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Lanai Grid-Connected PV-Battery System Analysis (And Related PV Variability Research)

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Lanai Grid

Koehle Lodge

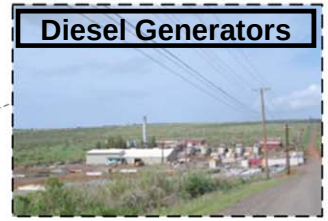
Well Pumps

(City #1 CKT)

(City #2 CKT)

Lanai City

Diesel Generators



(Harbor CKT)

Harbor

Airport

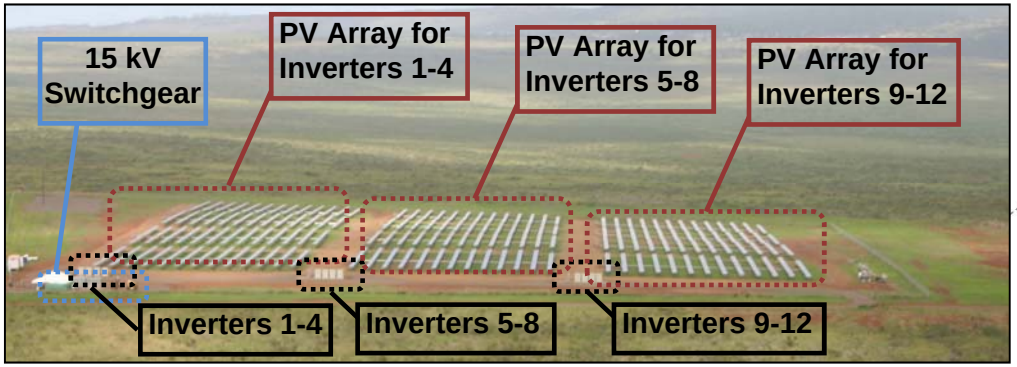
Miko Power Plant (10.4 MW)

(Hotel CKT)

PV Plant (1.2 MW)

(Hotel CKT)

Manele Hotel



1.2 MWac PV Plant with Battery system for ramp rate mitigation

5-MW Peak System Load

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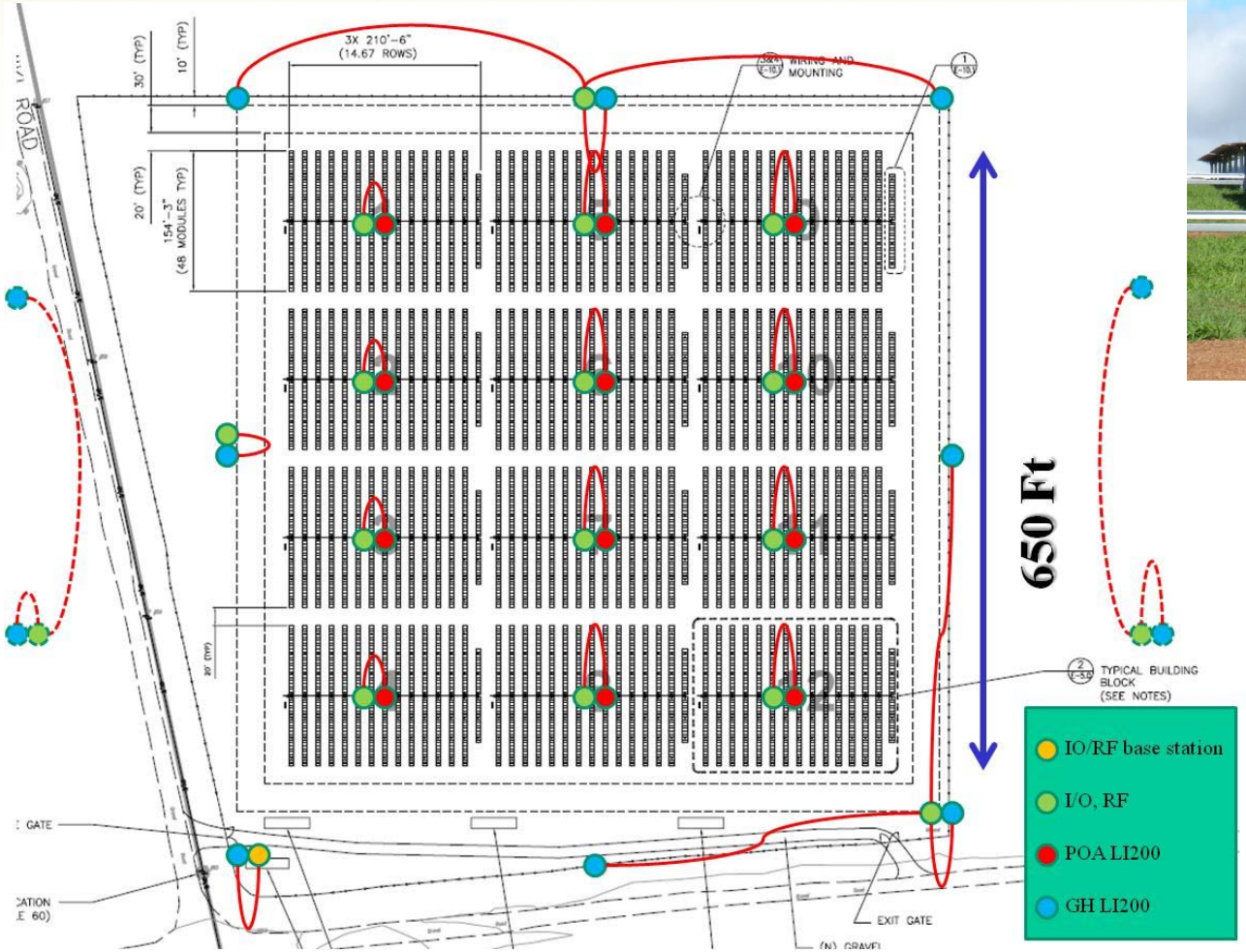
Lanai Irradiance Sensor Network



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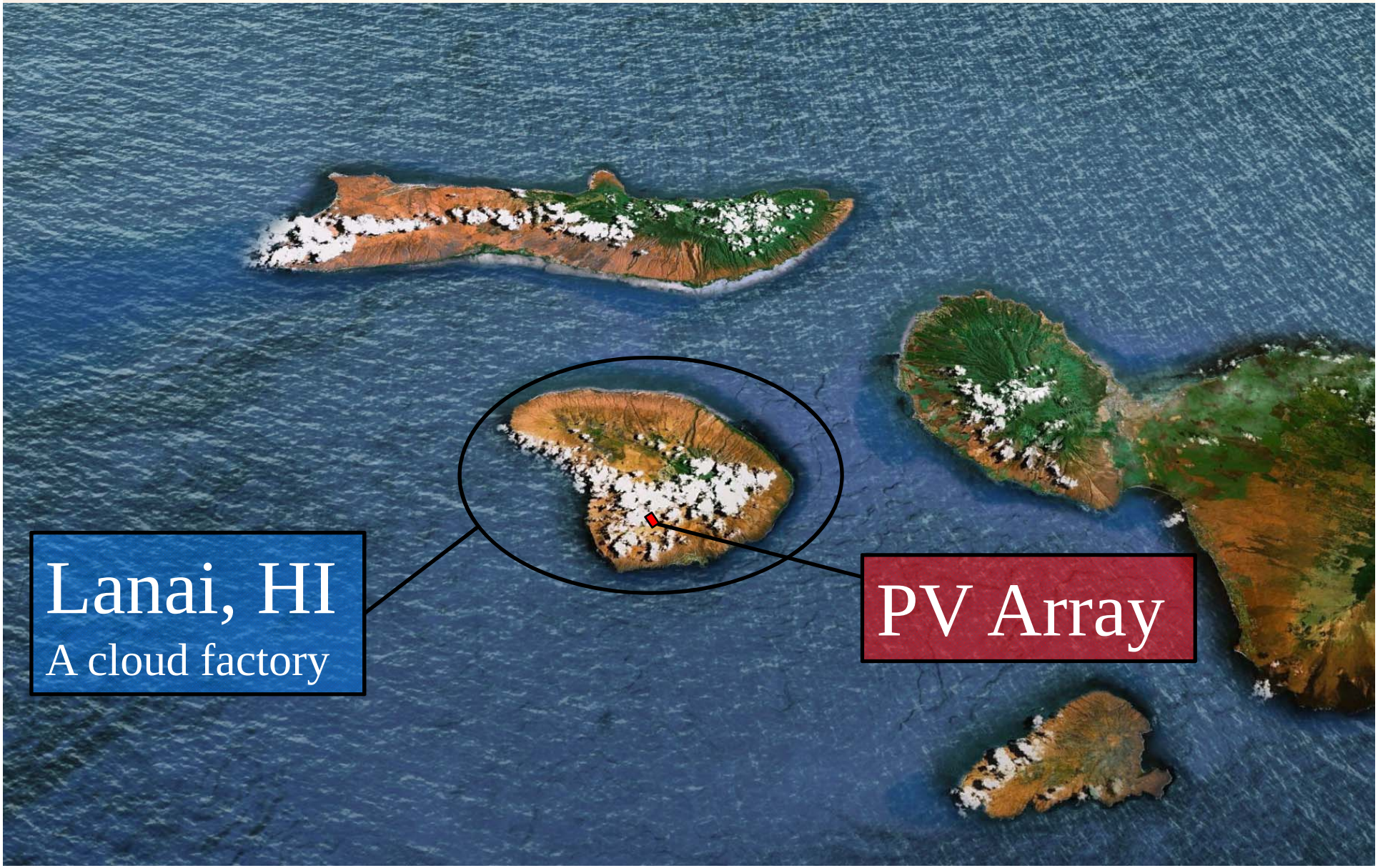
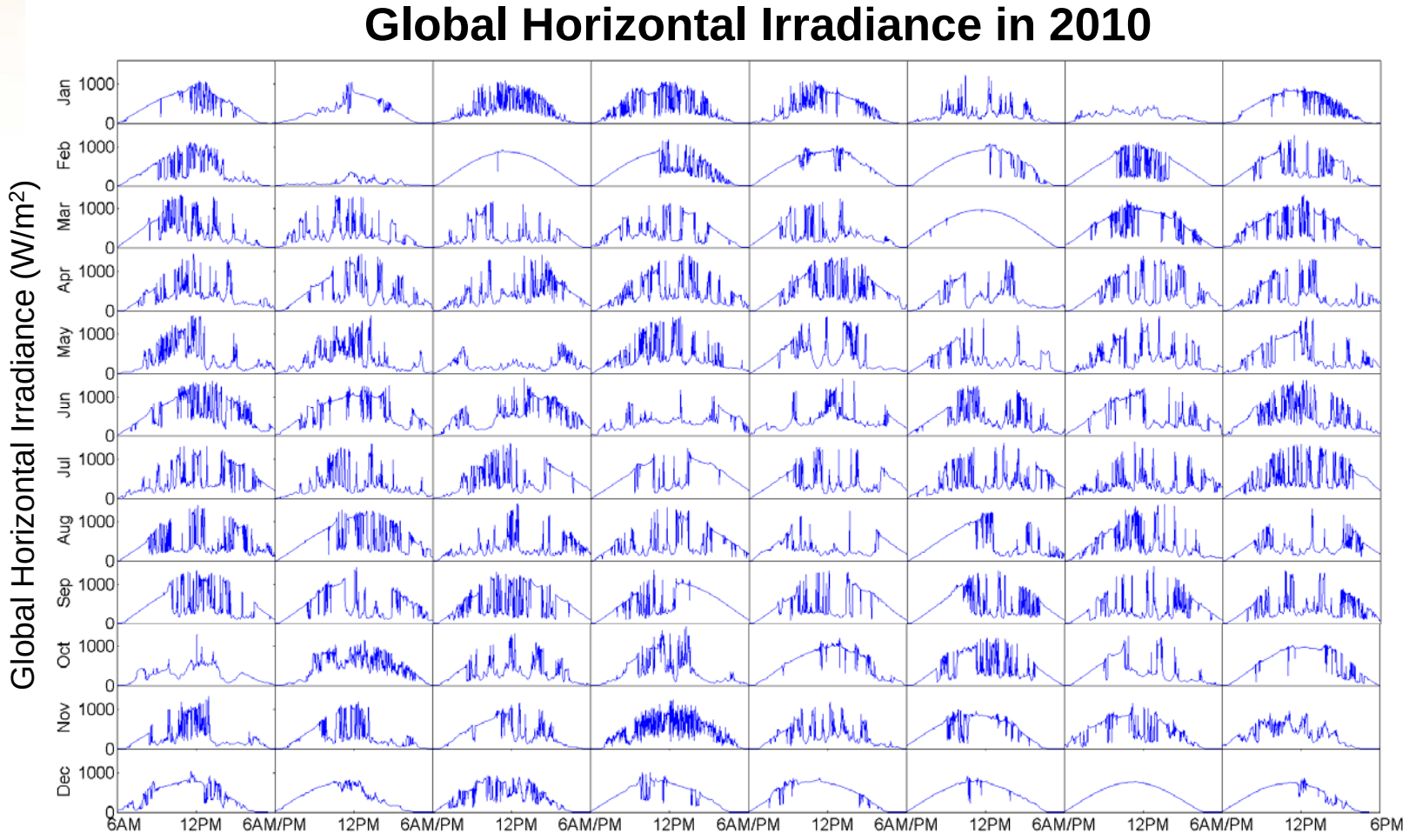
High Irradiance Variability in Lanai!



Irradiance on Lanai



GH Irradiance for first 8 days at the beginning of each month in 2010

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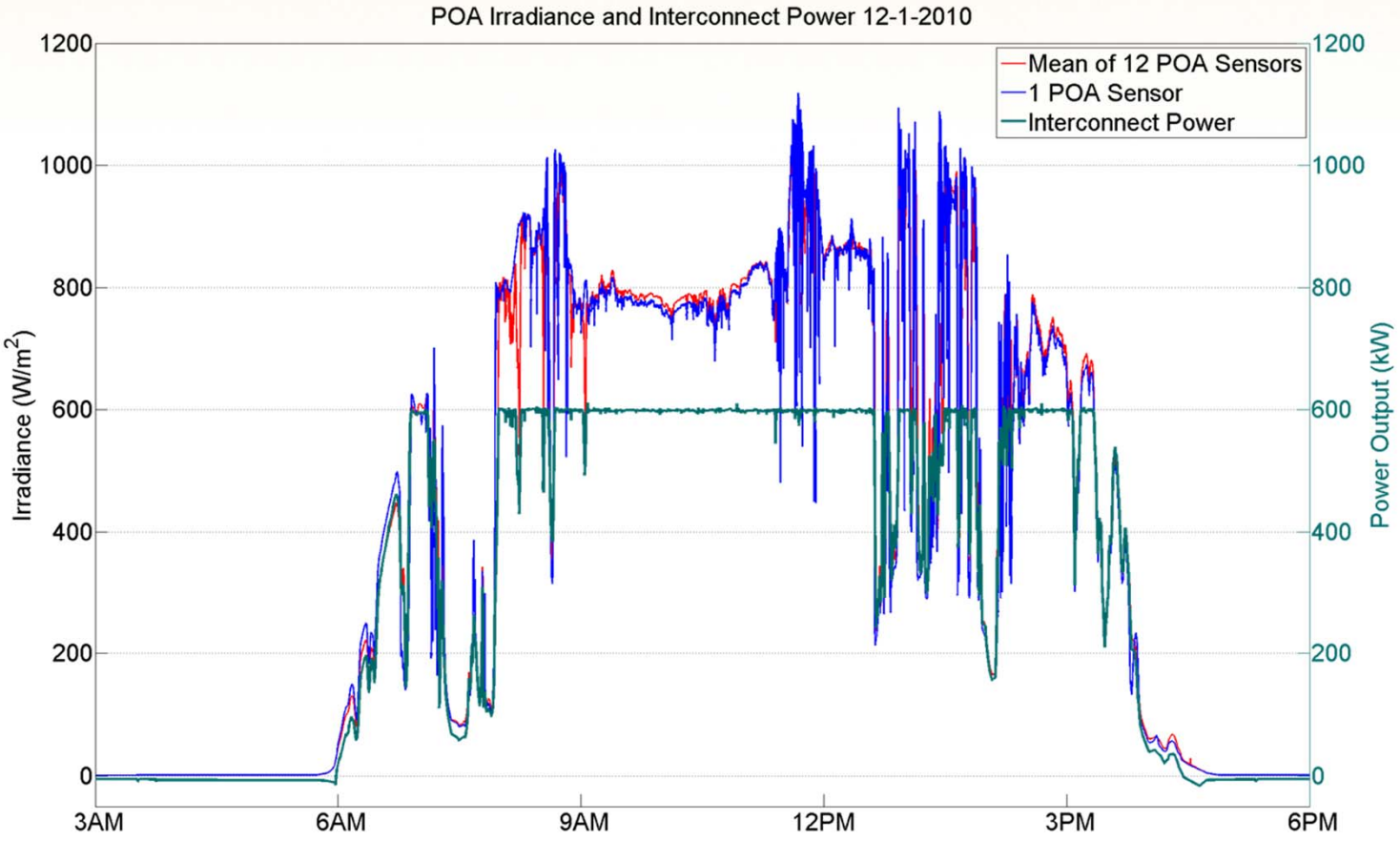
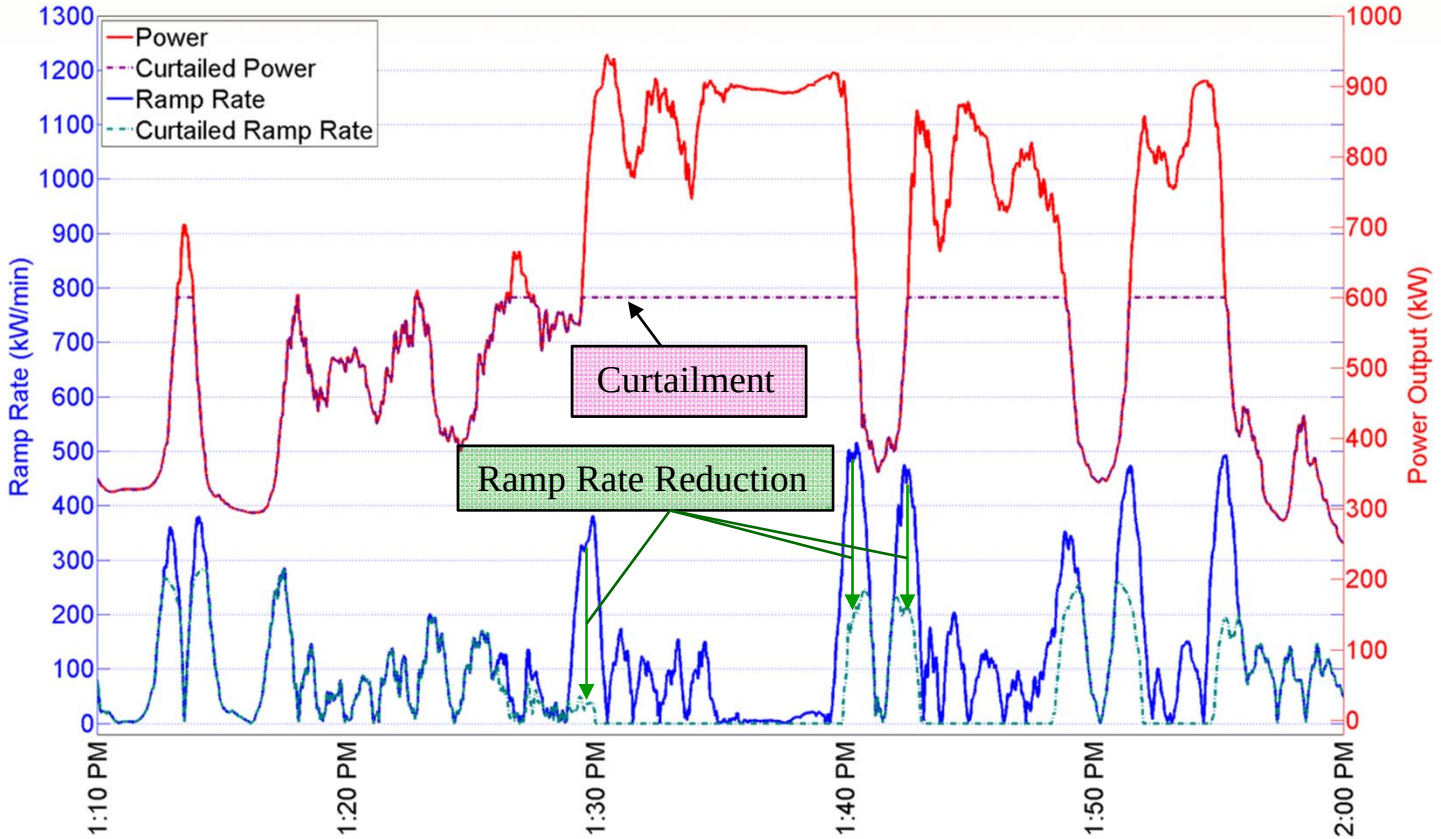
Interim Ramp Rate Control



Effect of Power Curtailment on Ramp Rates



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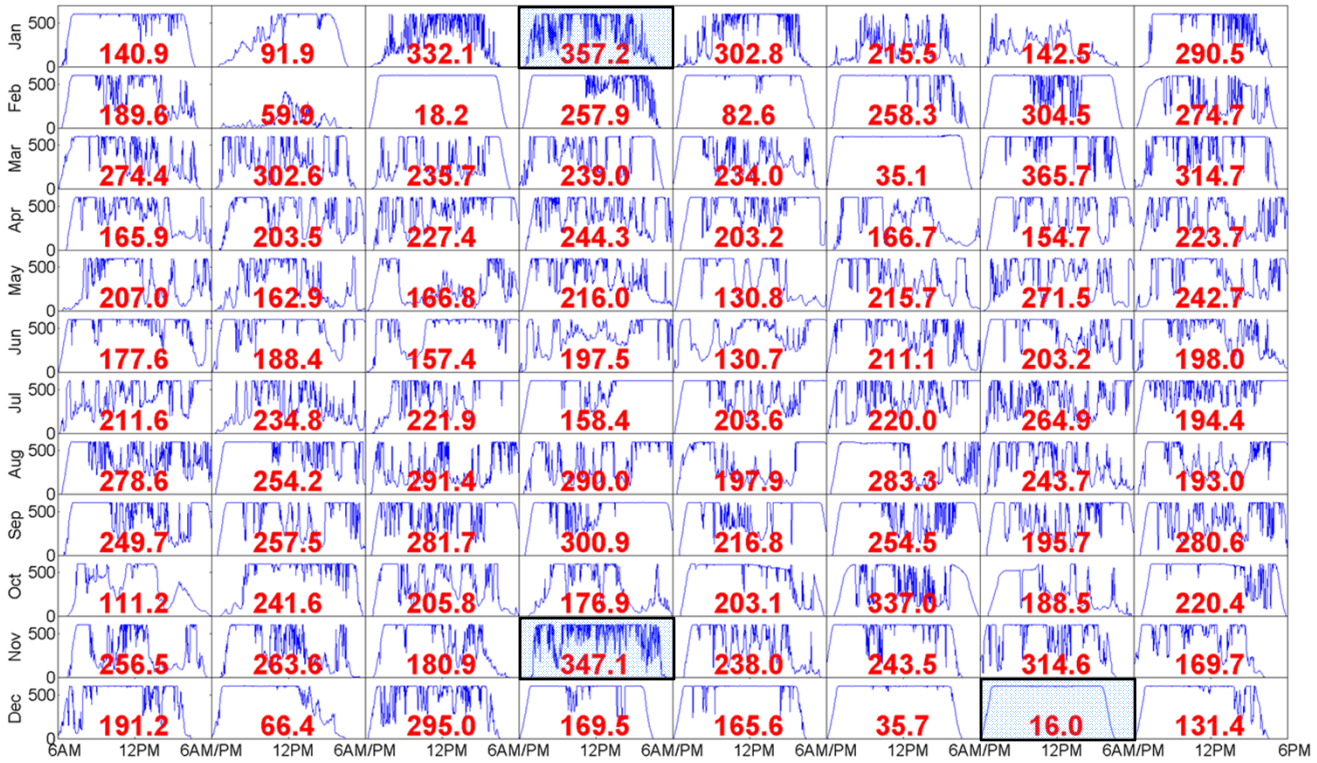
Max Ramp Rates in Lanai

Power output profiles and 99.5th percentile 1-minute ramps (kW/min) for 8 days at the beginning of each month in 2010



(using 99.5th percentile helps eliminate sensor noise)

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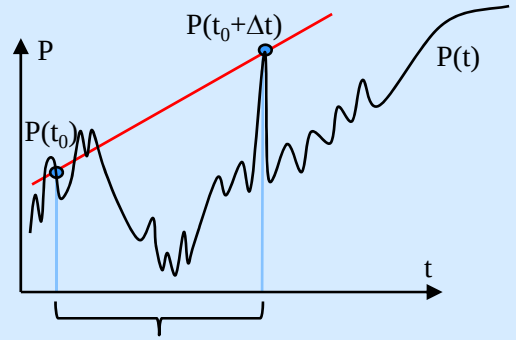
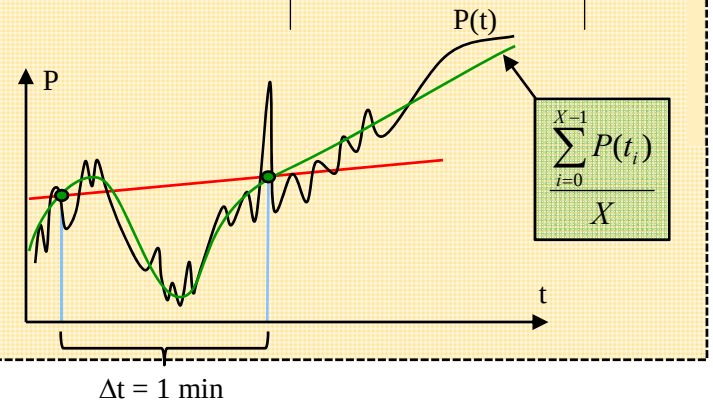
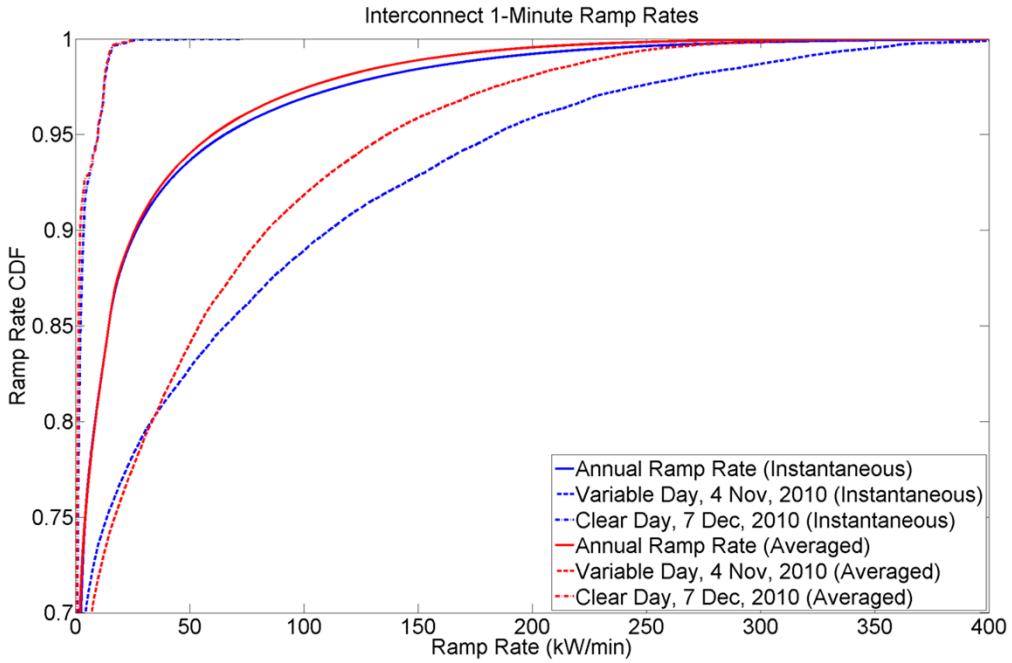
Instantaneous vs Averaged Ramp Rates

$$RampRate = \left| \frac{P(t_0) - P(t_0 + \Delta t)}{\Delta t} \right|$$



$$Ramp\ Rate_{averaged} = \left| \frac{\sum_{i=0}^{X-1} P(t_i) - \sum_{i=0}^{X-1} P(t_i + \Delta t)}{X \Delta t} \right|$$





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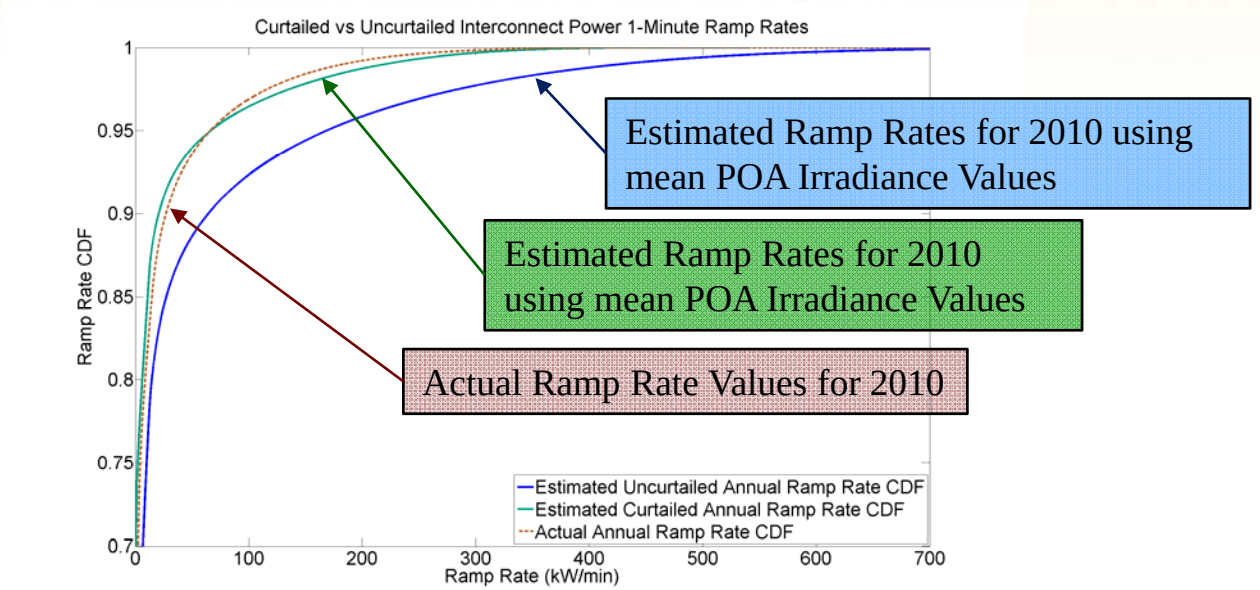
Estimating Ramp Rates without Curtailment



CDF percentage	Estimated Uncurtailed Ramp Rate (kW/min)	Estimated Curtailed Ramp Rate (kW/min)	Actual Curtailed Ramp Rate (kW/min)
80.0%	14.6	6.2	8.7
90.0%	64.4	20.7	27.1
95.0%	168.5	66.4	66.0
99.0%	428.7	220.0	184.1
99.5%	523.8	272.1	231.5
99.7%	587.3	304.4	265.7
99.9%	704.0	361.9	332.1

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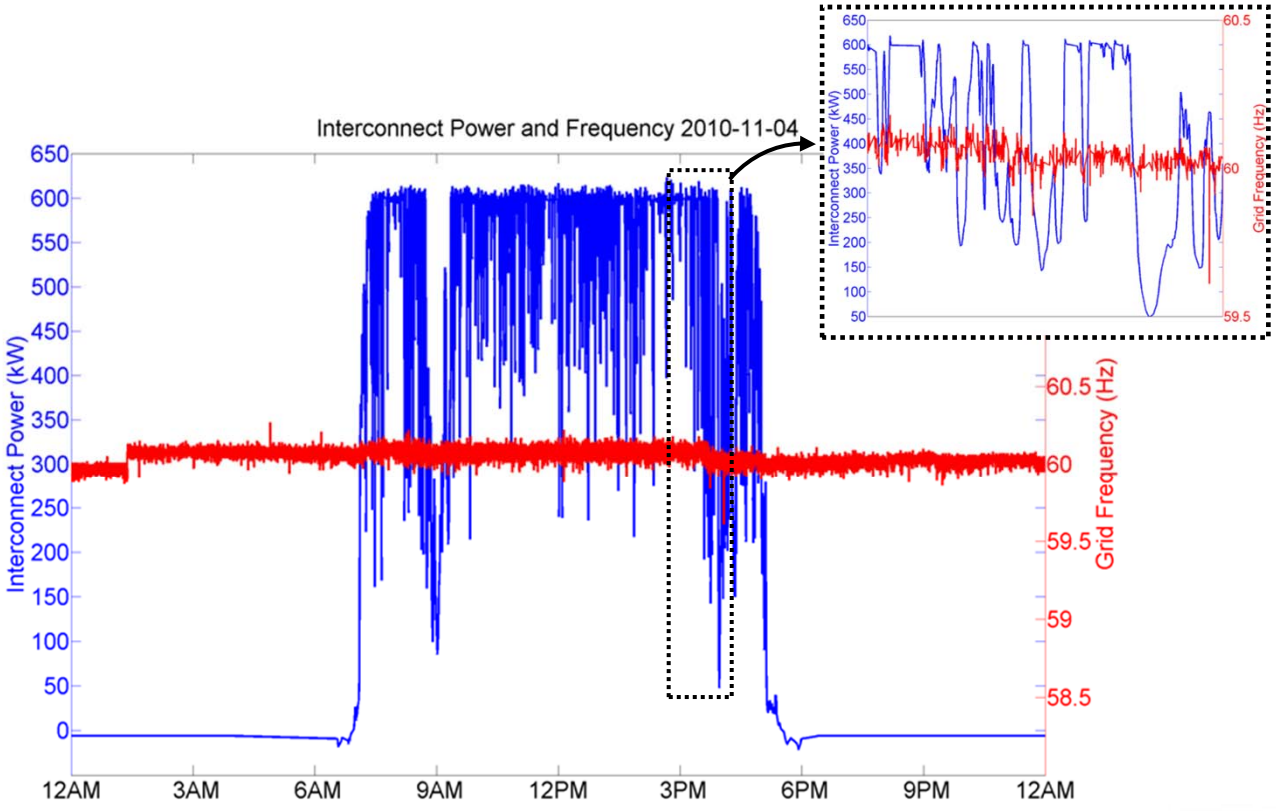
PV Ramp Rate Impact on Frequency

- **No significant frequency impacts observed at 600 kW output**
- **Impact on diesel generators ramping has not yet been evaluated**



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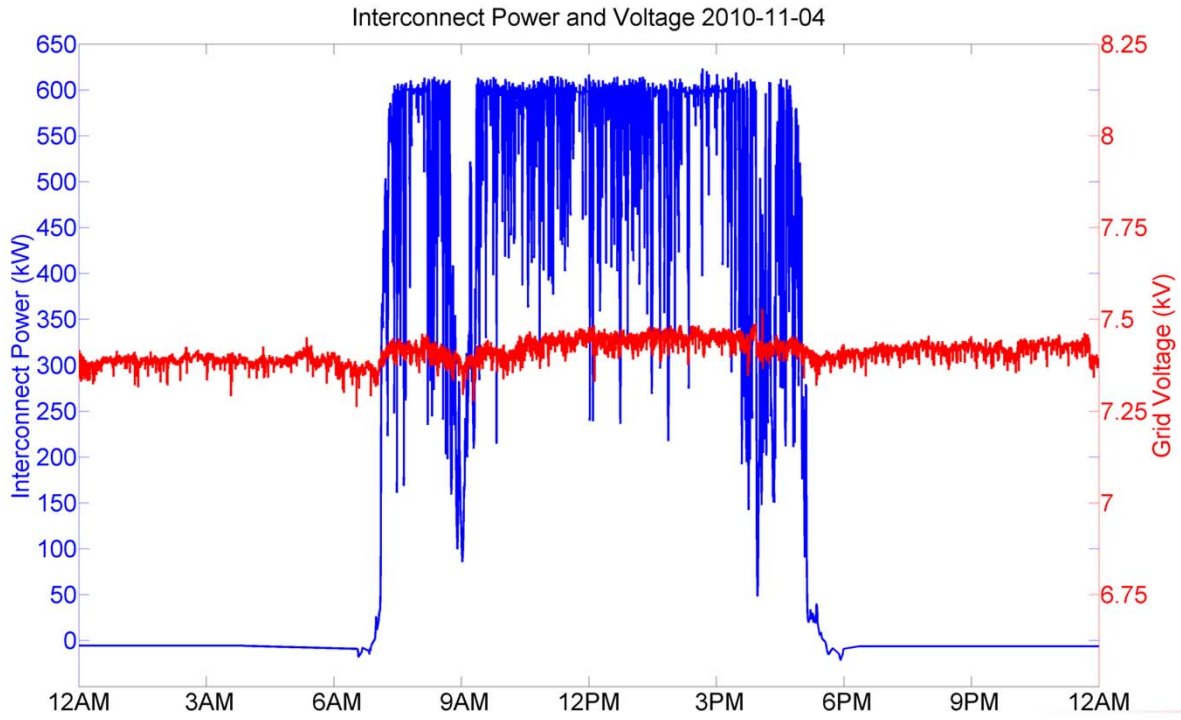
PV Plant Impact on Voltage

- **No significant local voltage impacts observed at 600 KW output**
- **Impact on generator reactive power output nor yet evaluated**
- **Local power factor (PF) set-point issued by the grid operator**
  - **Typically set unity**



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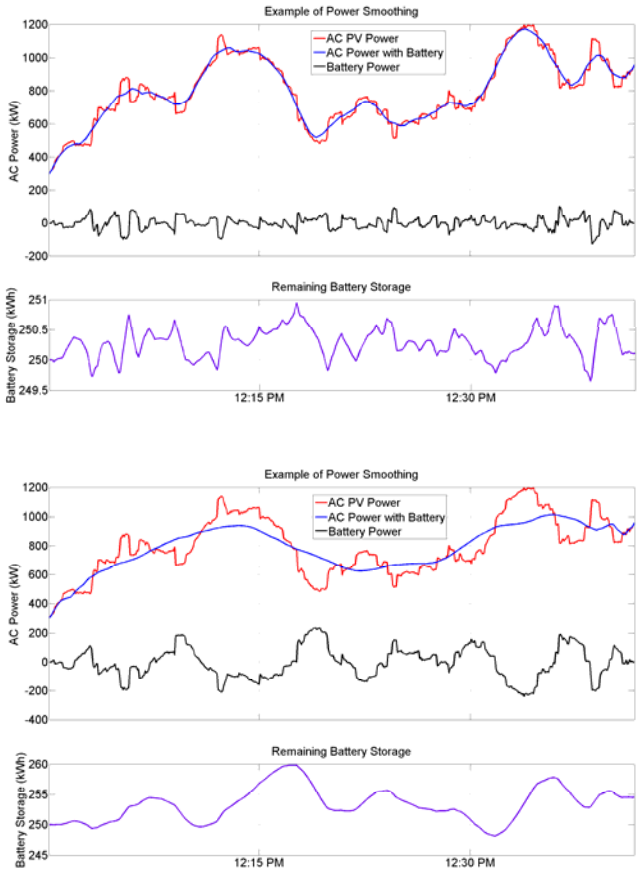
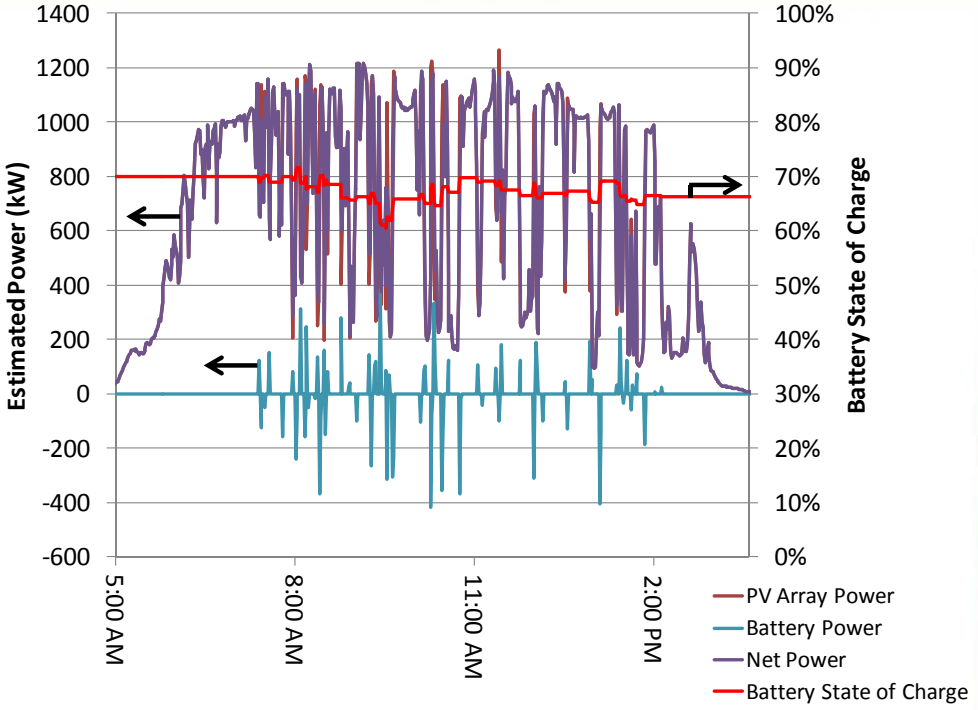
Energy Storage Application

Output <u>smoothing</u> using different time-scales.





Ramp rate limiting – avoids unnecessarily heavy battery use.

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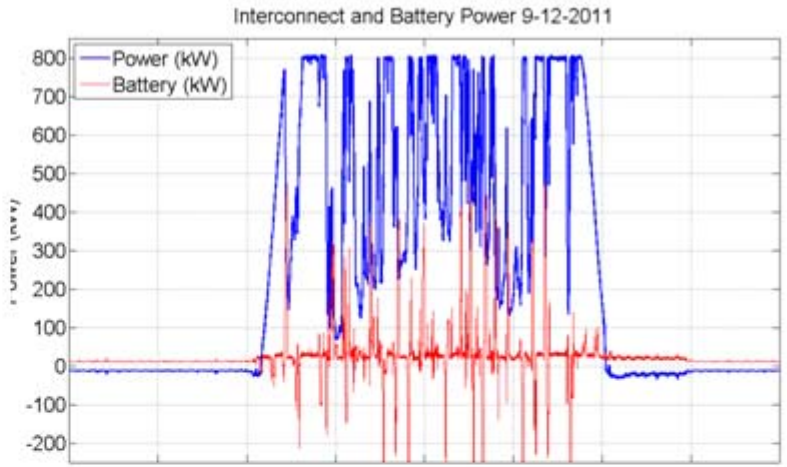
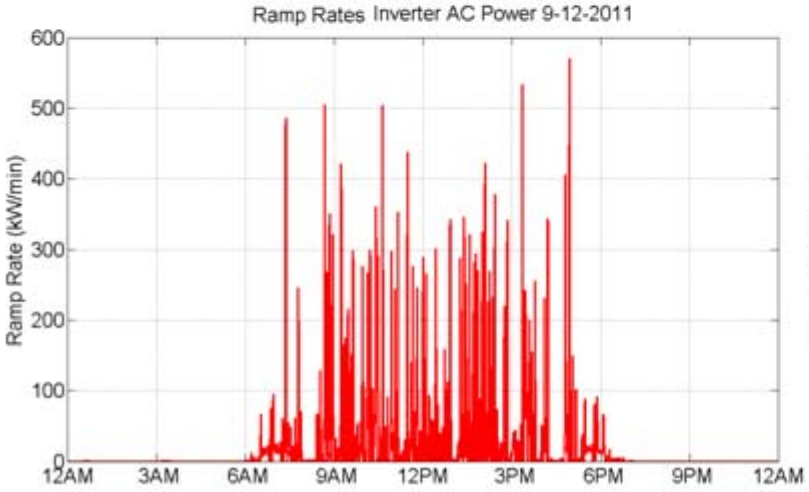
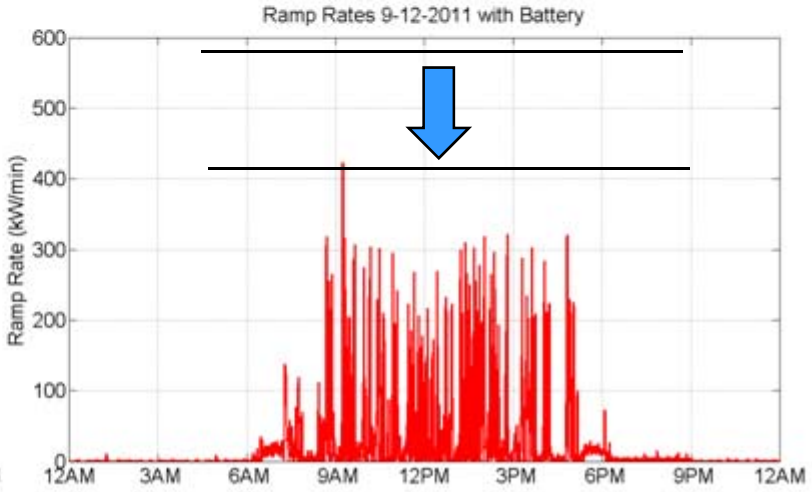
Ramp Rates with the Battery

- **Successful ramp limiting at 800 kW**
  - **System is now at full output (1.2 MWac)**







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NEWS RELEASE

Date: April 19, 2012

FOR IMMEDIATE RELEASE

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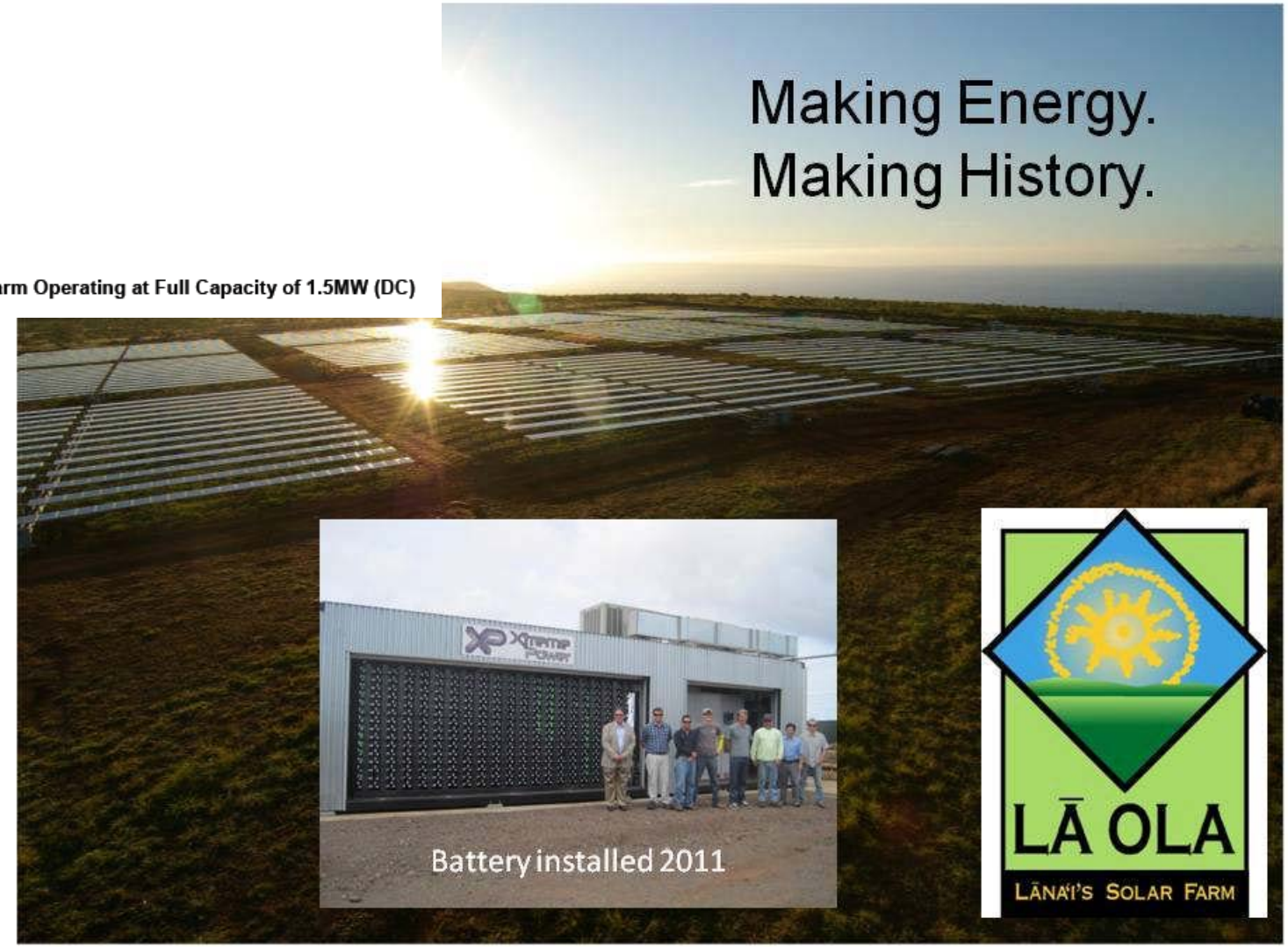
clovvorn@castlecooke.com

Lā Ola – Lāna'i Solar Farm Operating at Full Capacity of 1.5MW (DC)

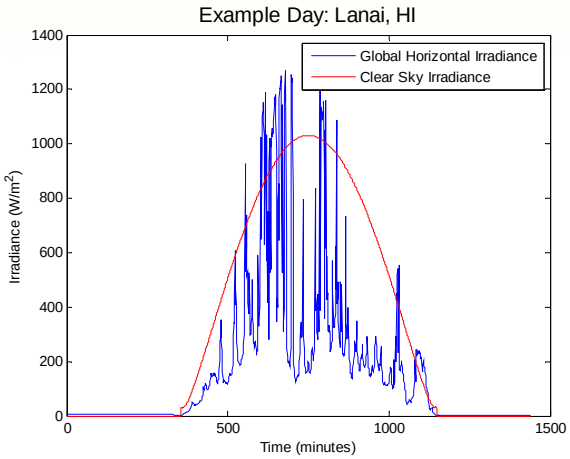


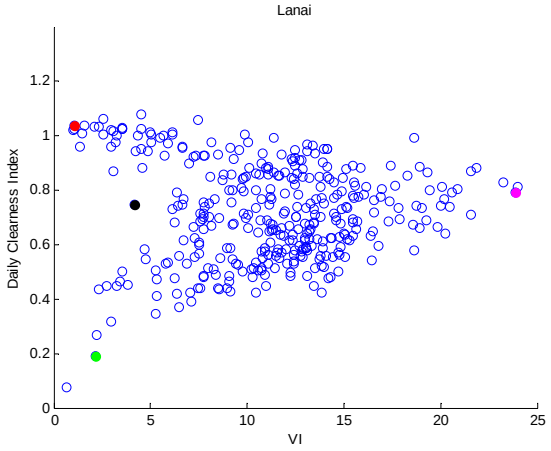
Related Research/Applications

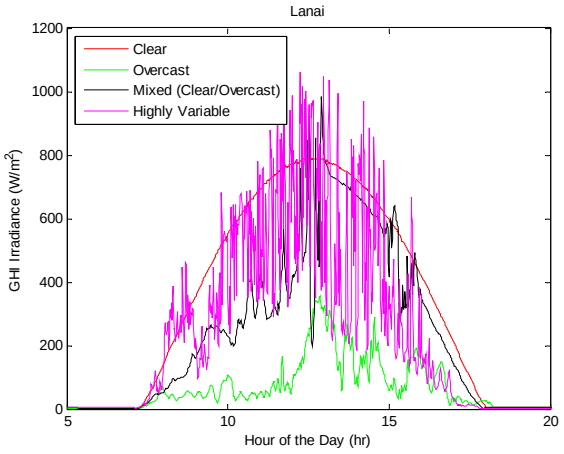
- **Quantification of variability**
  - **Stein, J., C. Hansen and M. Reno (2012). The Variability Index: A New and Novel Metric for Quantifying Irradiance and PV Output Variability. World Renewable Energy Forum, Denver, CO.**
- **Simulation of PV output data using ground irradiance measurements**
  - **Hansen, C., J. Stein and A. Ellis (2011). Simulation of One-Minute Power Output from Utility-Scale Photovoltaic Generation Systems. Albuquerque, NM, Sandia National Laboratories, SAND2011-5529.**
  - **Lave, M., J. Stein, A. Ellis, C. Hansen, et al. (2011). Ota City: Ota City: Characterizing Output Variability from 553 Homes with Residential PV Systems on a Distribution Feeder. Albuquerque, NM, Sandia National Laboratories, SAND2011-9011.**
  - **Lave, M., J. Kleissl and J. Stein (2012). "A Wavelet-based Variability Model (WVM) for Solar PV Powerplants." IEEE Transactions on Sustainable Energy. (in review).**

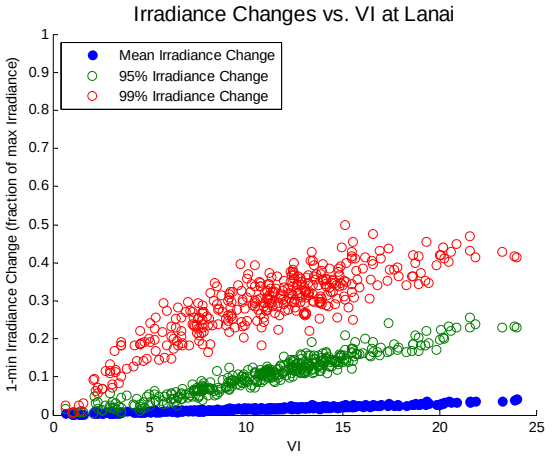
Describing Irradiance Variability

- **Ramp rate distributions and statistics**
  - **Mean and standard deviation**
  - **Cumulative distribution functions**
- **Correlation with distance and time scale**
- **Variability Index** $VI = \frac{\sum_{k=2}^{n} \sqrt{(GHI_k - GHI_{k-1})^2 + \Delta t^2}}{\sum_{k=2}^{n} \sqrt{(CSI_k - CSI_{k-1})^2 + \Delta t^2}}$









Variability Index metric described Stein et al. (2012)

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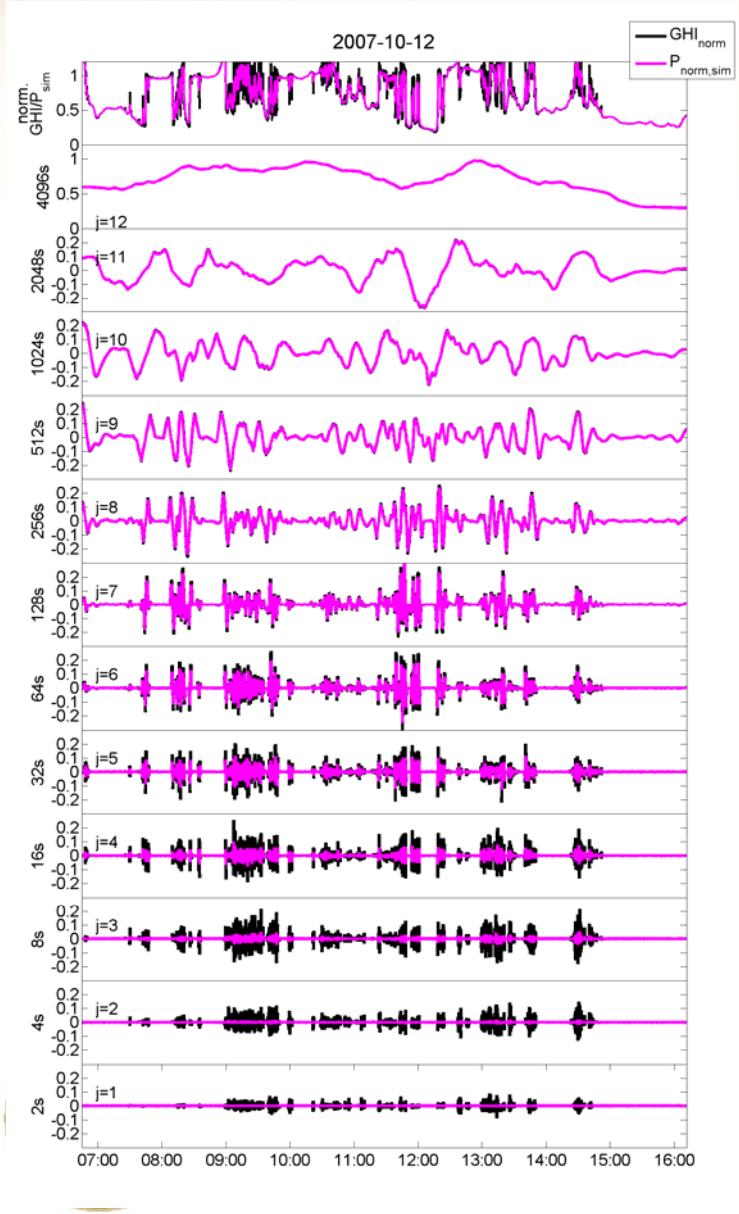
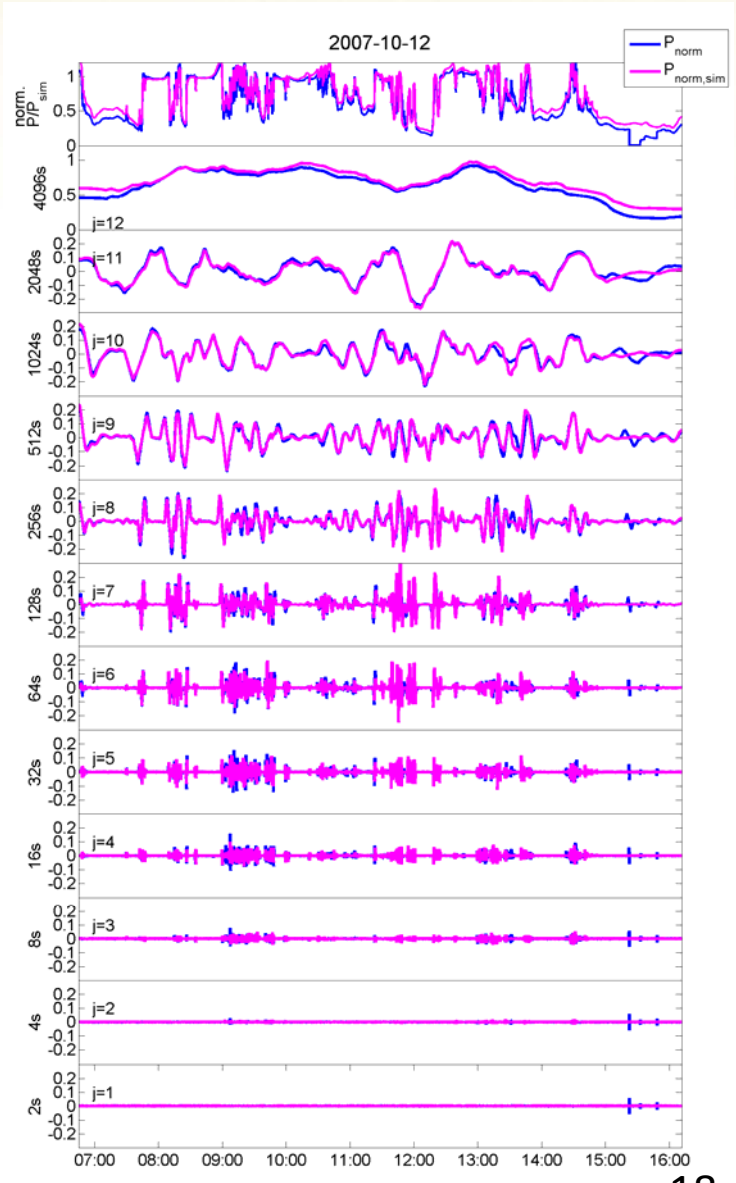
Wavelet Variability Model (WVM)



Simulated wavelet modes derived from GHI wavelet modes

Modeled and measured power compare well



Wavelet Variability Model (WVM)

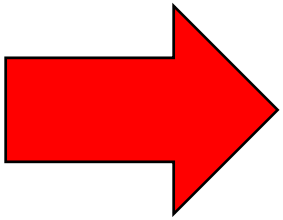
Model Inputs

PV Footprint

PV Plant Density

Point Sensor Timeseries

Correlation Structure
Location/day dependent
"A" coefficient



determine variability reduction (smoothing) at each wavelet timescale

Model Outputs

Plant Areal Average Irradiance

Irradiance to power model based on plant design (e.g., dc/ac ratio, tracking system), temperature, etc.

Plant Power Output

$$\rho(d_{m,n}, \bar{t}) = \exp(-\frac{d_{m,n}}{A\bar{t}})$$

$d_{m,n}$ is distance between two sites, m and n, and t is the timescale

ρ=0 when $d_{m,n}$ is very large or t is very small

ρ=1 when $d_{m,n}$ is very small or t is very large

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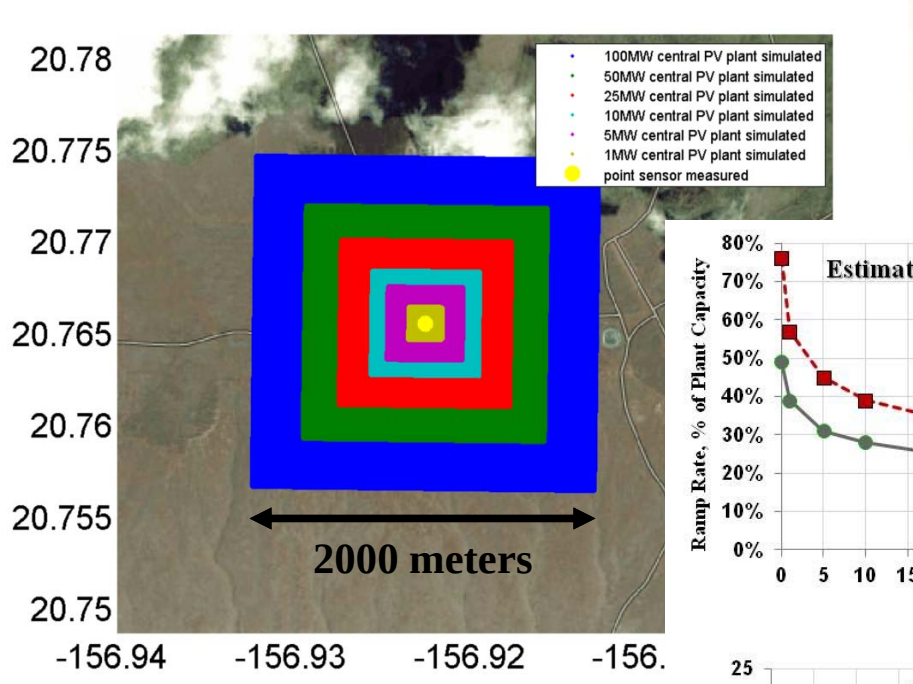
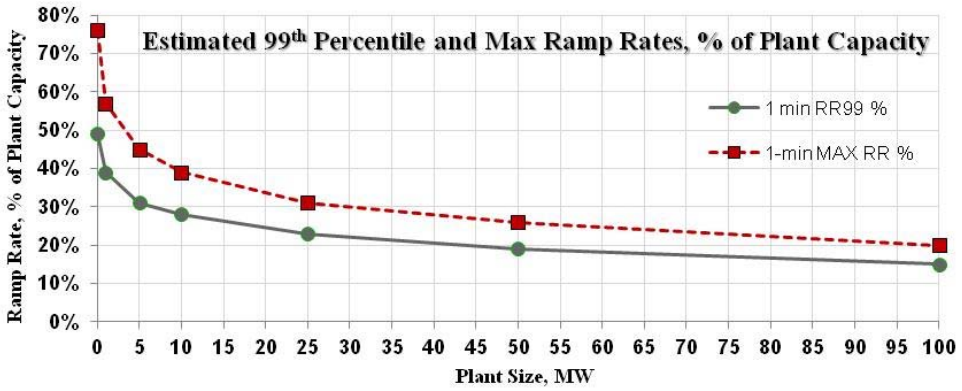
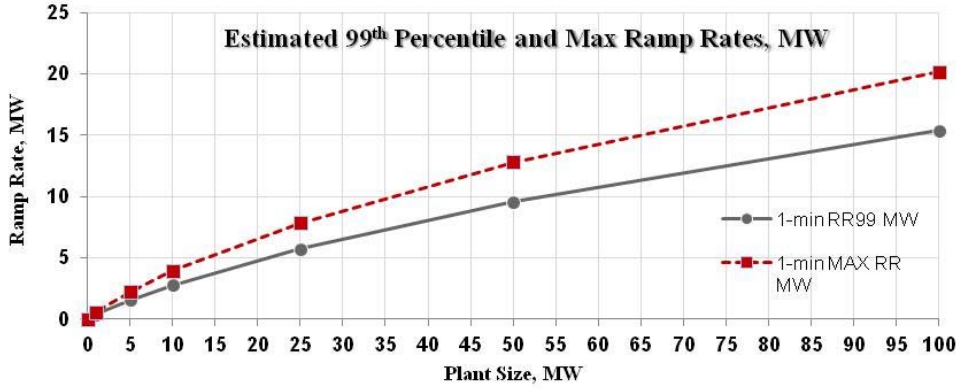
Single-Point Irradiance to Plant Output







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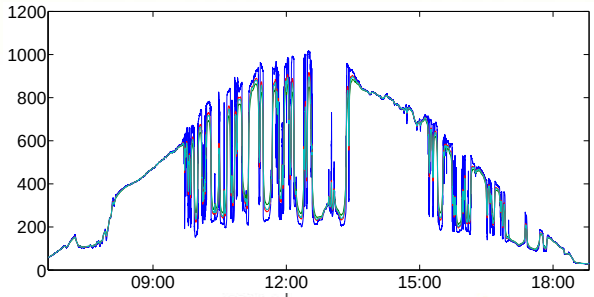
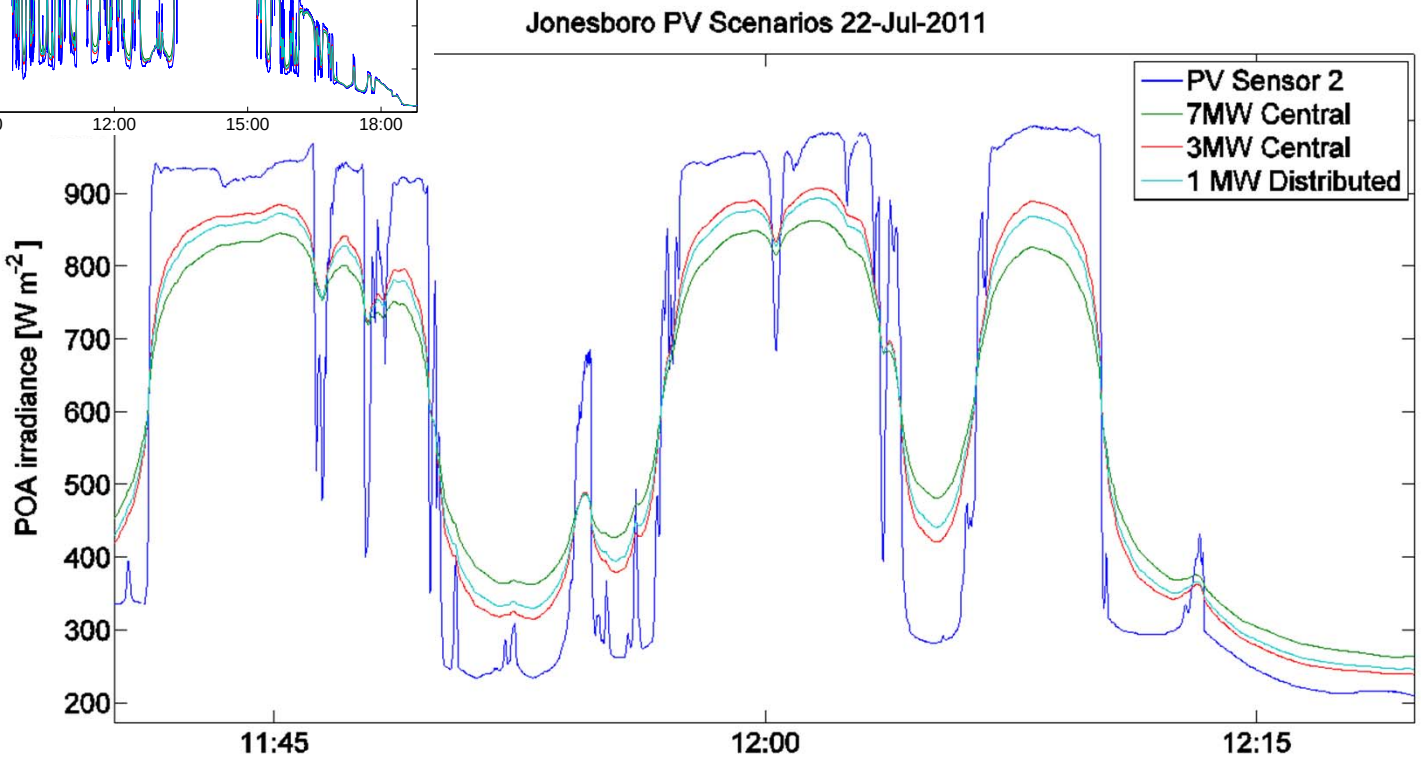
Application to Distribution Circuit Analysis

- Estimation of high resolution PV output data for central and distributed plants in distribution feeders

Plant Average Irradiance

- **Estimated equivalent irradiance**





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Conclusion

- **Analysis of Lanai LaOla PV system has helped develop important technical insights**
  - **Evaluation of system output characteristics and local system impacts**
  - **Evaluation of PV – energy storage application in small grids**
  - **Validation of methods to quantify of PV variability**
  - **Validation of techniques and models to simulate plant output for a variety of applications, using measured irradiance**

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