High Resolution with a Purpose: Photovoltaic System Monitoring and Analysis Using the PI System

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U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

FSEC®

High Resolution with Purpose

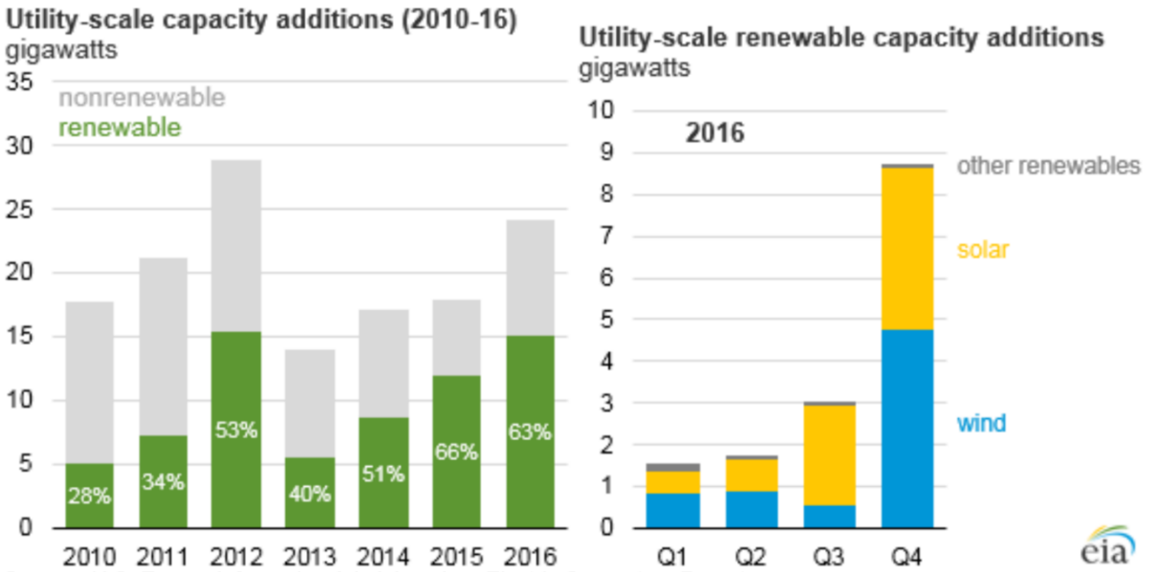
- Our perspective
- Photovoltaic (PV) power generation
- Levelized Cost of Energy (LCOE) is the driver
- Using the PI System for LCOE reduction
  - High resolution monitoring and analysis
  - Benefits
- Next steps
  - Partner with commercial industry

Our perspective

- US PVMC
  - US Photovoltaic Manufacturing Consortium
    - DOE funded, one of many SunShot initiatives
      - 5-year program (2012-2017), ends May 31st
    - Improve the US PV supply chain
      - Thin film track
      - c-Si track
    - Industry lead consortium
      - Work issues industry deemed important
  - University of Central Florida
    - Florida Solar Energy Center
      - State’s energy research institute since 1975
    - Led c-Si track, focused on metrology
    - Advanced metrology for PV modules

PV Capacity Going Strong

- 2016 another banner year of solar capacity additions
  - Renewables > Nonrenewable
  - Solar > Wind



Source: U.S. Energy Information Administration, *Electric Generators Report*
Note: The last two months of 2016 are based on planned reported additions and are subject to change.

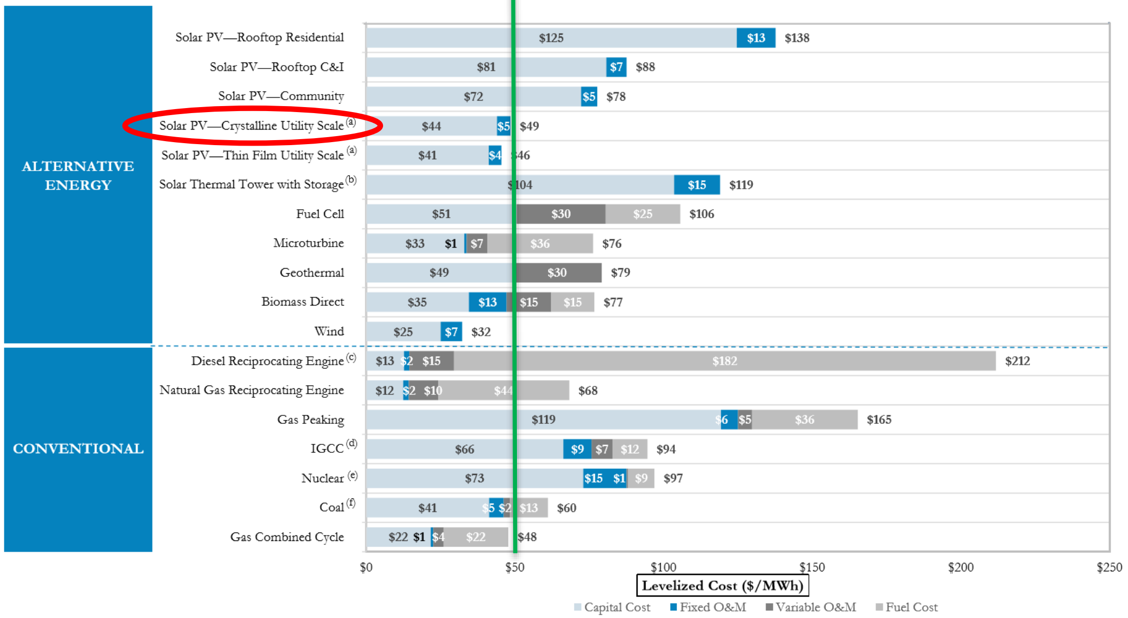
Data source: U.S. Energy Information Administration

Levelized Cost of Energy

- Solar exponential growth due to economic competitiveness with other energy sources

$$LCOE = \frac{Cost\ (\frac{\$}{MW})}{Energy\ Output\ (\frac{MWh}{MW})}$$

- Lazard's LCOE (2016)
  - unsubsidized
  - Capital cost
  - O&M cost
- Influencing LCOE
  - Reduce capital cost
    - Reduce risk
      - Lowers finance costs



https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf

Using the PI System for LCOE Reduction

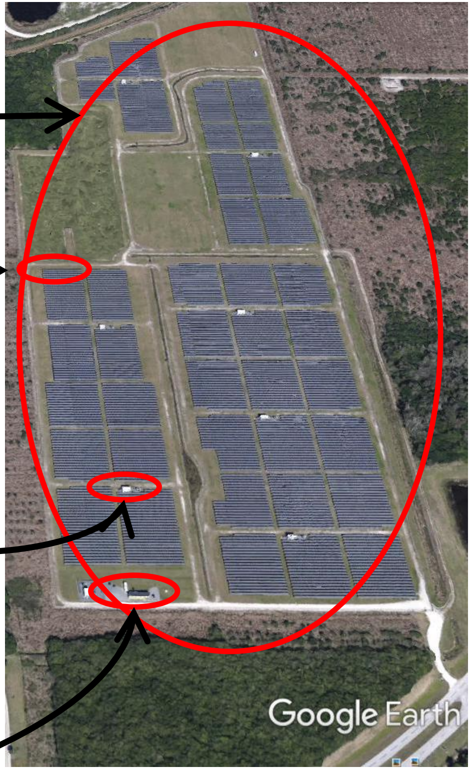
- Reduce risk
  - ➢ Energy degradation over time is assumed based historical data
    - ▪ Data is obtained through manual system intervention
      - – Disconnect module, strings, perform field measurements
  - ➢ Real-time degradation rates will provide confidence in performance trends and lifetime predictions
    - ▪ Lower risk equates to lower financing rates
    - ▪ Increased asset value for re-sale or refinance
    - ▪ Data is obtained *in situ*, no intervention with equipment

PV Plant Architecture

- Typical PV plant
  - Ten of thousands of modules
    - ~350 W each (7 A, 50 V)
    - ~3000 panels per 1 MW (DC)
  - Thousands of strings

    - 20 to 30 modules connected in series
    - 1000 V DC moving to 1500 V DC
      - Strings meet at combiner box
      - Connect to re-combiner or to inverter
  - Inverters to Transformers
    - DC to AC conversion
    - Multiple inverters per site

  - Site transmission



Apply the PI System in PV system monitoring

System setup

- Calibrated meteorological station
  - Irradiance, temperatures, humidity, pressure, wind speed and direction, PV reference cells monitored with Campbell Scientific data logger
    - Use PI Interface Configuration Utility™, PICSILoggerNet to port data
- PV module monitoring setup
  - AC and DC parameters monitored from micro-inverter
    - Use PI Interface Configuration Utility™, PICSILoggerNet
  - *In situ I-V* curve monitoring using I-V tracer
    - Use PI Interface Configuration Utility™, PI_UFL to port data
- Connect to the PI System
  - Meteorological data, inverter data and *I-V* tracer data are stored and structured in PI Server™
  - Different tools and functions provided by the PI System are used for data processing and analysis

PV system analysis

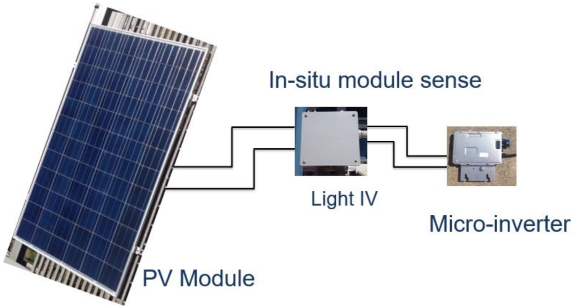
Use micro-inverter and I-V tracer to get real-time performance data of PV modules

Store and structure real-time data in PI server™

Use the PI system tools and combination of external platforms (python) to analyze PV module performance data

Calculate power losses on different loss mechanisms

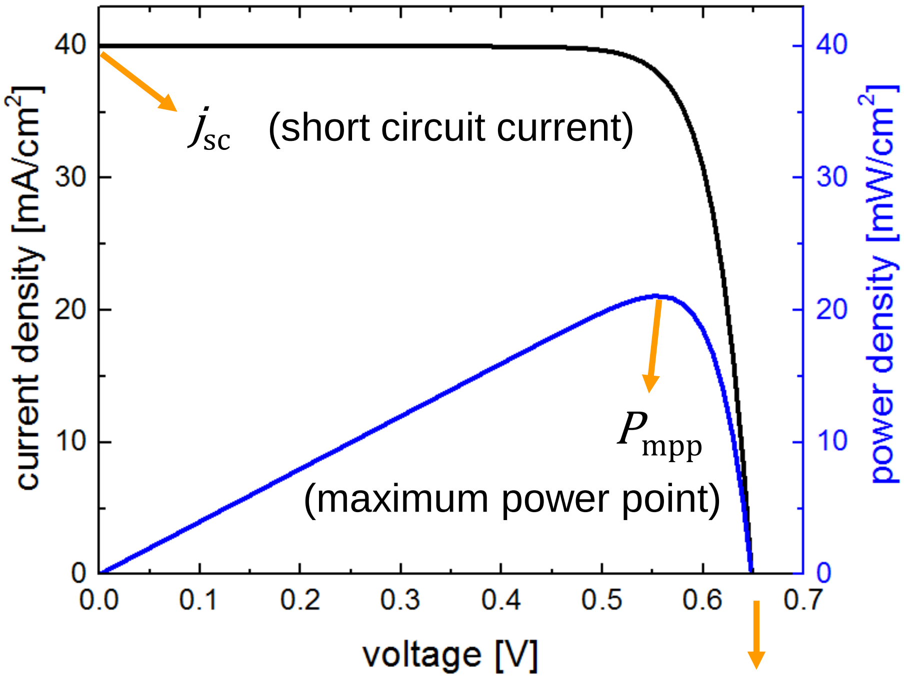
Generate degradation factors over time, perform long-term degradation analysis and predictions



Technique *not limited* to micro-inverters
Will work with string configuration and large inverters

Basic current-voltage parameters monitoring

Solar cell current-voltage (*I-V*) characteristics



j_{sc} (short circuit current)

P_{mpp} (maximum power point)

V_{oc} (open circuit voltage)

Efficiency:

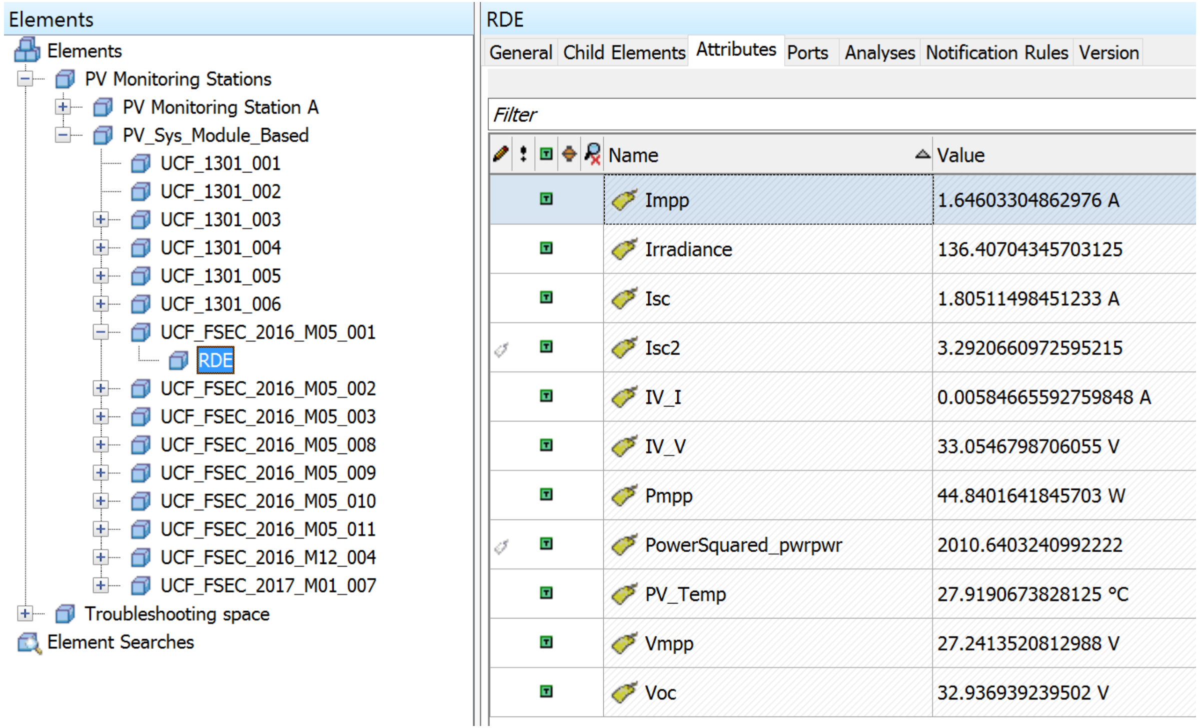
$$\eta = \frac{p_{mpp}}{p_{in}}$$

Fill factor: ('*squareness*' of IV)

$$FF = \frac{p_{mpp}}{j_{sc} \times V_{oc}}$$

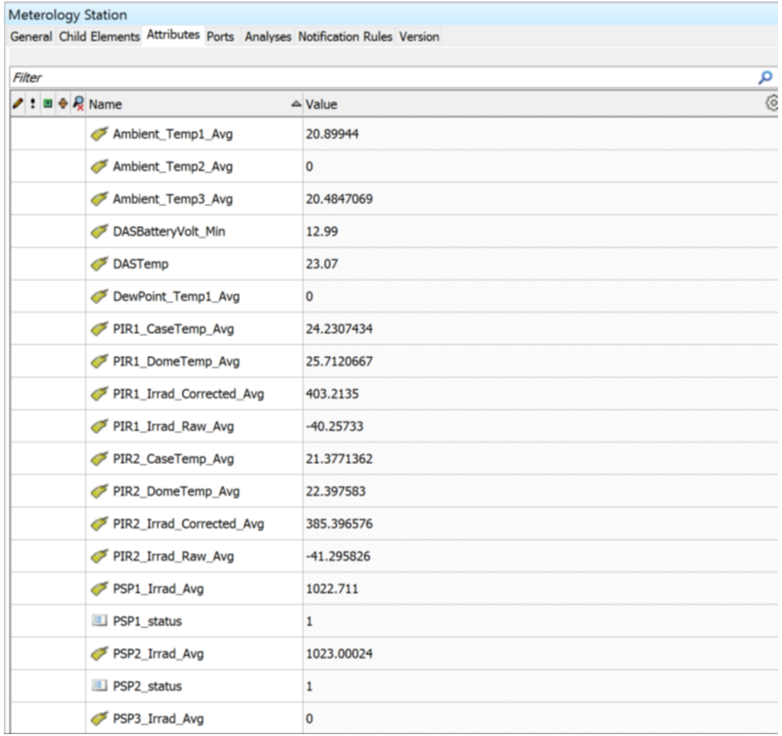
PV module performance parameters

- Data structure in the PI System



Meteorological data

- Data structure in the PI System



Meterology Station

General | Child Elements | Attributes | Ports | Analyses | Notification Rules | Version

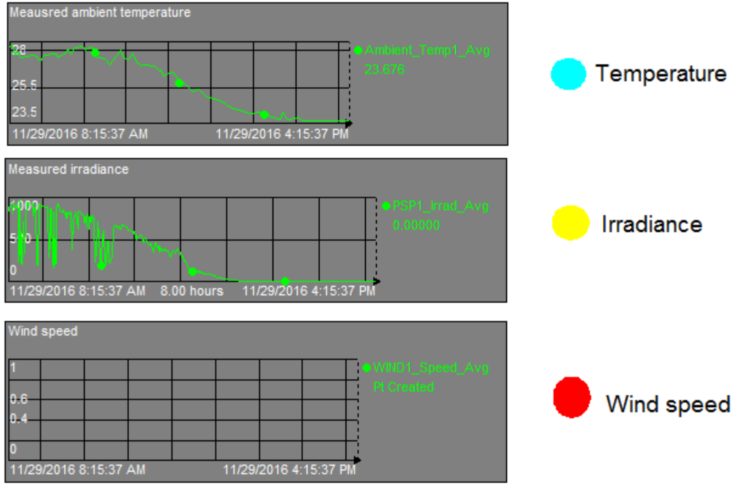
Filter

Name	Value
Ambient_Temp1_Avg	20.89944
Ambient_Temp2_Avg	0
Ambient_Temp3_Avg	20.4847069
DASBatteryVolt_Min	12.99
DASTemp	23.07
DewPoint_Temp1_Avg	0
PIR1_CaseTemp_Avg	24.2307434
PIR1_DomeTemp_Avg	25.7120667
PIR1_Irrad_Corrected_Avg	403.2135
PIR1_Irrad_Raw_Avg	-40.25733
PIR2_CaseTemp_Avg	21.3771362
PIR2_DomeTemp_Avg	22.397583
PIR2_Irrad_Corrected_Avg	385.396576
PIR2_Irrad_Raw_Avg	-41.295826
PSP1_Irrad_Avg	1022.711
PSP1_status	1
PSP2_Irrad_Avg	1023.00024
PSP2_status	1
PSP3_Irrad_Avg	0

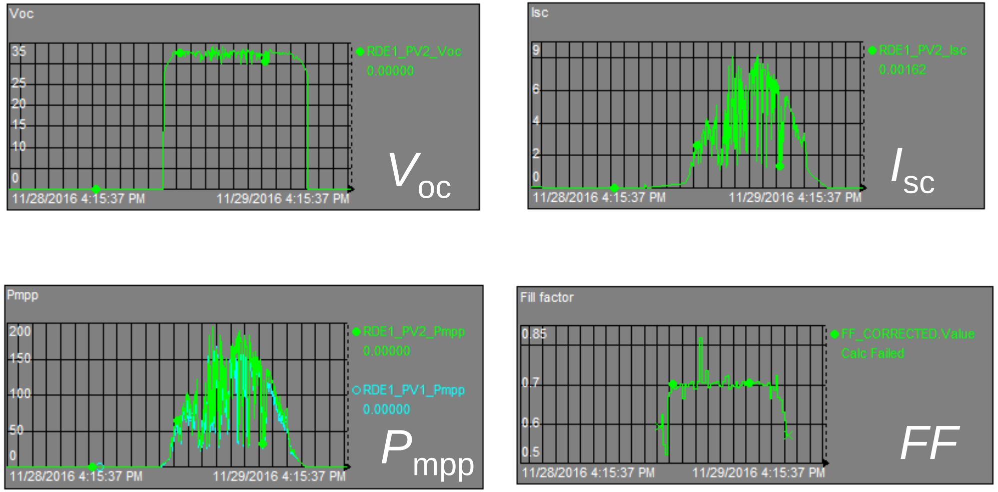
Data visualization using PI ProcessBook®

- Ambient condition data, temperature, irradiance, wind speed.
- Measured PV module performance parameters

Ambient condition



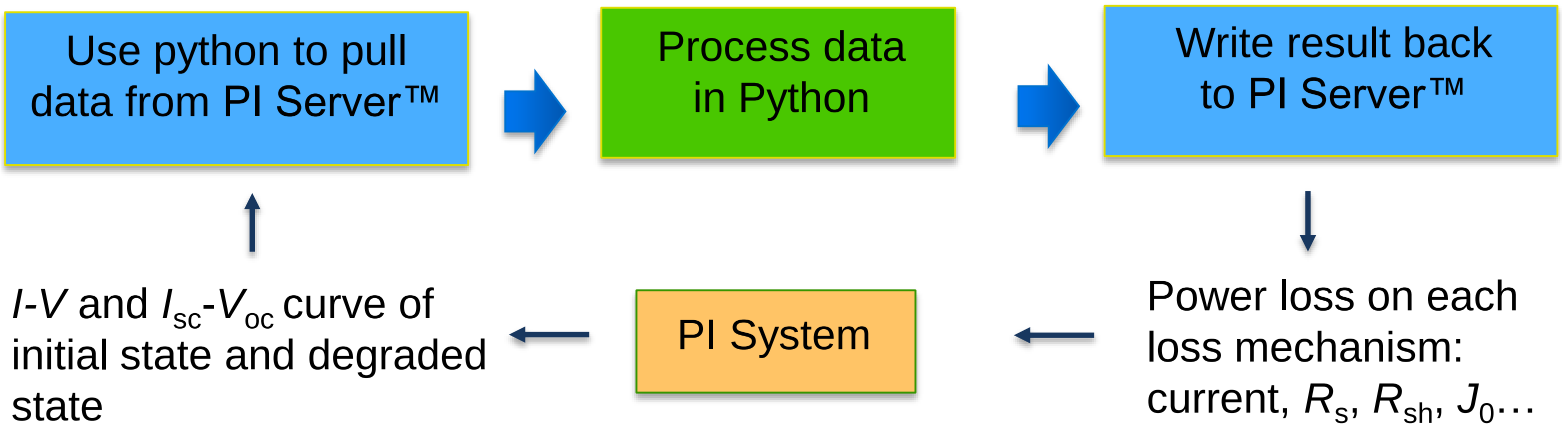
PV module performance



Advanced power loss analysis

Real-time PV module loss analysis

- Stand alone analysis is not enough for PV modules
- Functions provided by the PI System tools have limitations in doing complicated analysis
- Python is used to combine with the PI System to perform detailed analysis



Diode model of PV device

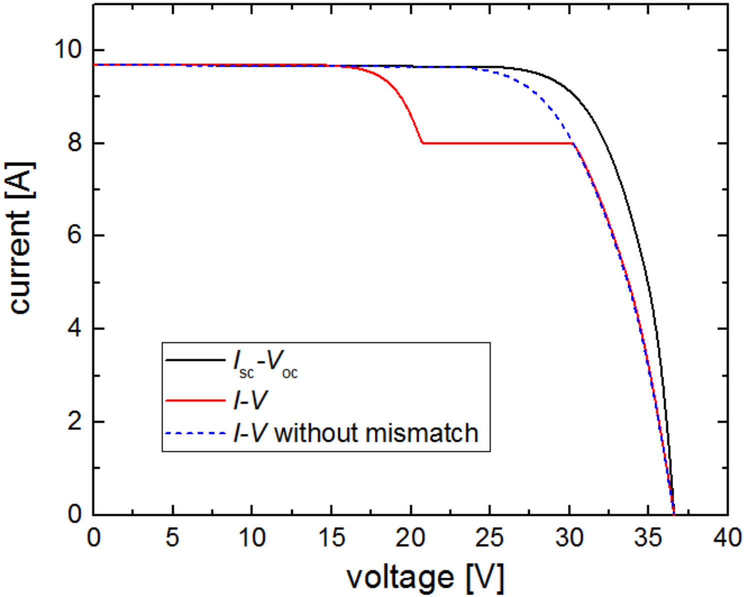
- Based on the p-n junction nature, one-diode model can be applied to model the I-V characteristics of a solar cell

$$I(V) = j_{\mathrm{ph}} - j_0 \left\{ \exp\left[\frac{q(V + j(V)R_{\mathrm{s}})}{nkT} \right] - 1 \right\} - \frac{V + j(V)R_{\mathrm{s}}}{R_{\mathrm{sh}}}$$

- Important parameters:
  - R_{s}: Resistive loss due to current transport
  - R_{sh}: Defects causing leakage current
  - j_0: Impurities of semiconductor

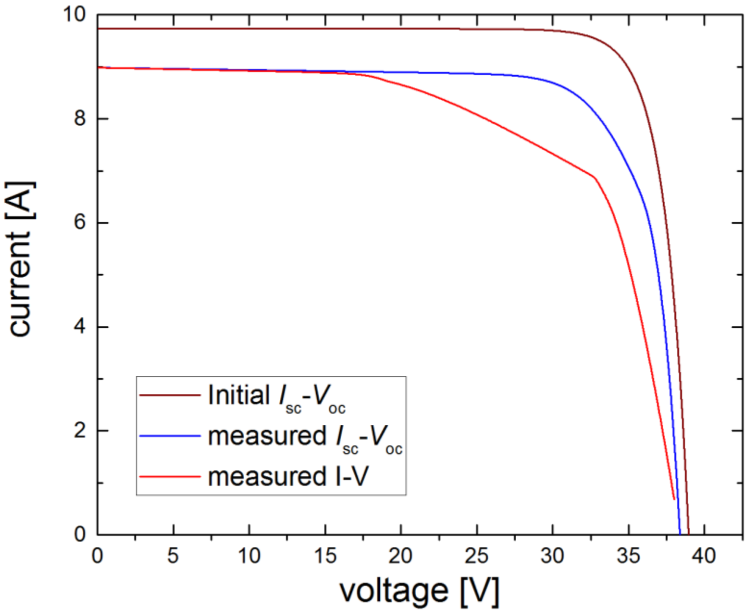
I_{sc}-V_{oc} curve of a PV module

- I_{sc}-V_{oc} curve is constructed of (I_{sc}, V_{oc}) points of individual PV modules measured under different illumination condition



Power loss analysis procedure

- I_{sc}-V_{oc} curve is constructed of (I_{sc}, V_{oc}) points of individual PV modules measured under different illumination condition



Compare I_{sc}-V_{oc} before and after degradation at I_{sc} region

↓ I_{sc} , uniform & non-uniform R_{sh} loss

Compare I_{sc}-V_{oc} before and after degradation at V_{oc} region

↓ J_0 loss

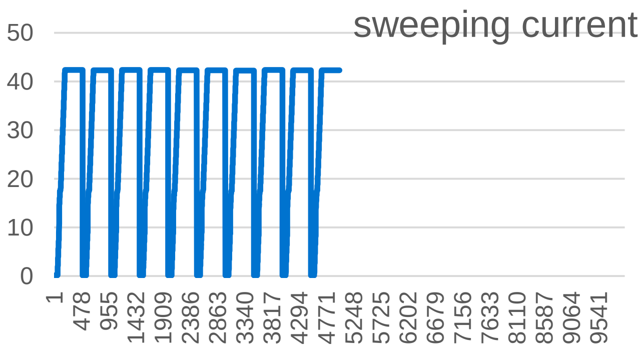
Compare I-V & I_{sc}-V_{oc} after degradation

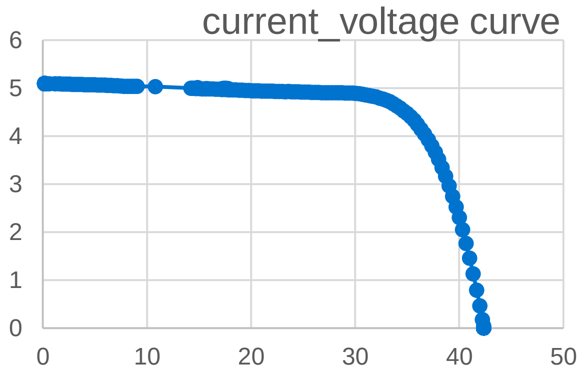
↓ R_s and current mismatch loss

Link the extracted parameters to specific failure modes

Data Processing

- Current-Voltage (*I-V*) data of individual PV modules
  - I-V sweep is done periodically in our PV System.
  - PI DataLink® is useful in data download and visualization

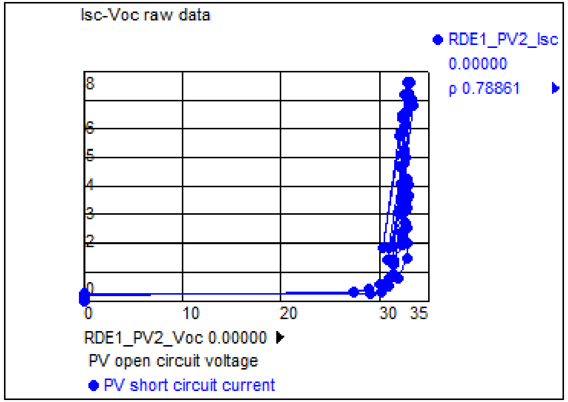


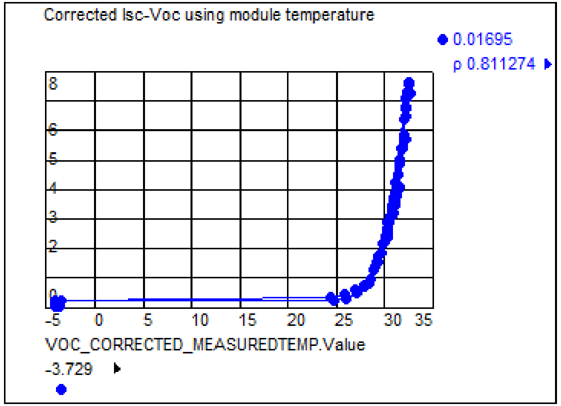


Data processing

- I_{sc}-V_{oc} data is corrected based on measured temperature
  - ➢ Python is used for data correction, but it can also be achieved by using Performance Equations or Analysis functions

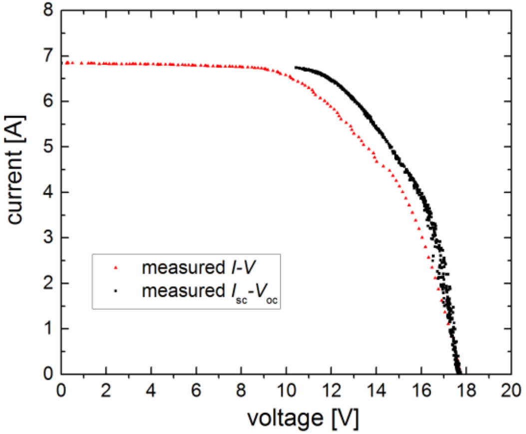
Isc-Voc curve for a single PV module

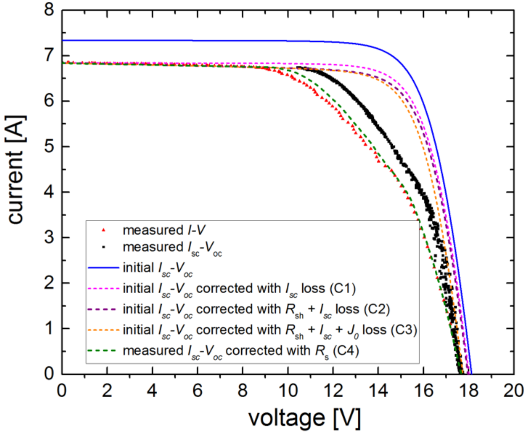


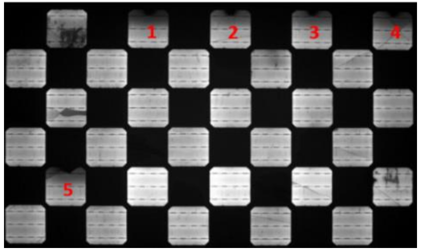


Case study of a PV module

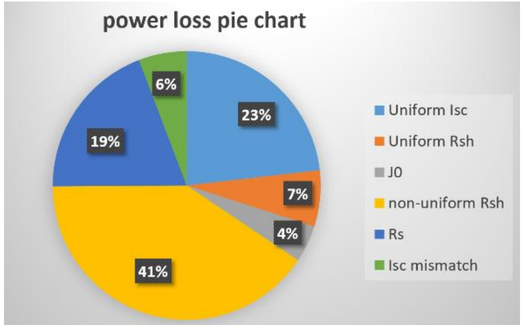
- One PV module in FSEC PV system







102.5 W →70.6 W



Future plan

- Applying all the algorithms on the string level
- Looking for Industrial partnerships to expand methodology
- Optimize data capture frequency
- Create standard set of time-series parameters
  - ➢ R_s, R_{sh}, J_0, …
- Create the time-series power loss statistics
- Perform predictions using PI System future data capability

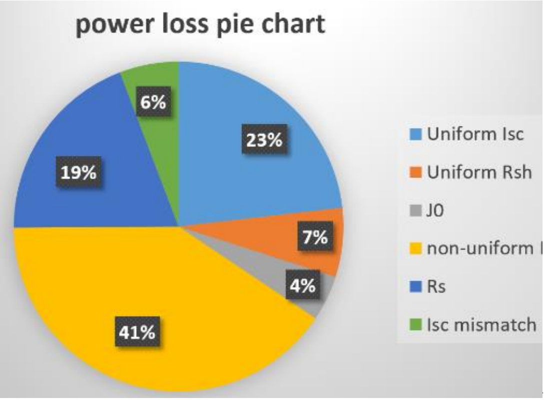
Conclusion

- Advanced PV system monitoring requires a powerful tool for data storage, analysis, and visualization
  - ➢ the PI system meets those challenges

Asset Framework	PI ProcessBook®
PI Server™	PI System Explorer™
PI Interface Configuration Utility™	PI DataLink®

- Integration with Python provides more detailed analysis capability
- Provided example of power loss analysis with real-time degradation
- Uncovering the unknown reduces risk, reduces LCOE

Photovoltaic System Monitoring and Analysis Using the PI System



COMPANY and GOAL

Florida Solar Energy Center applied high-resolution monitoring and analysis in PV system and achieved real-time degradation analysis.

FSEC

Florida Solar Energy Center, University of Central Florida

CHALLENGE

High resolution monitoring of PV system requires powerful data storage and analysis method.

- Current data collection is usually obtained through manual operation
- Advanced data storage and analysis method are required by high-resolution monitoring.

SOLUTION

PI System is used for real-time PV system data storage and management.

- Meteorological data, inverter data and I-V tracer data are stored and structured in PI Server.
- Real-time power loss analysis is achieved by combining with Python.

RESULTS

LCOE, O&M reduction

- Automatic data processing instead of stand-alone analysis performed manually.
- Automatic fault detection and degradation analysis based on the power loss calculation.

Contact Information

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Questions

Please wait for the **microphone** before asking your questions

State your **name & company**

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Complete the Online Survey for this session

http://bit.ly/uc2017-app

Thank you for your attention !