SAND2017-4987C

Pecos, Open Source Software for PV Performance Monitoring

8th PV Performance Modeling and Monitoring Workshop

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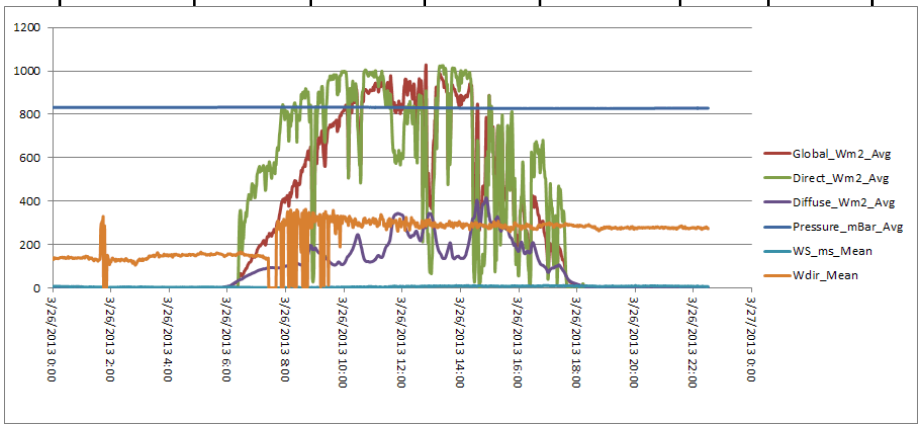
Overview

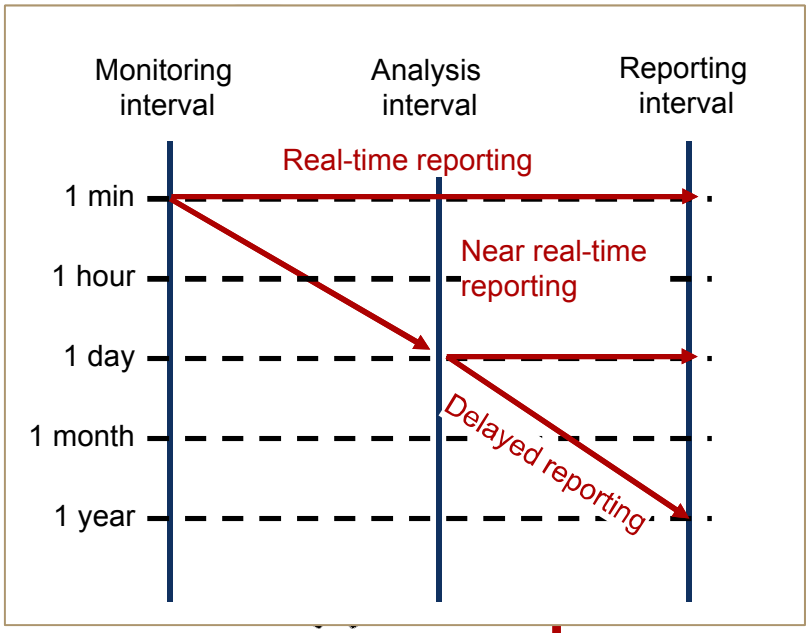
- What is Pecos?
  - Software for automated quality control and performance monitoring of time series data
- Why use Pecos?
  - Collect large amounts of data on multiple systems and locations
  - Run automatic quality control tests on that data
  - Alert system operators when the system has changed
  - Generate reports
  - Collect performance statistics to track long term system health
  - Compare system performance across sites

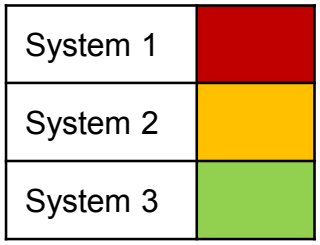
TOA5	CR1000	46385	CR1000.Std.24	CPU:ABQ_RTC_MET_2013_03_21.CR1	58869	DataOut
TIMESTAMP	Global_Wm2_Avg	Direct_Wm2_Avg	Diffuse_Wm2_Avg	Pressure_mBar_Avg	WS_ms_Mean	Wdir_Mean
TS						Deg
	Avg	Avg	Avg	Avg	WVc	WVc
3/26/2013 0:00	-1.16195	-0.45458	0	832.121	6.338	135.7
3/26/2013 0:01	-1.14918	-0.5455	0	832.123	5.8	136.4
3/26/2013 0:02	-1.14918	-0.52277	0	832.106	5.988	131.2
3/26/2013 0:03	-1.14918	-0.45458	0	832.0875	6.838	139.6
3/26/2013 0:04	-1.14918	-0.45458	0	832.0799	6.825	136.8
3/26/2013 0:05	-1.14918	-0.45458	0	832.0693	6.775	137
3/26/2013 0:06	-1.14919	-0.40155	0	832.0547	6.825	135.2
3/26/2013 0:07	-1.14919	-0.31063	0	832.0114	6.85	137.4
3/26/2013 0:08	-1.14921	-0.46217	0	832.0062	7.013	136.3
3/26/2013 0:09	-1.14922	-0.45459	0	832.0159	7	135.1
3/26/2013 0:10	-1.14922	-0.45459	0	832.0093	6.063	136.4
3/26/2013 0:11	-1.14921	-0.45459	0	832.0027	6.825	134.6
3/26/2013 0:12	-1.14921	-0.45459	0	831.9932	6.813	135.8
3/26/2013 0:13	-1.14921	-0.36367	0	831.9811	6.65	137.2
3/26/2013 0:14	-1.14921	-0.28791	0	832.0098	7	137.1
3/26/2013 0:15	-1.14921	-0.45459	0	832.0153	6.738	138.6
3/26/2013 0:16	-1.1492	-0.45459	0	831.9963	6.613	141.1
3/26/2013 0:17	-1.1492	-0.60612	0	832.0099	6.125	139.8
3/26/2013 0:18	-1.1492	-0.84099	0	832.0046	6.113	139.9

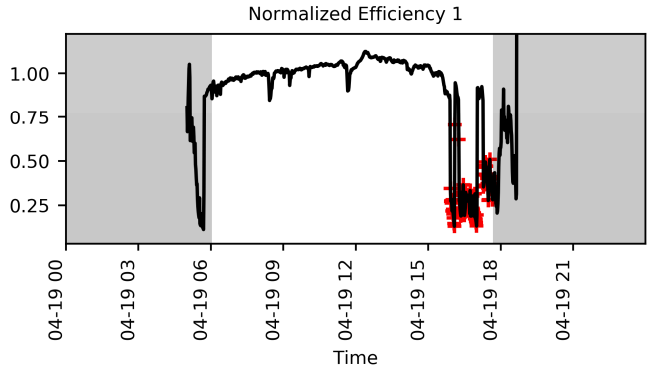


Getting started

- Retrieve data
  - From sensor, database, files, or from the web
  - 3Vs (volume, velocity, and variety)
  - Historical or real-time
  - Single or repeat (automated)
- Define analysis
  - Analysis/reporting time interval
  - Filters
  - Integrate models
  - Quality control tests
  - Metrics
- Final product
  - Simple to complex
  - Red/yellow/green approach
  - Time series or interactive graphics
  - Performance history
  - Dashboards hosted on the web
  - Email alerts







Time series data

- Time series data loaded into Pecos as a Pandas DataFrame
  - Data can be easily loaded from database, file, or web
  - Powerful time series analysis options
  - Datetime and timezone recognition
  - Merge multiple DataFrames in a single analysis (i.e. electrical and weather)
- Data acquisition methods recently added to Pecos
  - Transfer data from sensors to an SQL database
- User defines the analysis timeframe (minute, hour, day, month, …)
- Data can be grouped and renamed according to type
- Repeat analysis automated using OS task scheduler (cron, tasks)

From database

```
sql_con= MySQLdb.connect(host=ip_address, port=…)
sql_query = "SELECT * FROM table…"
df = pandas.read_sql(sql_query, con=sql_con)
```

From file

```
df = pandas.read_csv(filename)
```

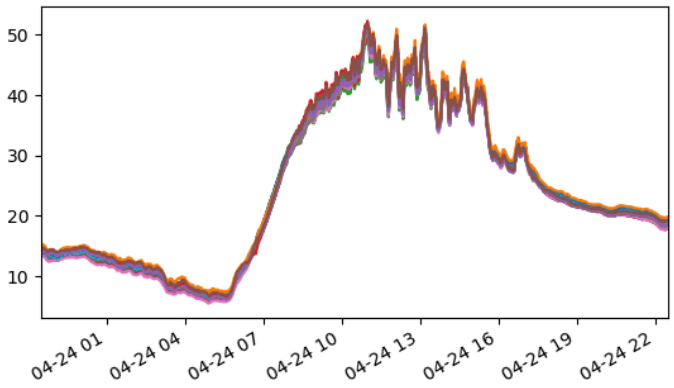
From the web

```
response = requests.get(url=http://developer.nrel.gov/pvdaq/api/…)
data = json.loads(response.text)
df = pandas.DataFrame(data=data['outputs']['data'])
```

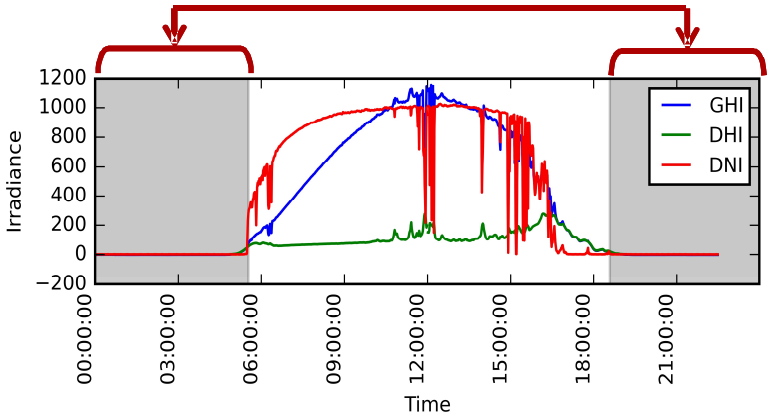
Pre-processing filters

- Filter data
  - Smoothing
  - Upscale/downscale
- Fill missing data
  - Interpolation (linear, polynomial, etc.)
  - Duplicate sensors
  - Historic/regional data
  - Data generated from models
- Time filter
  - Conditional statement that exclude specific timestamps from quality control tests
  - Time filter can be based on:
    - Time of day (i.e. before 8 am and after 5 pm)
    - Sun position (i.e. sun elevation < 10 degrees)
    - Data properties (i.e. irradiance < 200 W/m^2)

Module temperatures from 16 sensors

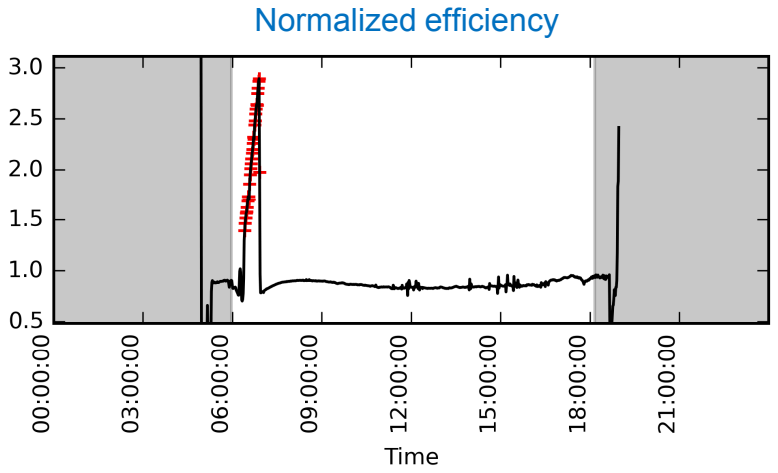


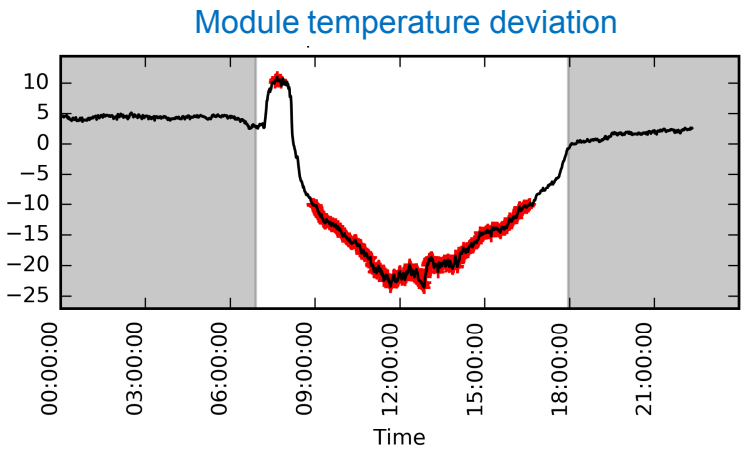
Time filter based on sun position



Composite signals

- Composite signals are used to create new data from existing data or from a model
  - Compute relationships between data columns
  - Compare measured data to a model
    - PVLIB performance model
    - Machine learning
- Examples
  - DC Power from current and voltage
  - Inverter efficiency from DC and AC power
  - Normalized efficiency from power and irradiance
  - Module temperature deviation
  - Relative error between model and data
- Composite signals can be used in the quality control tests





Quality Control tests

- Quality controls tests fall into five categories
  - Timestamp test
  - Missing data test
  - Corrupt data test
  - Range test
  - Dead sensor/abrupt change test
- When a test fails, information is stored in a summary table which can be included in automated reports and saved to file/database. Graphics can be produced that pin point the data points that caused the failure.

System Name	Variable Name	Start Date	End Date	Timesteps	Error Flag
PV System 1	ModTemp3_Avg	2015-06-09 19:08:00	2015-06-09 20:36:00	89.0	Data > upper bound, 90

Quality Control tests

- Timestamp test identifies duplicate, non-monotonic, and missing timestamps. Irregular timestamps can be preserved.
- Missing data test identifies column-time pairs that are missing.
- Corrupt data test screens for datalogger values that indicate corrupt data.

Original data

TIMESTAMP	Column A	Column B
1/1/2017 0:00	0	1
1/1/2017 1:00		2
1/1/2017 2:00	2	3
1/1/2017 3:00	3	4
1/1/2017 5:00	5	1
1/1/2017 6:00	6	2
1/1/2017 8:00	8	
1/1/2017 7:00	7	
1/1/2017 9:00	9	1
1/1/2017 9:00	9.5	2

Missing data

Missing timestamp

Non-monotonic timestamp

Duplicate timestamp

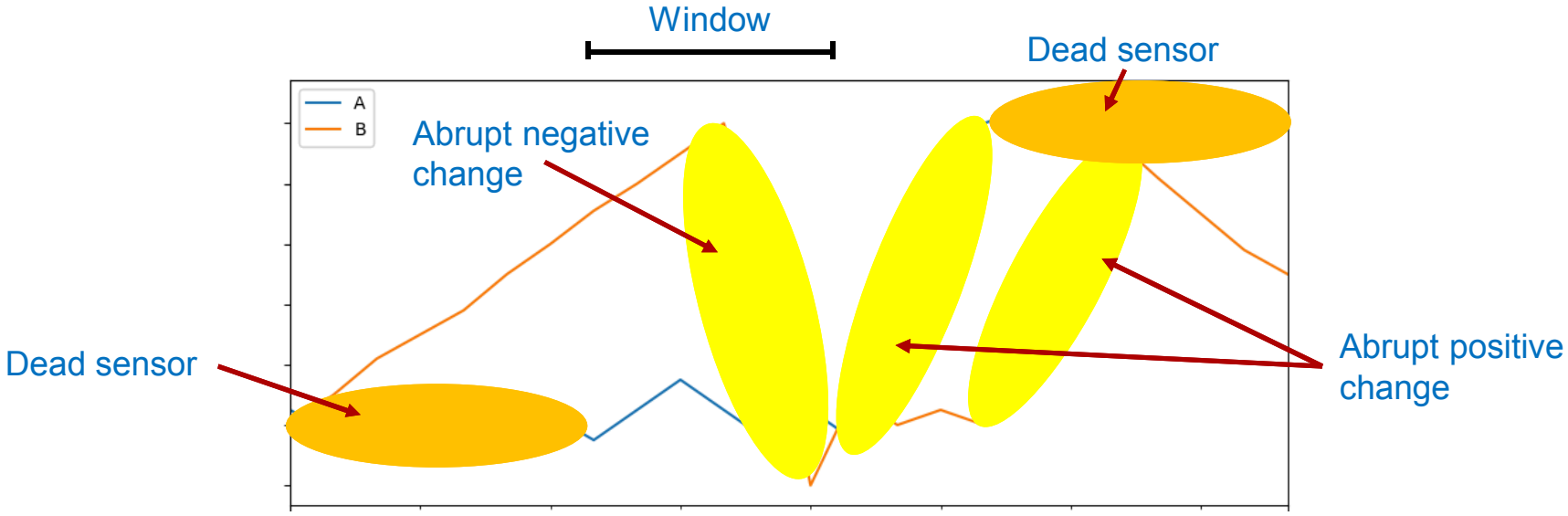
Corrupt data

Corrected data

TIMESTAMP	Column A	Column B
1/1/2017 0:00	0	1
1/1/2017 1:00	NaN	2
1/1/2017 2:00	2	3
1/1/2017 3:00	3	4
1/1/2017 4:00	NaN	NaN
1/1/2017 5:00	5	1
1/1/2017 6:00	6	2
1/1/2017 7:00	7	NaN
1/1/2017 8:00	8	NaN
1/1/2017 9:00	9	1

Quality Control tests

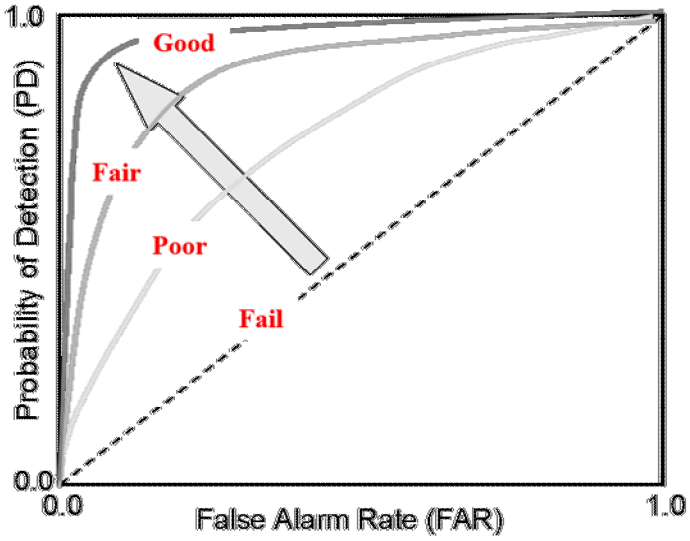
- Range tests checks if data is within expected bounds
  - Ambient temperature should be between -30 and 50 degrees C
  - Normalized efficiency (composite signal) should be between 0.5 and 1
- Dead sensor/abrupt change test checks if the difference between min and max is within expected bounds over a given time span
  - Voltage should not change by more than 80% rating within 3 hours
  - The rain gauge should not increase by more than 2 inches in an hour
  - If the irradiance sensor changes by less than 0.0001 in 5 hours, it's probably dead



Evaluating quality control tests

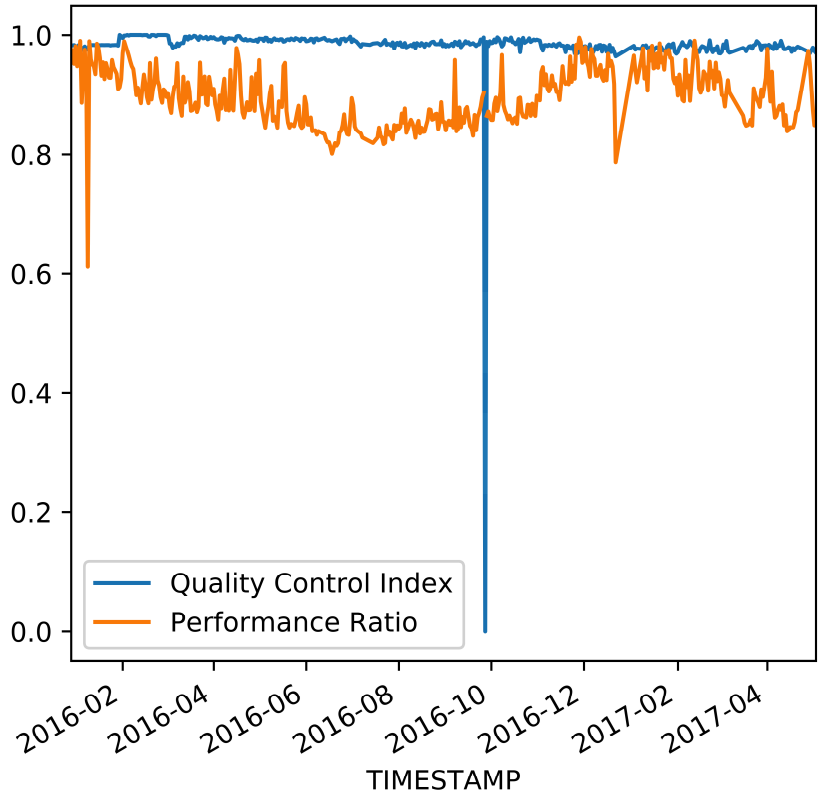
- Evaluate how well a quality control test (or set of quality control tests) distinguishes normal from anomalous conditions.
  - Probability of detection
  - False alarm rate
- Strategies to reduce false positives and false negatives
  - Adjust thresholds
  - Specify the minimum number of consecutive failures needed to signal a warning
  - Smooth data before running quality control tests

	Actual normal condition	**Actual anomalous condition**
Estimated normal condition	True negative (TN)	False negative (FN)
Estimated anomalous condition	False positive (FP)	True positive (TP)
	FAR = TN / (TN+FP) FAR = 1-Specificity	PD = TP / (TP+FN) PD = Sensitivity



Performance metrics

- Track long term system health
- Example metrics
  - Data availability: percent of data that was recorded
  - Quality control index: percent of available data that passed all quality control tests
  - System availability: percent of data associated with I, V, P, inverter efficiency, and normalized efficiency that passed all quality control tests.
  - Performance ratio: Ratio of normalized energy to normalized irradiance
  - Energy performance index: ratio of measured energy to expected energy.
- Metrics can be included in automated reports and saved to file/database.



Reports, Dashboards, Results

Test results (file/database)

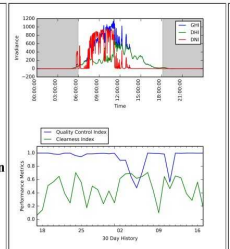
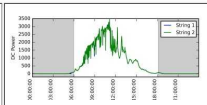
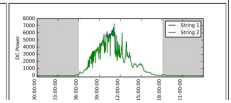
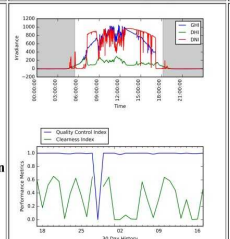
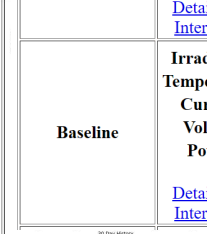
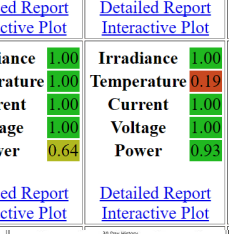
	System_Name	Variable_Name	Start Date	End Date	Timesteps	Error Flag
1	SNLA_Baseline6kW	LocalAmbientTemp	2016-09-26 22:30:00-07:00	2016-09-27 21:00:00-07:00	1351	Missing data
2	SNLA_Baseline6kW	ModTemp10	2016-01-08 11:21:00-07:00	2016-01-08 11:36:00-07:00	16	|Delta| > upper bound, 20
3	SNLA_Baseline6kW	Sys2Iac	2016-02-08 10:17:00-07:00	2016-02-08 14:07:00-07:00	231	Data > upper bound, 10.42
4	SNLA_MET	Wdir_Mean	2016-07-22 06:29:00-07:00	2016-07-22 18:14:00-07:00	706	|Delta| < lower bound, 0.0001

Performance metrics (file/database)

TIMESTAMP	Quality Control Index	Performance Ratio
1/1/2016	0.981411	0.981115
1/2/2016	0.980317	0.947567
1/3/2016	0.983019	0.955536
1/4/2016	0.981449	0.98997
1/5/2016	0.974129	0.886877
1/6/2016	0.97772	0.935395

Dashboards (html)

Pecos Dashboard

	Weather Station	PV System 1	PV System 2
Location 1			
	Quality Control Index 0.999249 Clearness Index 0.179962 Link to Monitoring Report		
Location 2			
	Quality Control Index 1.000000 Clearness Index 0.470922 Link to Monitoring Report	Quality Control Index 0.763886 Performance Ratio 0.000000 Link to Monitoring Report	Quality Control Index 0.966600 Performance Ratio 0.889406 Link to Monitoring Report

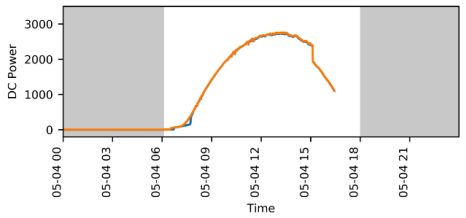
RTC Dashboard for 2017-03-24

	New Mexico	Florida	Vermont	Nevada
Weather	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 0.57 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot
Baseline	Irradiance 1.00 Temperature 1.00 Current 1.00 Voltage 1.00 Power 0.64 Detailed Report Interactive Plot	Irradiance 1.00 Temperature 0.19 Current 1.00 Voltage 1.00 Power 0.93 Detailed Report Interactive Plot	Irradiance 1.00 Temperature 1.00 Current 0.27 Voltage 1.00 Power 0.24 Detailed Report Interactive Plot	Irradiance 1.00 Temperature 1.00 Current 1.00 Voltage 1.00 Power 1.00 Detailed Report Interactive Plot

Monitoring reports (html)

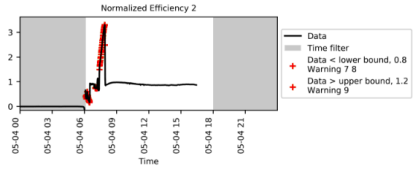
SNLA_Baseline_2017-05-04

Start time: 2017-05-04 00:00:00-07:00
End time: 2017-05-04 23:59:00-07:00
Test Failures: 60
Notes: 0



Test Results:

	System Name	Variable Name	Start Date	End Date	Timesteps	Error Flag
1			2017-05-04 14:08:00-07:00	2017-05-04 15:07:00-07:00	60	Duplicate timestamp
2		Normalized Efficiency 2	2017-05-04 06:07:00-07:00	2017-05-04 06:30:00-07:00	24	Data < lower bound, 0.8
3		Normalized Efficiency 2	2017-05-04 07:01:00-07:00	2017-05-04 07:10:00-07:00	10	Data < lower bound, 0.8
4		Normalized Efficiency 2	2017-05-04 07:24:00-07:00	2017-05-04 07:55:00-07:00	32	Data > upper bound, 1.2
...						



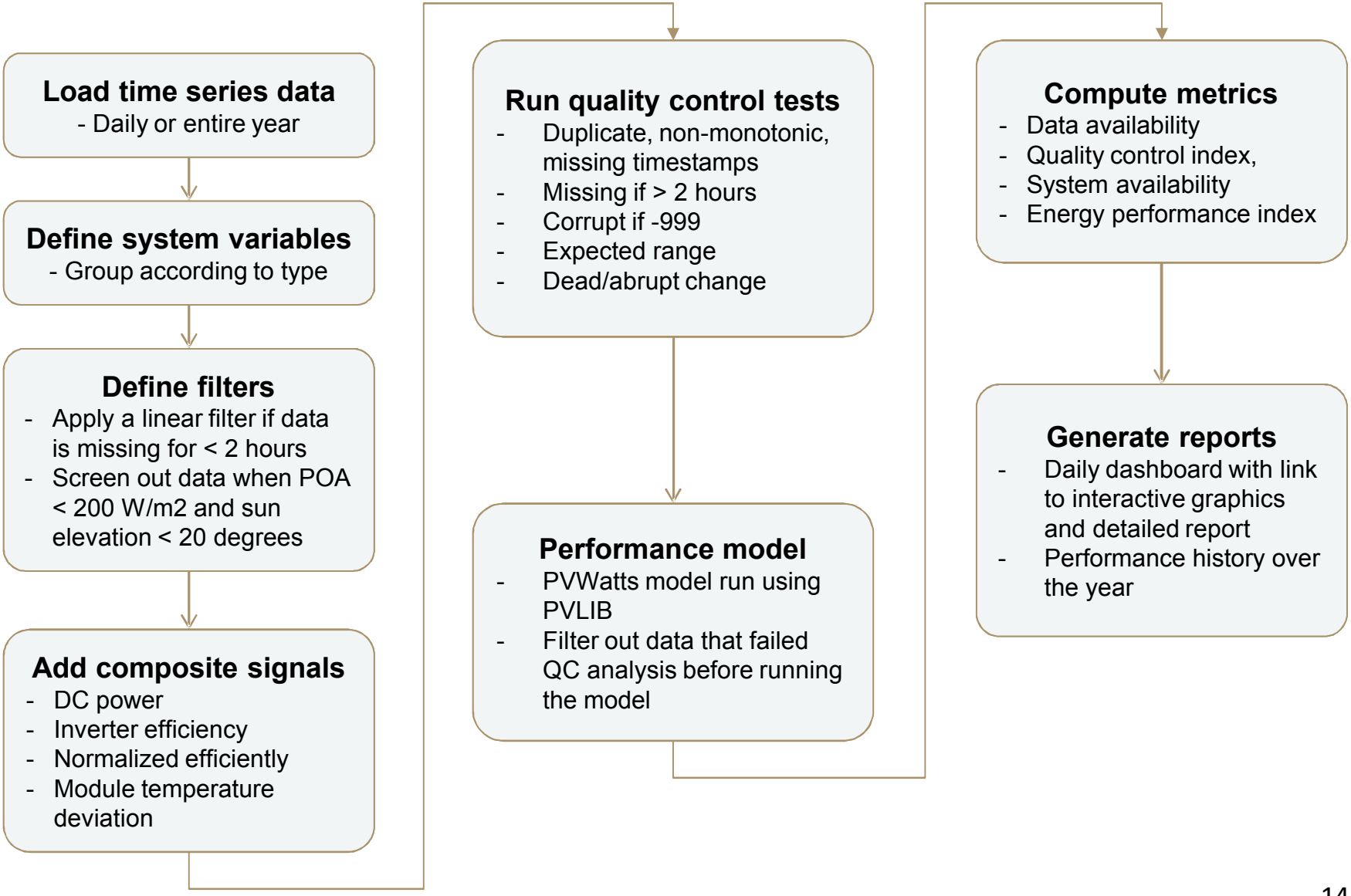
RTC quality control analysis

- Regional Test Center Baseline and Weather systems
  - New Mexico, Florida, Vermont, Nevada
  - 2 strings of 12 Suniva Optimus 270 Black modules
- Quality control tests and performance metrics based on IEC 61724
  - Check for data outside expected range, dead sensors, and abrupt changes
  - Compute in-service and all-in energy performance index
- Analysis run daily (near real-time), results emailed to stakeholders.
  - Two tiered reporting: Red/yellow/green dashboard with links to detailed reports and interactive graphics
- End of year report

Module specs: Pmax = 270 W, Vmp = 31.2 V, Voc = 38.5 V, Imp = 8.68 A, Isc = 9.15 A

Weather data	Baseline PV data
GHI, DNI, DHI, air pressure, wind speed, wind direction, relative humidity	For each string: DC voltage, DC current, AC voltage, AC current, AC power, power factor, frequency, reference cell irradiance, and reference cell temperature

RTC quality control analysis



RTC quality control analysis

- Expected range, dead sensor, abrupt change thresholds

Variable	Expected range	Dead sensor threshold	Abrupt change threshold
DC current and AC current (A)	> 0 and < Imp*1.5	< 0.0001 in 5 hours	> Imp*0.8 in 15 minutes
DC voltage and AC voltage (V)	> 0 and < Vmp*12*1.5	< 0.0001 in 5 hours	> Vmp*12*0.8 in 15 min
DC power* and AC power (W)	> 0 and < Pmp*12*1.5	< 0.0001 in 5 hours	> Pmp*12*0.8 in 15 min
Power factor	> -1 and < 1	< 0.0001 in 5 hours	
Frequency(Hz)	> 57 and < 63	< 0.0001 in 5 hours	
POA, DNI, GHI, and ref cell irradiance (W/m^2)	> 0 and < 1500	< 0.0001 in 5 hours	
DHI (W/m^2)	> 0 and < 500	< 0.0001 in 5 hours	
Air pressure (mbar)	> 800 and < 1020	< 0.0001 in 5 hours	> 100 in 15 minutes
Wind speed (m/s)	> 0 and < 32	< 0.0001 in 5 hours	
Wind direction	> 0 and < 360	< 0.0001 in 5 hours	
Relative humidity	> 0 and < 100	< 0.0001 in 5 hours	> 50 in 15 minutes
Ambient temperature (^oC)	> -30 and < 50	< 0.0001 in 5 hours	> 20 in 15 minutes
Module and ref cell temp (^oC)	> -30 and < 90	< 0.0001 in 5 hours	> 20 in 15 minutes
Module temp deviation (^oC)*	> -10 and < 10		
Inverter efficiency*	> 0.5 and < 1		> 0.25 in 15 minutes
Normalized efficiency*	> 0.5 and < 1		> 0.25 in 15 minutes

* Composite signal

RTC quality control analysis

Daily report, red/yellow/green dashboard with links to details and interactive graphics

RTC Dashboard for 2017-03-24

	New Mexico	Florida	Vermont	Nevada
Weather	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 0.57 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot	Irradiance 1.00 Wind 1.00 Air Pressure 1.00 Humidity 1.00 Rainfall 1.00 Datalogger 1.00 Detailed Report Interactive Plot
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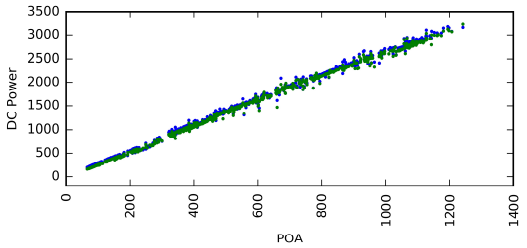
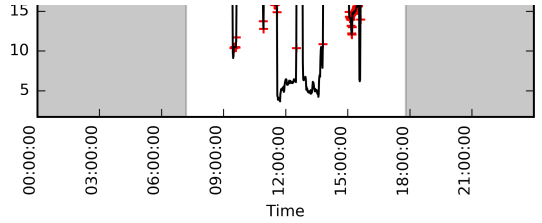
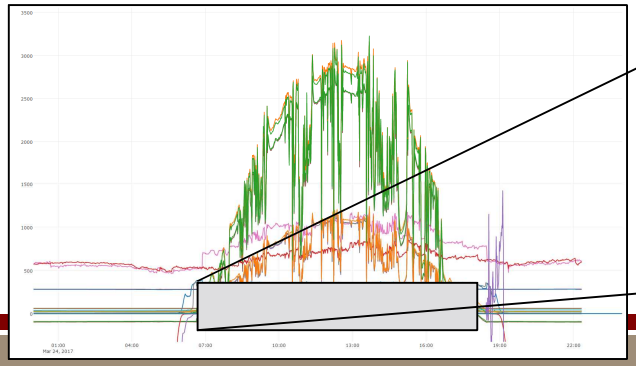
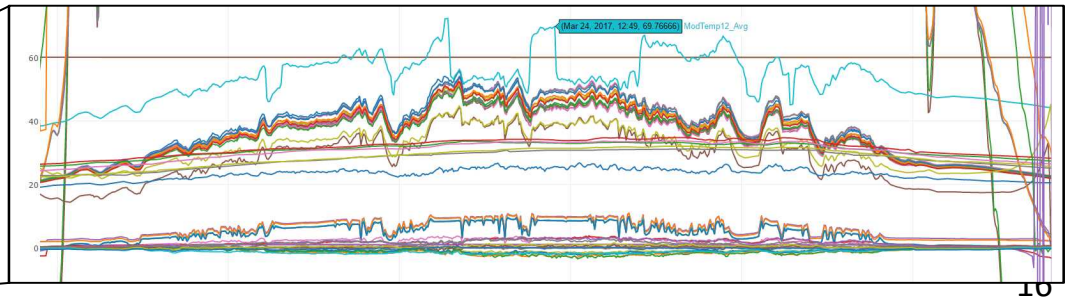


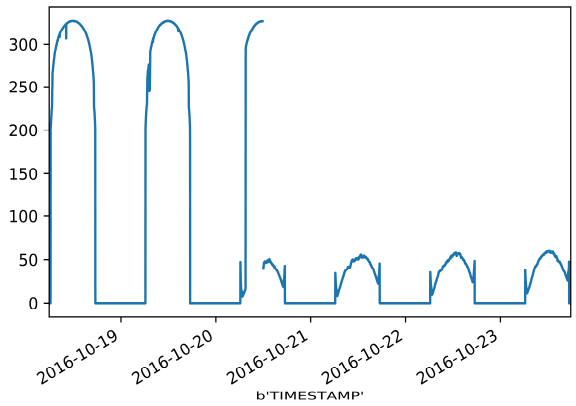




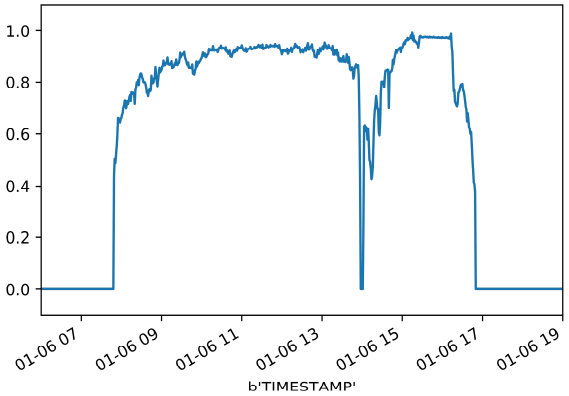


RTC quality control analysis

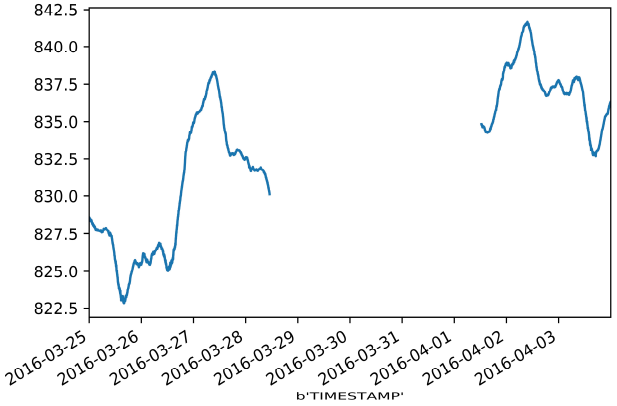
Data > upper bound



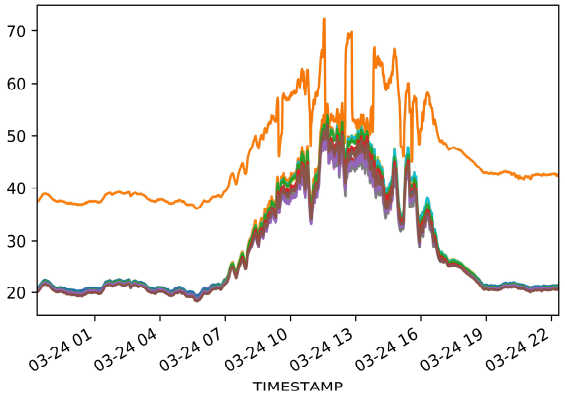
Abrupt change



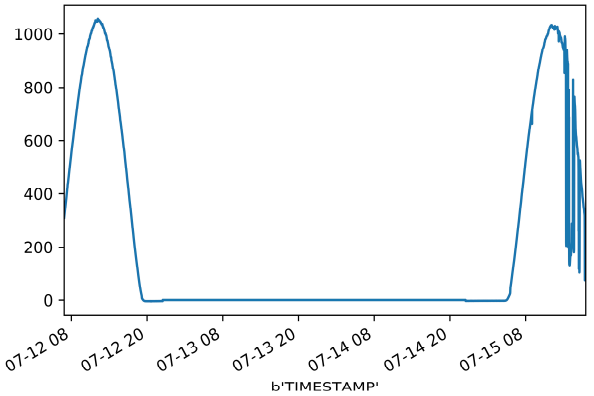
Missing data



Mismatch



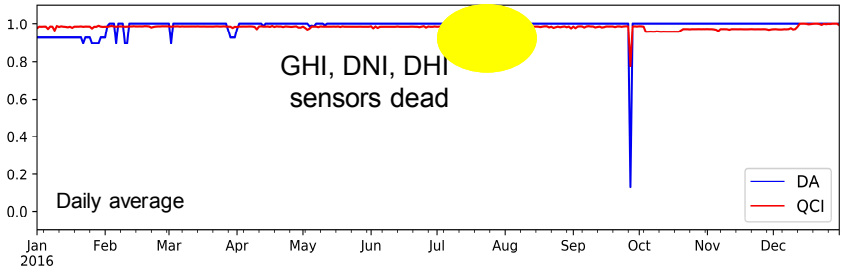
Dead sensor

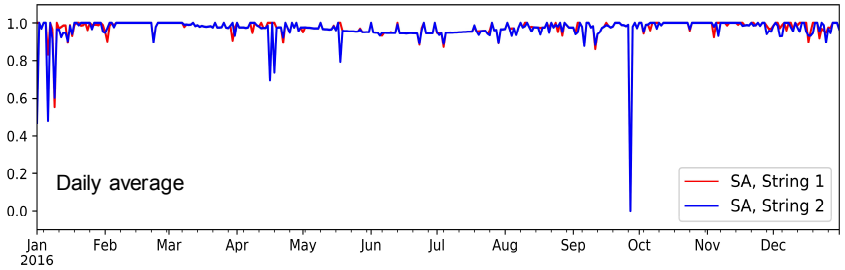


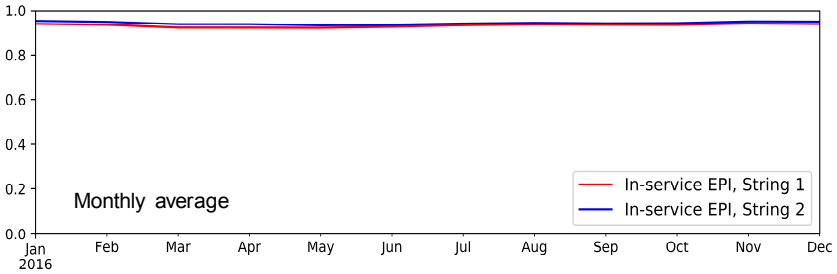
RTC quality control analysis

Yearly report, daily and monthly metrics

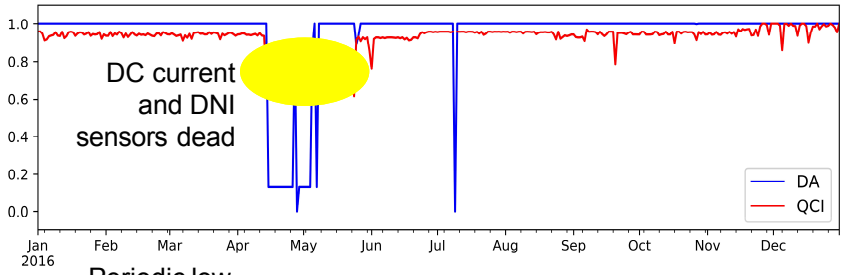
New Mexico



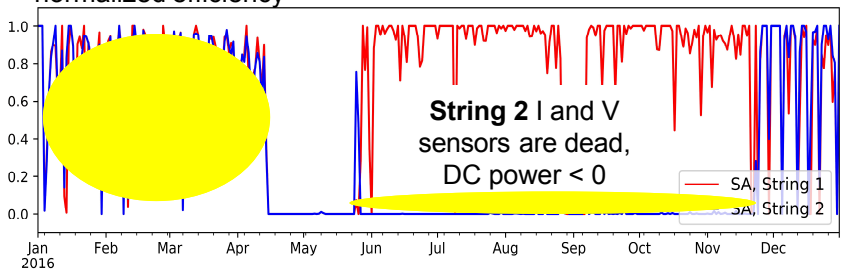


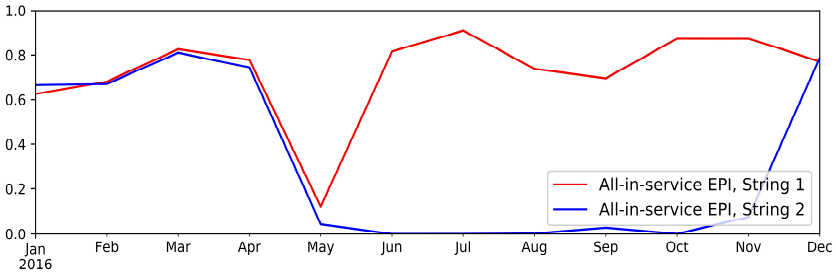


Vermont



Periodic low
normalized efficiency





Pecos

- Open-source python package
  - Python 2.7, 3.4, or 3.5
  - Revised BSD License
- Software repository
  - https://github.com/sandialabs/pecos
- Documentation
  - http://pecos.readthedocs.io
- Software testing
  - https://travis-ci.org/sandialabs/pecos
- ‘Getting started’ examples included with the software
- Version 0.1.5 (master branch)
  - New features include data acquisition, more flexible dashboards, PD and FAR metrics, compatibility with irregular timestamps, improved efficiency