature
- Inverter output (kW, kWh) - Calibration, inverter power limiting, MPPT, accounting for outages

Calculation Issues

- Plane of Array from horizontal GHI
- Average temperature for PR correction
- Soiling effect (effective irradiance per D. King) and Derate Factors when using SAM
- Methods to calculate and reduce uncertainty

Applications of SAM

SAM is used for three purposes related to EPI calculation:

- Calculate **expected kWh AC output** using actual hourly weather data over the assessment period for denominator of EPI-SAM ratio
- Used to simulate a systems output based on input to aid in development of Regression Model to reduce data quality issues seen on actual system data
- Calculate Plane of Array (POA) irradiance from horizontal GHI measurement data for use in Regression model

Applications of SAM

Method used to calculate EPI-SAM:

1. Obtain hourly metered kWh_{AC} for assessment period.
2. Sum hourly kWh_{AC}, for each day using Excel SUMIF function.
3. Calc DNI, DHI from GHI using NREL DISC.
4. Create climate file in SAM in TMY3 format.
5. Model system in SAM, estimate derate factors.
6. Calc hourly kWh_{AC} output.
7. Sum hourly kWh_{AC} for day using Excel SUMIF function.
8. Calc EPI for day, plot daily trend.

Applications of SAM

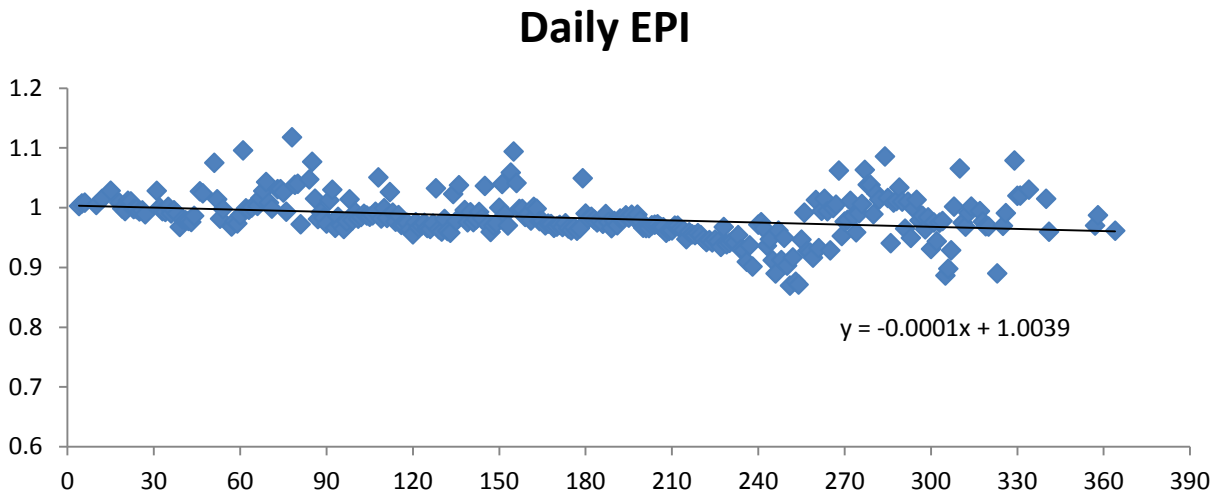
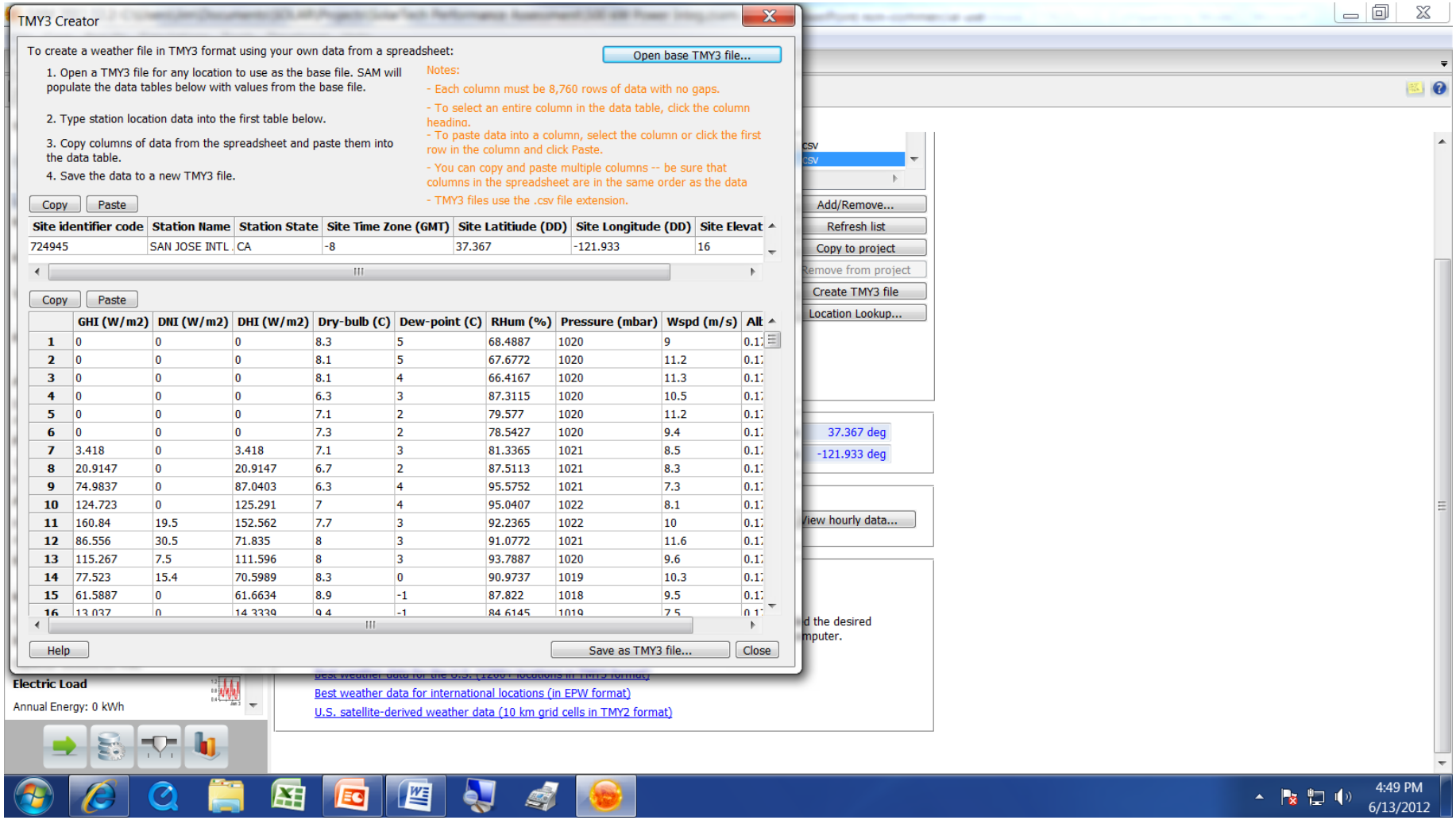


Figure 7. Daily Energy Performance Index (EPI) over one year using SAM and actual climate

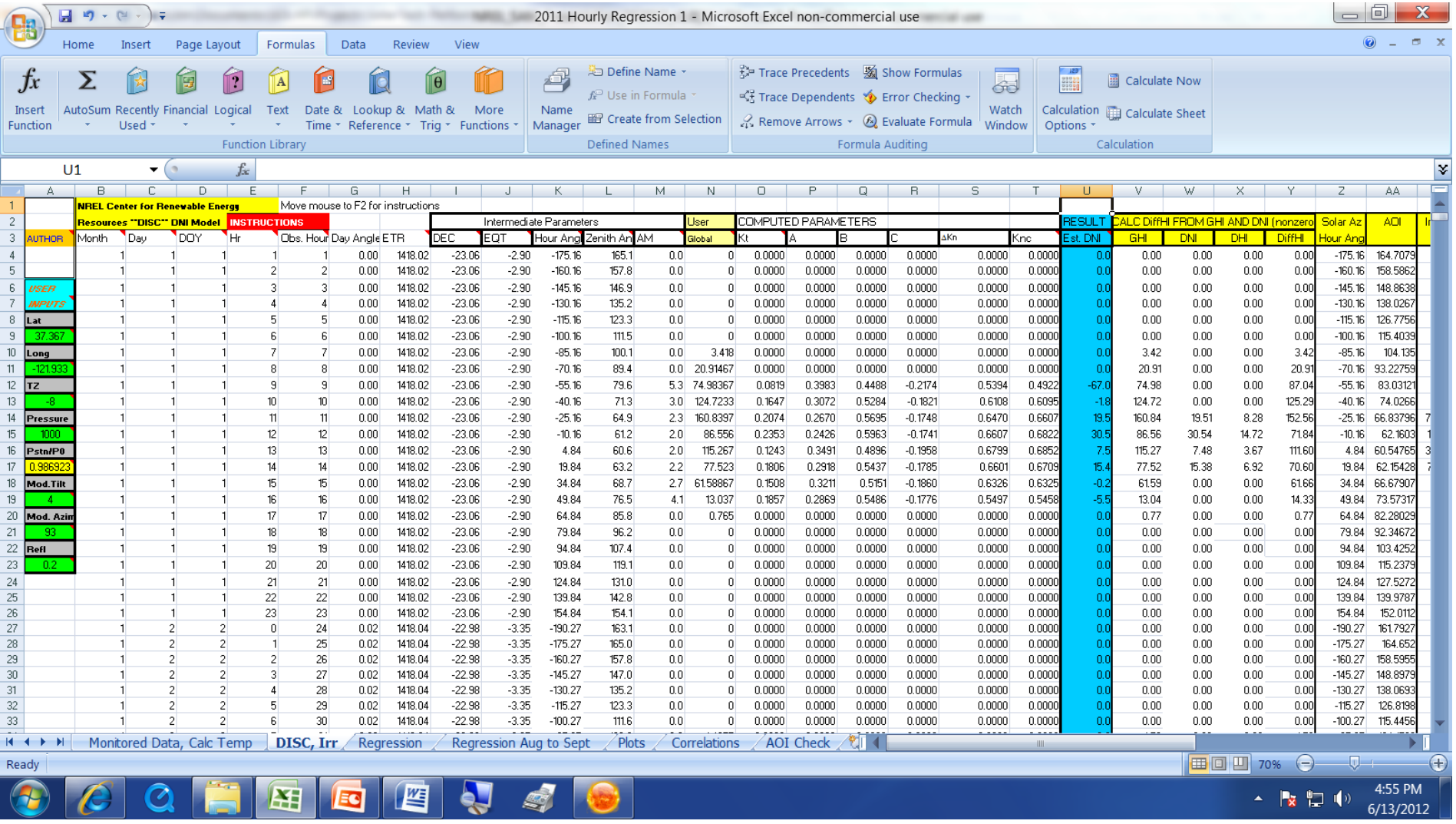
Applications of SAM

Actual weather data in TMY3 format input to SAM



Applications of SAM

NREL-DISC model used to calculate DNI and DHI for TMY3 formatted input to SAM



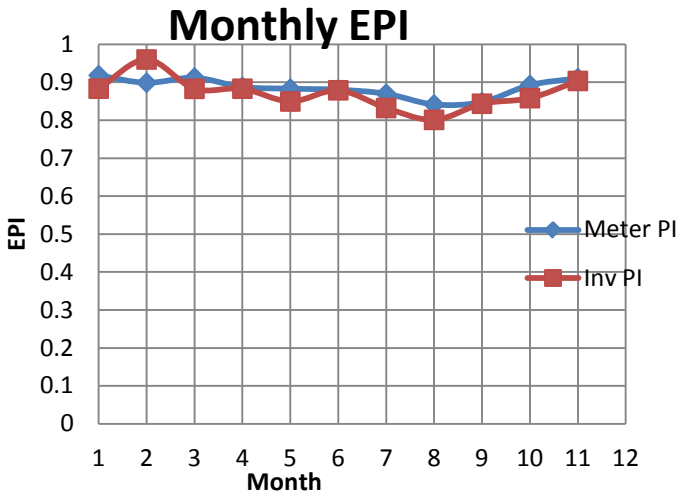
Applications of SAM

Calculate system expected output for EPI-SAM

MONTHLY ENERGY PERFORMANCE INDEX (EPI) - 600kW System

DECK monitored monthly averaged values used and compared to hourly values

Month	SAM AC Energy Output (kWh), Monthly	Actual Inverter Power Avg	Inverter kWh	Watt Meter kWh	Watt Meter EPI	Inverter EPI
Jan	39220	48.10367	34634.65	36013.53	0.918244	0.883086
Feb	51742.7	68.98071	49666.11	46508.66	0.898845	0.959867
Mar	62963.7	77.18619	55574.06	57435.16	0.912195	0.882636
Apr	98081.9	120.2729	86596.46	87048.53	0.887509	0.8829
May	111480	131.4912	94673.66	98442.75	0.883053	0.849243
Jun	115595	141.0791	101577	101760.5	0.880319	0.878732
Jul	127555	147.4075	106133.4	110913.8	0.869537	0.83206
Aug	116077	129.111	92959.92	97639.88	0.841165	0.800847
Sep	89641.2	104.9953	75596.6	75976.56	0.847563	0.843324
Oct	66055.7	78.72101	56679.13	58964.5	0.892648	0.858051
Nov	42201.9	52.94521	38120.55	38431.09	0.910648	0.90329
Dec	29477	57.78605	41605.96	10412.38	0.353237	1.411472



Applications of SAM

Calculate POA irradiance for EPI-Regression

CALCULATED RESULTS FROM SAM MODEL OF 600KW SYSTEM

SAM results for modelled 600kW system with actual weather data

AC Power (kWh), Monthly	Expected system hourly output (kWh)	Incident Total POA (kW/m2), Hourly	Incident Radiation (kWh), Hourly	Cell Hourly Temperature (C)	Incident Total POA (W/m2), Hourly	System AC Output nonzero
36061.9	0	0	0	0	0	0
46792	-0.13108	0	0	6	0	0
56134	-0.13108	0	0	5.5	0	0
89474.7	-0.13108	0	0	4	0	0
101346	-0.13108	0	0	3	0	0
106309	-0.13108	0	0	2.5	0	0
117638	-0.13108	0	0	2.5	0	0
105188	2.1934	0.020889	72.0133	3.54048	20.8889	2.1934
82431.3	29.3149	0.074904	258.228	6.43809	74.9042	29.3149
53676.3	51.1864	0.124594	429.531	12.9768	124.594	51.1864
41686.7	65.7219	0.158559	546.623	14.1003	158.559	65.7219
23056.1	33.1362	0.085702	295.452	13.7125	85.7017	33.1362
	45.4009	0.114619	395.142	16.5207	114.619	45.4009
	29.192	0.077618	267.583	16.9421	77.6176	29.192
	22.3394	0.061528	212.114	17.4332	61.5277	22.3394

Output truncated to show only a few rows

Applications of SAM

POA irradiance from SAM used in regression equation to calculate system output

EPI Regression SAM Results - Microsoft Excel non-commercial use

K8: {=MMULT(MINVERSE(MMULT(TRANSPOSE(F8:I1061),F8:I1061)),MMULT(TRANSPOSE(F8:I1061),E8:E1061))}

POLYNOMINAL REGRESSION MODEL OF SAM SIMULATED SYSTEM TO EVALUATE DATA QUALITY ISSUES

Purpose: Develop an equation to calculate expected system AC output as a function of POA irradiance and cell temperature, based on SAM simulated system to eliminate typical data quality issues with actual system.

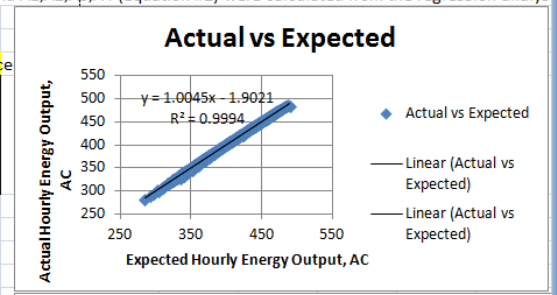
The equation was developed using linear algebra matrix analysis using pseudo inverse to find least squares fit to measured data. Coefficients ABCD (Equation #1) and A1,A2,A3,A4 (Equation #2) were calculated from the regression analys

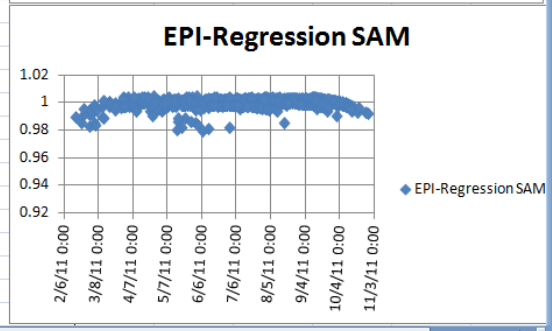
Results show that regression equation has <0.3% uncertainty without data quality issues typically present in actual system measured data.

ANALYSIS OF ONE YEAR DATA >800 W/m2

Average 399.868 | Std Dev 1.05271 | 0.26% Unce

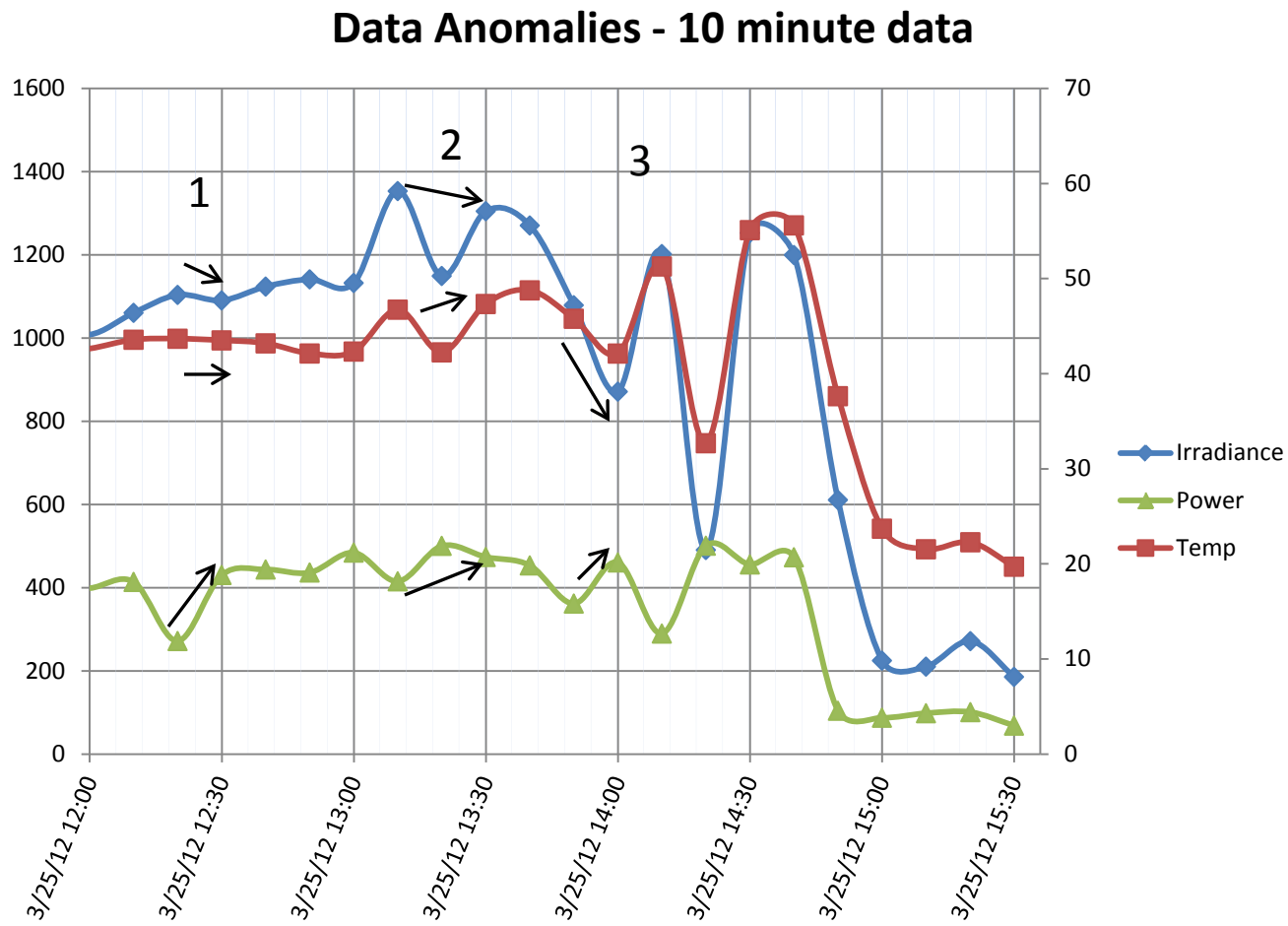
ID	Time (end of hour)	Calc Average Cell Temp.(C) T	POA Irrad (W/M²) H	Actual Hourly Energy (kWh) E	Coefficient matrix for Equation #1				E = A + T H B + H C + H² D Equation #1		Apply Equation #1	Residual Eqn #1	EPI
3565	5/29/11 13:00	32.9989	1215.68	484.308	1	40.1161	1.21568	1.47788	A	-0.01522	485.715	1.4066	0.9971
3878	6/11/11 14:00	32.6433	1214.36	484.306	1	39.6407	1.21436	1.47467	B	-1.90627	486.046	1.74016	0.99642
3231	5/15/11 15:00	30.9665	1214.27	482.885	1	37.6017	1.21427	1.47445	C	489.606	489.894	7.00892	0.98569
4429	7/4/11 13:00	37.9726	1203.47	468.846	1	45.6989	1.20347	1.44834	D	-22.3309	469.754	0.90781	0.99807
2869	4/30/11 13:00	29.8889	1203.01	486.334	1	35.9566	1.20301	1.44723			488.125	1.79067	0.99633
3853	6/10/11 13:00	34.7558	1202.47	475.799	1	41.7928	1.20247	1.44593			476.764	0.96498	0.99798
4165	6/23/11 13:00	34.4465	1202.42	476.422	1	41.4192	1.20242	1.44581			477.454	1.03246	0.99784
4069	6/19/11 13:00	33.8787	1200.68	477.099	1	40.6775	1.20068	1.44163			478.11	1.01077	0.99789
4070	6/19/11 14:00	31.8137	1200.56	481.441	1	38.1943	1.20056	1.44134			482.791	1.35014	0.9972
2893	5/1/11 13:00	38.5297	1196.15	464.863	1	46.0873	1.19615	1.43077			465.822	0.95872	0.99794
3109	5/10/11 13:00	35.3408	1196.14	472.174	1	42.2725	1.19614	1.43075			473.089	0.91532	0.99807
3566	5/29/11 14:00	32.7452	1195.93	477.691	1	39.161	1.19593	1.43025			478.929	1.23823	0.99741
3589	5/30/11 13:00	39.1912	1194.77	463.293	1	46.8245	1.19477	1.42748			463.814	0.52149	0.99888
2845	4/29/11 13:00	33.3316	1194.7	475.823	1	39.8213	1.1947	1.42731			477.134	1.31098	0.99725
4166	6/23/11 14:00	32.6835	1194.6	477.459	1	39.0437	1.1946	1.42707			478.573	1.11358	0.99767
4525	7/8/11 13:00	36.5697	1193.45	468.51	1	43.6441	1.19345	1.42432			469.301	0.79125	0.99831
4189	6/24/11 13:00	31.9231	1191.9	478.317	1	38.0491	1.1919	1.42063			479.29	0.97345	0.99797
4549	7/9/11 13:00	41.545	1191.89	456.915	1	49.5171	1.19189	1.4206			457.425	0.51009	0.99888



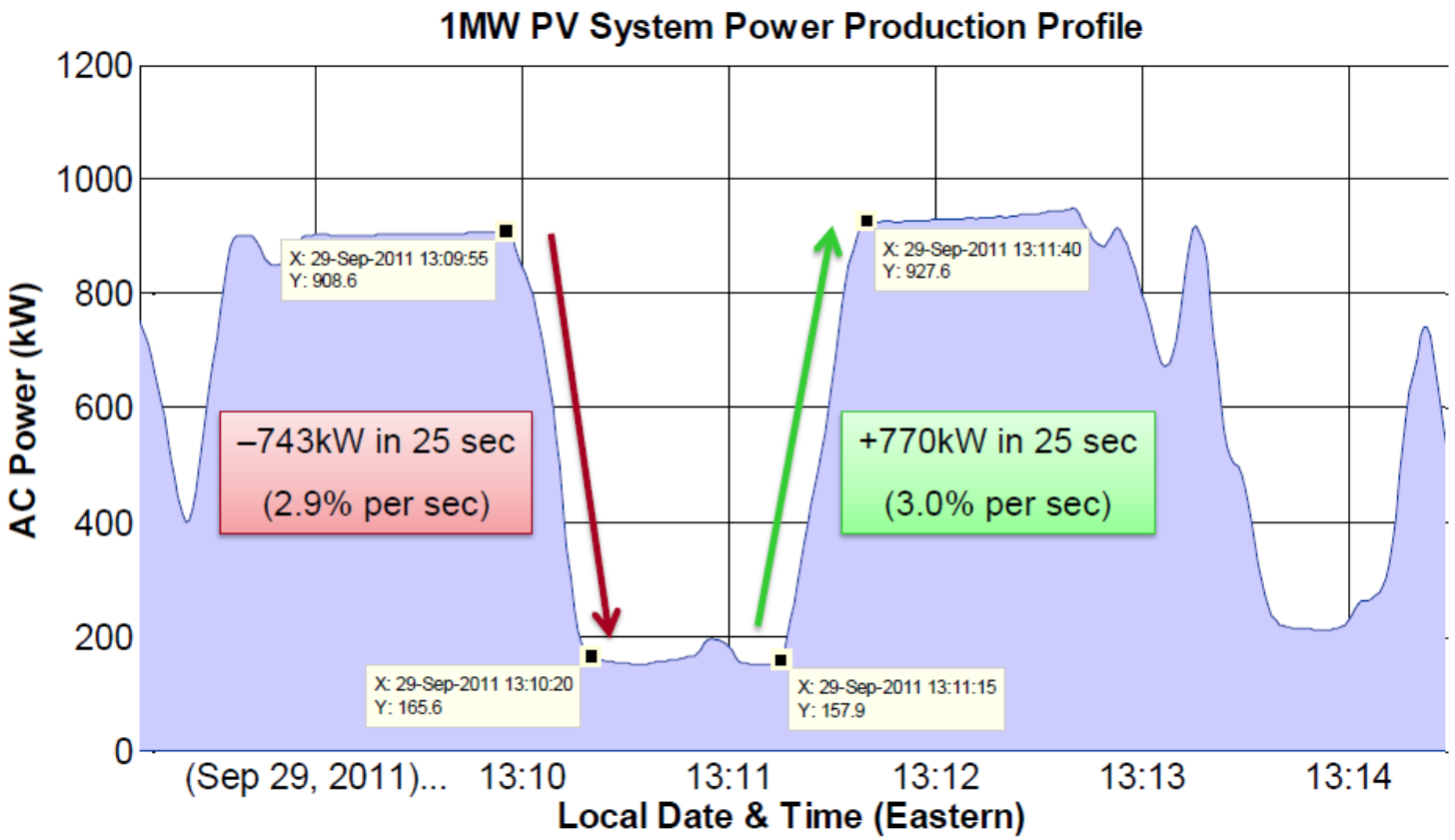


Observed Data Quality Issues:

1. Irradiance decreases, cell temp constant, power increases
2. Irradiance decreases, cell temp increases, power increases
3. Irradiance change compared to temp change and power change



Potential for Data Quality Issues:



EPRI Presentation

Uncertainty:

- Increased uncertainty leads to higher cost (1% adds $1M to finance costs on large system)
- Considered methods to do uncertainty analysis [traditional propagation of uncertainty]
- Use commercial data analysis software (JMP, IBM-SPSS, MiniTab, etc.) to calculate uncertainty
- Regression model uncertainties of <1%, data quality and derate factors result in uncertainties of >10%

Conclusions

- SAM works well for performance assessment application using actual climate data
- SolarTech will promote use of SAM and similar programs for use in Performance Assessments
- Project has been worthwhile student project that led to internships

Recommendations

- Consider adding feature into SAM to calculate EPI
- Consider adding feature into SAM to convert GHI to DNI DHI for input
- Request feedback how to get NREL involved with SolarTech Performance Assessment project