Characterization of short-term PV variability for large PV systems

October 7, 2009

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Utility Wind Integration Group: Utility-Scale PV Integration Workshop
Cedar Rapids, IA

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How Important is Variability?

- **Utilities are in the business of servicing a variable load.**
- **Ancillary services provide variability control**
  - **Voltage Control (seconds) [VAR support]**
  - **Regulation (~ 1 min) [online AGC*]**
  - **Spinning Reserve (seconds to <10 min) [online]**
  - **Supplemental Reserve (<10 min) [offline but staffed]**
  - **Replacement Reserve (<30 min) [offline but staffed]**
  - **Planning and forecasting (hours – days)**

* Automatic generation control

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When is Variability Important?

- **Variability is only important if it significantly adds to the net load variability.**

  net load = load – non-dispatchable generation

- **Impact of variability depends on where the PV system is connected to the grid, penetration level, types of load serviced, and available generation options.**
- **On clear days, solar (diurnal) variability can help utilities serve peak loads.**

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Presentation Outline

- **Part 1: Discuss differences between irradiance and PV power.**
  - **Identify factors affecting power variability for clear and partly cloudy days**
- **Part 2: Explore measures of variability**
- **Part 3: Present variability analysis results for existing PV systems.**
  - **Small (30kW)**
  - **Large (many MWs)**

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Part 1

- **The difference between irradiance and PV output power…**

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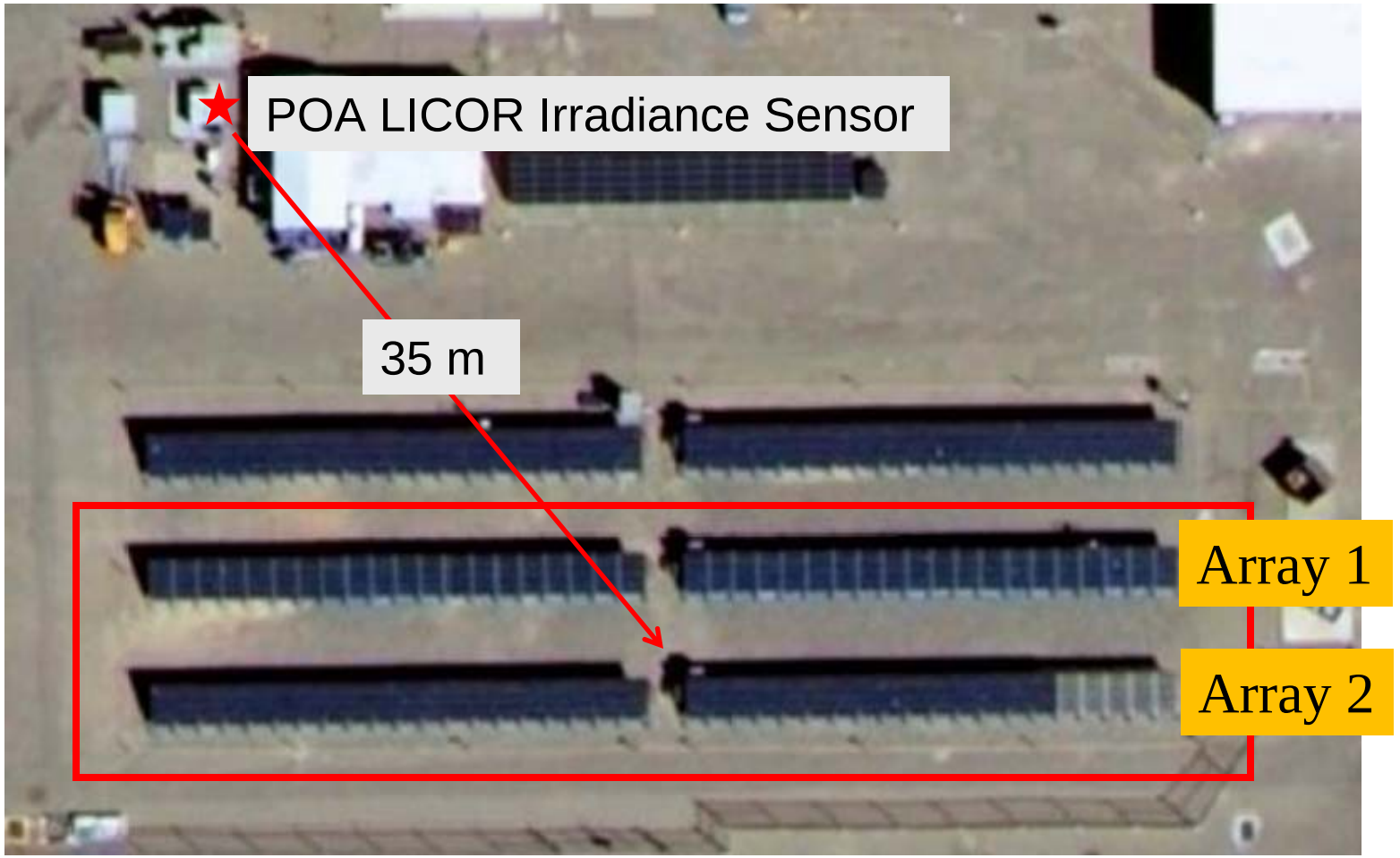
Sandia 30 kW Array (1-Sec Data)



30 kW latitude tilt array

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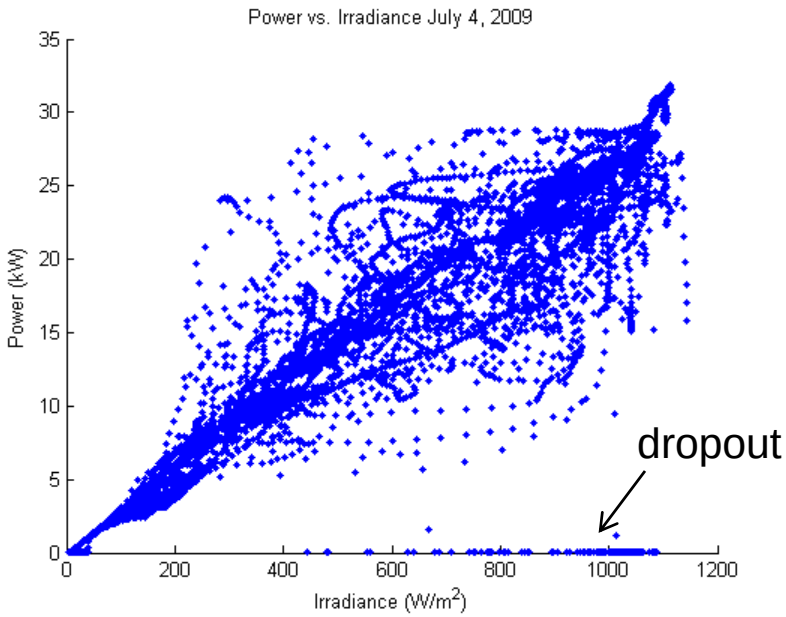
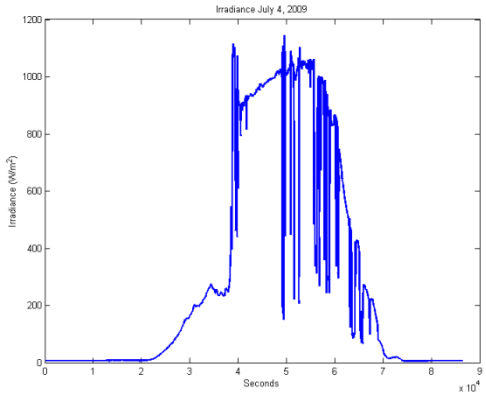
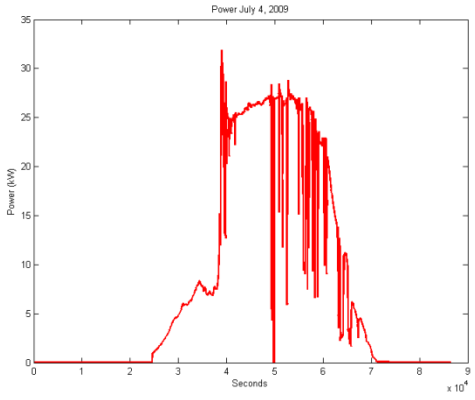
Difference Between Irradiance and PV Power

- **PV power output is not a simple linear function of irradiance, especially on partly cloudy days.**
  - **Spatial-temporal effects**
  - **Inverter effects**
  - **Incident angle effects**
  - **Temperature effects**







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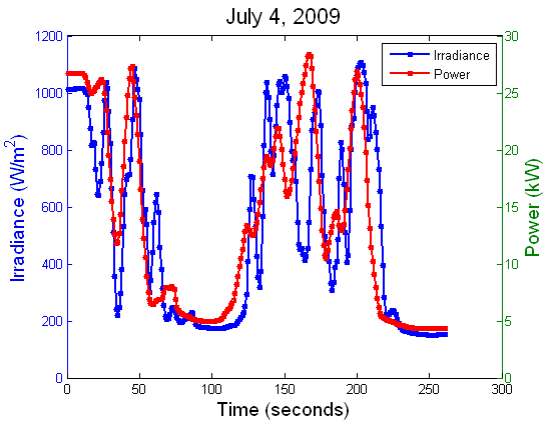
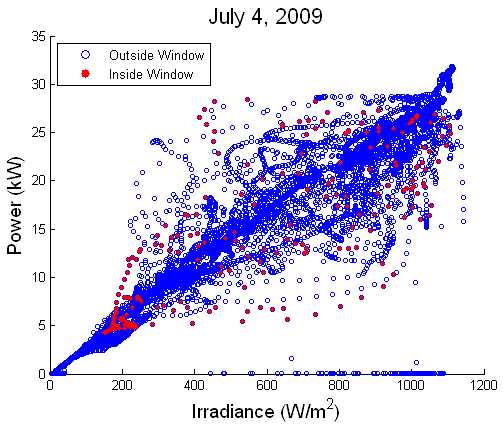
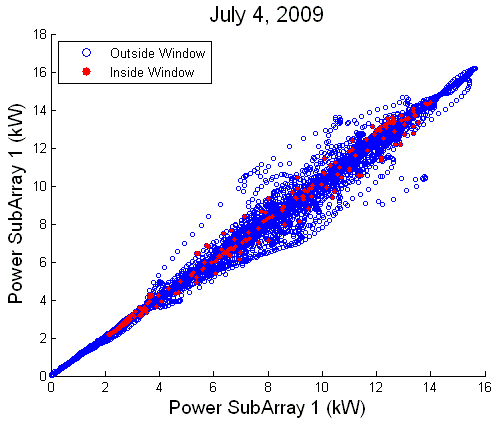
Spatial-Temporal Effects

- **Short periods (5-20 seconds) of non-linear excursion are likely due to spatially- heterogeneous irradiance over distances as small as 30-50 m (slow moving, sharp shadows).**







- **Sandia is developing a wireless 1-sec irradiance sensor network**
  - **Deployments in: Albuquerque, NM, Lanai, HI, and other sites in the near future**

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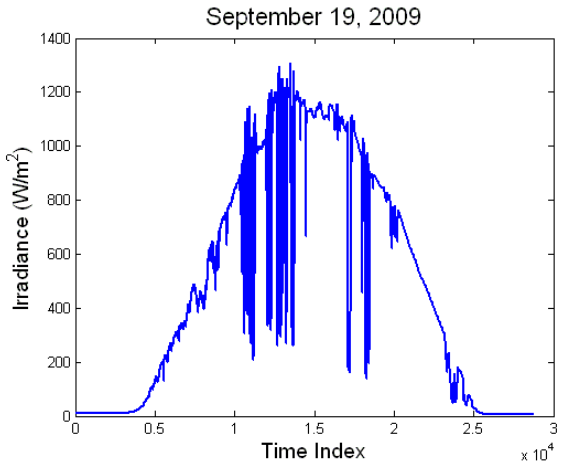
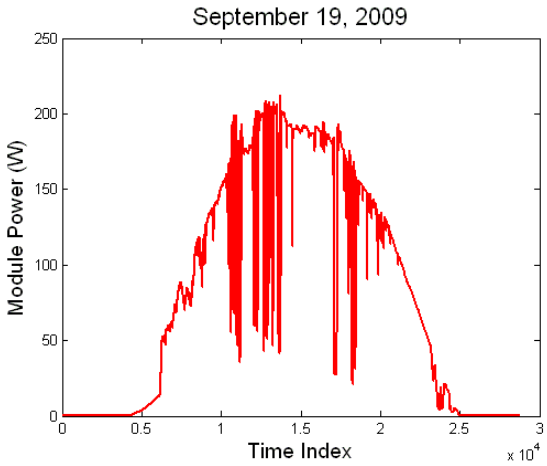
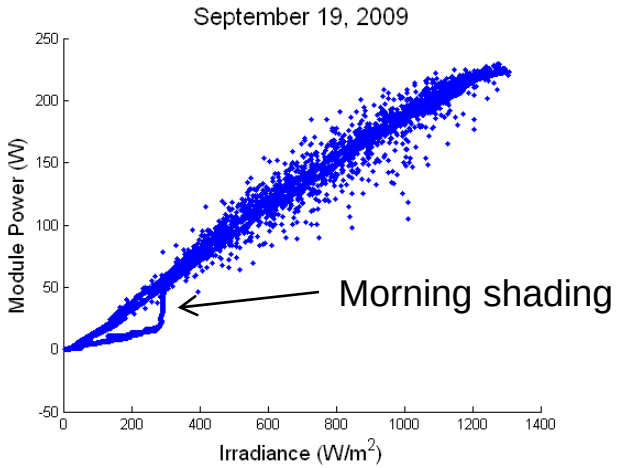
Inverter Effects

- **Array + Inverters may not convert 100% of available irradiance.**
  - **MPPT issues, IEEE 1547 dropouts, inverter "clipping", partial shading, … etc.**
- **Single 200 W module with micro-inverter**







- **Scatter indicates that inverter causes some of the variation between irradiance and A/C power.**

Module located 5 m from irradiance sensor (2-sec data frequency).

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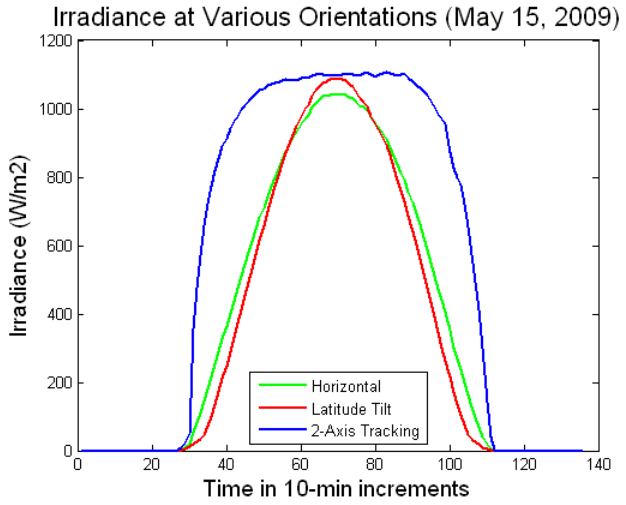
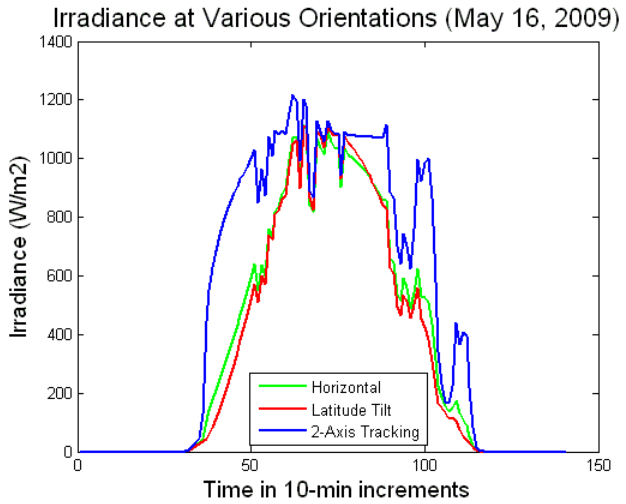
Incident Angle Effects (1)

- Global irradiance is measured on a horizontal plane
- PV arrays are either fixed or tracked.
- PV output is proportional to irradiance on the plane of array
- Tracked systems can harvest more energy than fixed tilt systems and therefore have greater potential for larger power changes from passing clouds.





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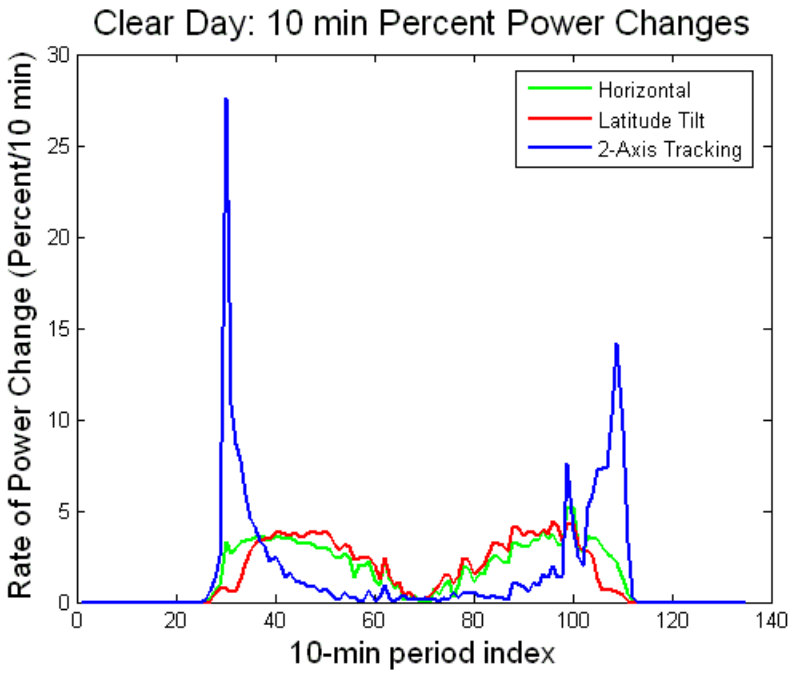
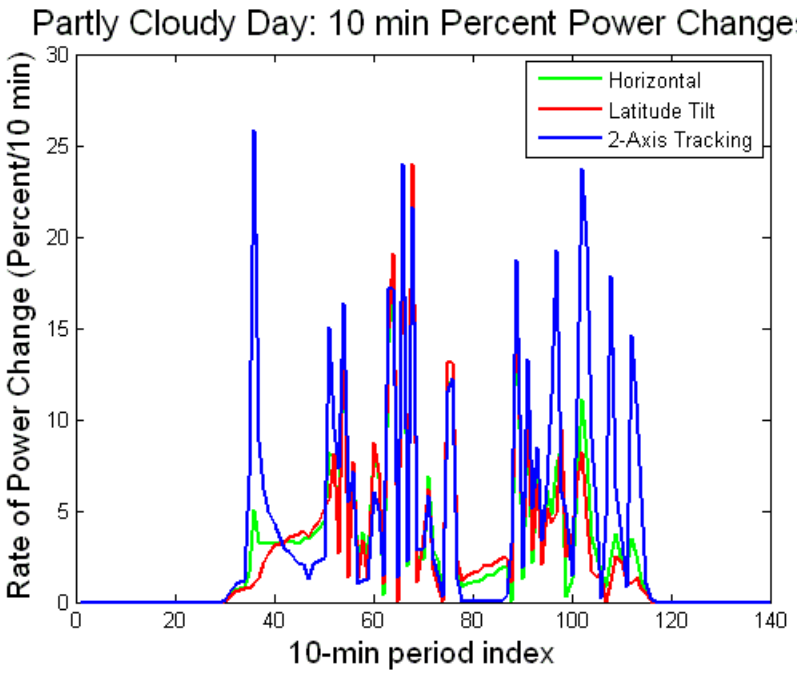
Incident Angle Effects (2)

- **Power changes will be greater with tracked PV systems than for fixed tilt systems at the beginning and end of the day.**





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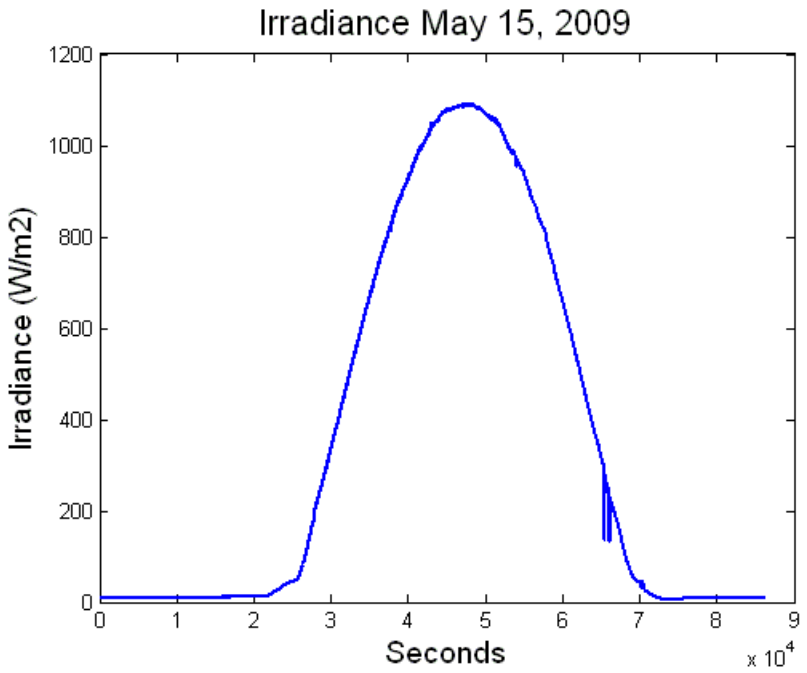
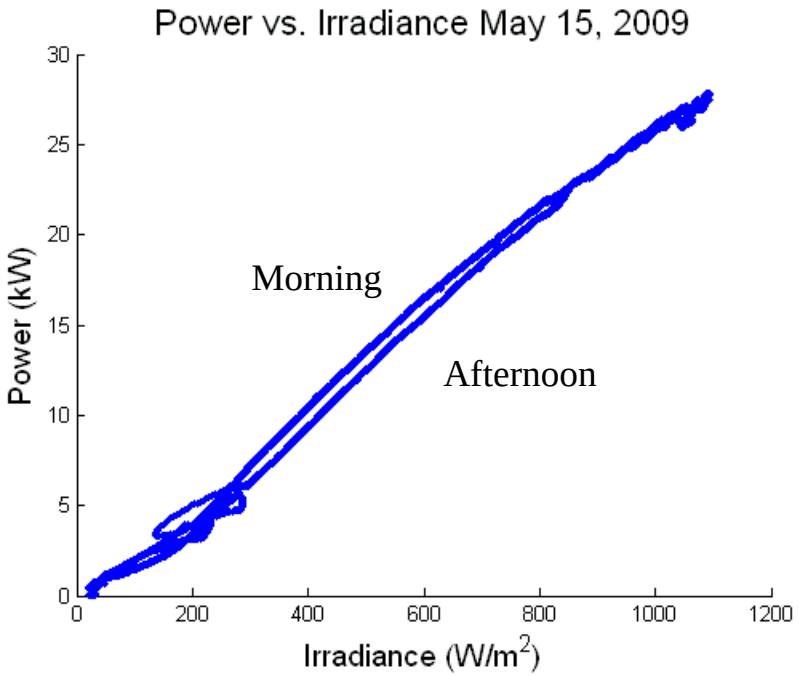
Temperature Effects

- **PV efficiency decreases as temperature increases.**
- **May 15, 2009, air temp increased all day from 16 to 30 deg C**





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Part 2

- **Measures of variability…**

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How to Characterize PV Output Variability?

- **Examine the distribution of irradiance and power changes ('ramps') over a fixed time interval (e.g., 1-sec, 1-min, 10-min, etc.) (e.g., Wan and Bucaneg, 2002)**
- **<u>Step Changes</u>*: $P_t - P_{t+k}$*, where *t* is time (1 to *nt*) and *k* is fixed time interval**
- **<u>Ramping Rates</u>:**
  - **1) rate of change of moving average**
  - **2) least squares linear regression slope of $P_{t \rightarrow t+k}$**

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Steps for Characterizing Variability

- Normalize irradiance and power
- Calculate ramp rates for fixed time intervals (e.g., 1-sec, 10-sec, 1-min, 10-min, etc.). (absolute value).
- Compare distributions of ramp rates for different unit sizes (irradiance sensor, single inverter, multiple inverters, etc.)

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Part 3

- **Analysis of PV output variability for two existing PV systems.**
  - **Small system (30kW)**
  - **Very large system (many MWs)**

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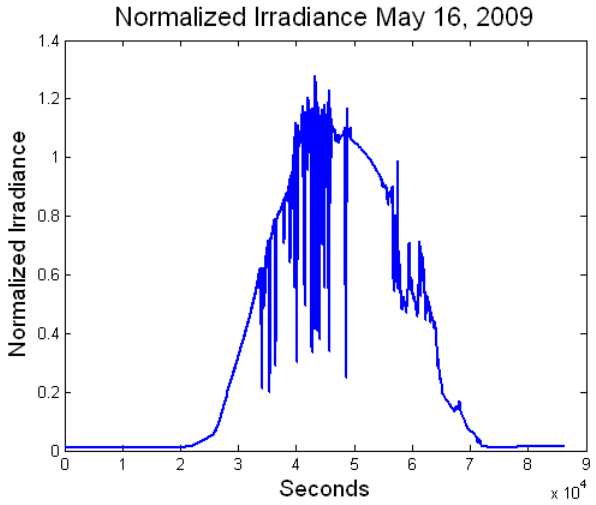
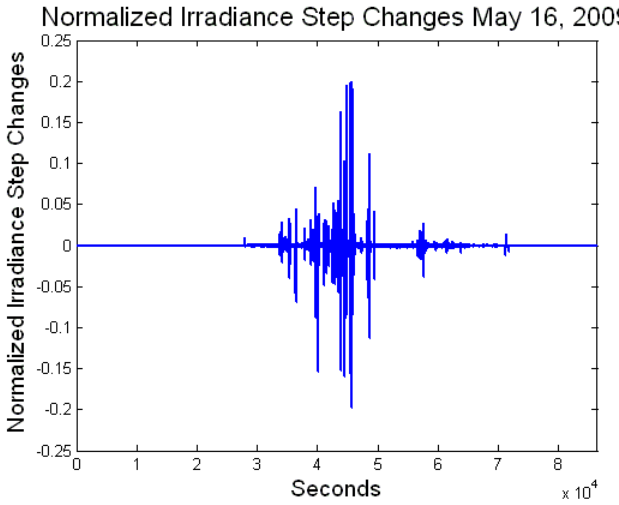
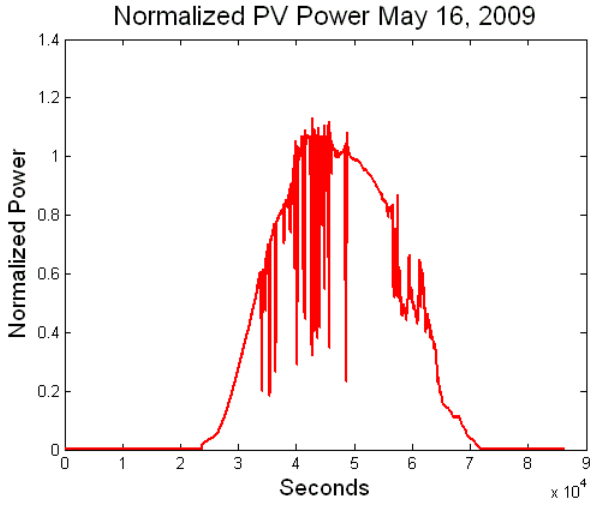
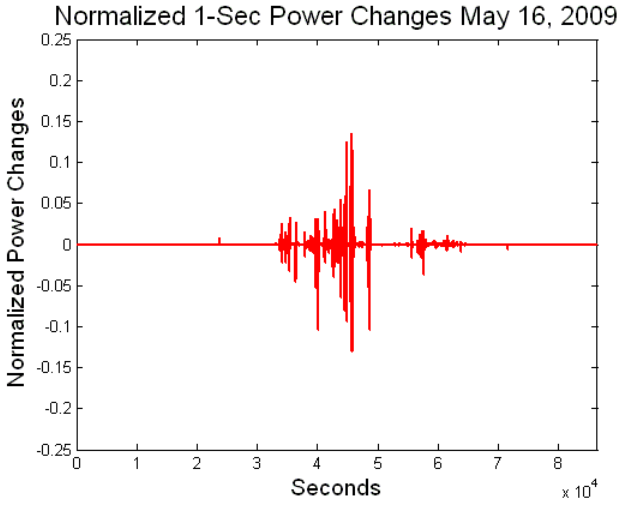
Example of PV Output Variability Reduction for 30 kW Latitude-Tilt System









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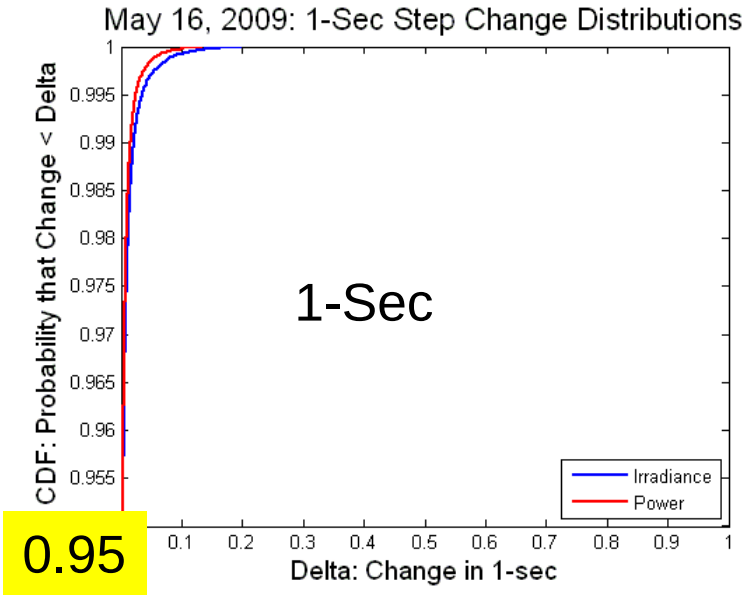
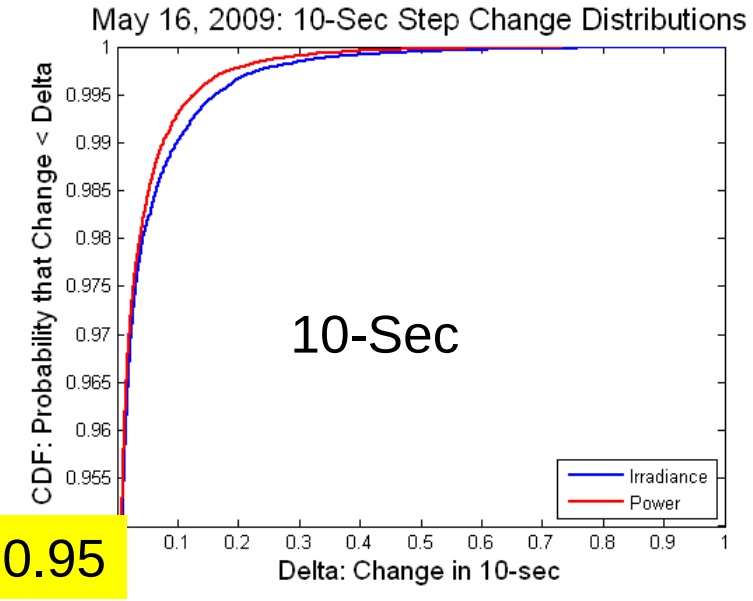
How Much Reduction?





- **For small systems ramp rate reduction is measurable for intervals between 1-10 sec but essentially disappears when 1-min ramps are analyzed.**

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Variability Analysis of Large PV Plant Output

- PV plant is multi-megawatt in capacity.
- 1-sec irradiance and power output has been normalized.
- Explore variability reduction with increasing plant size.
  - Irradiance (cm^2)
  - Single inverter output (hundreds of kWs)
  - Half of plant's inverters (multi MW)
  - Total plant output (multi MW x 2)

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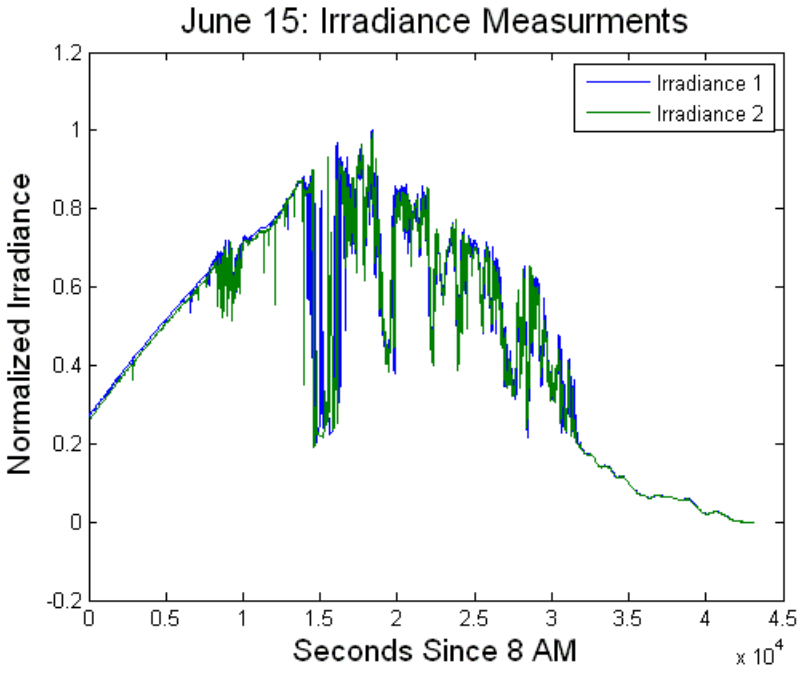
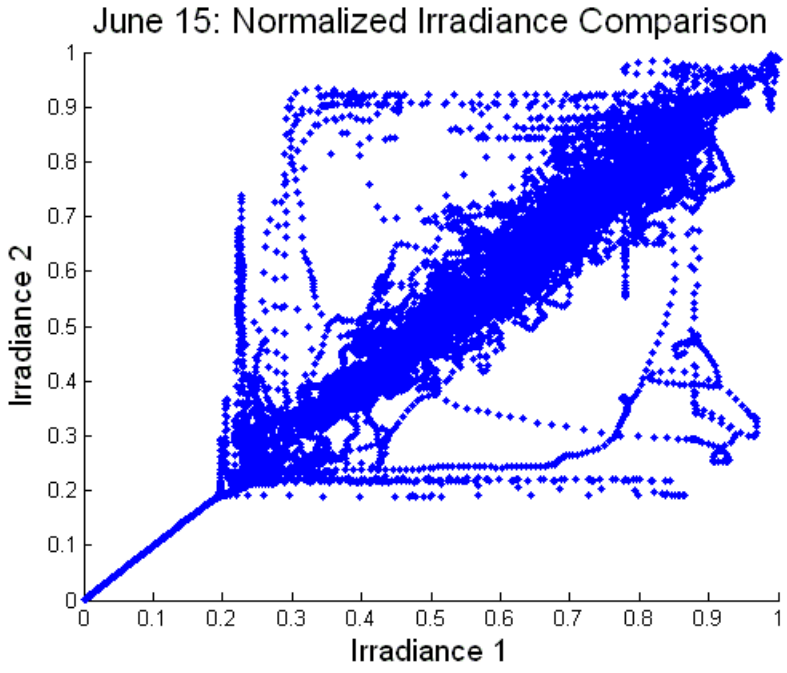
Irradiance Measurements

- **June 15, 2009: Partially cloudy day selected for analysis**
- **Two irradiance measurements (opposite ends of plant)**
- **Irradiance is normalized.**





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Analysis Method

- **Compare distributions of power changes for different combinations of unit sizes and time intervals**

  Irradiance → Single Inverter → Half Plant → Whole Plant.

  1 sec → 10 sec → 1 min → 10 min

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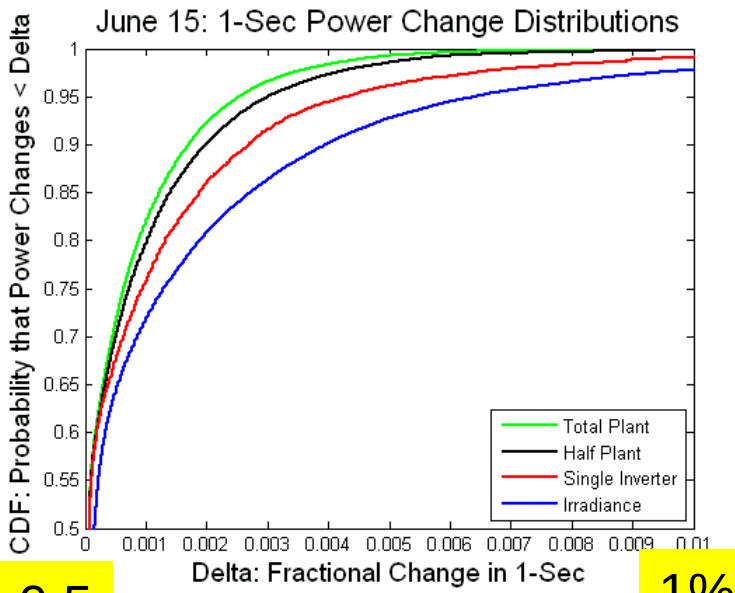
1-Sec Changes



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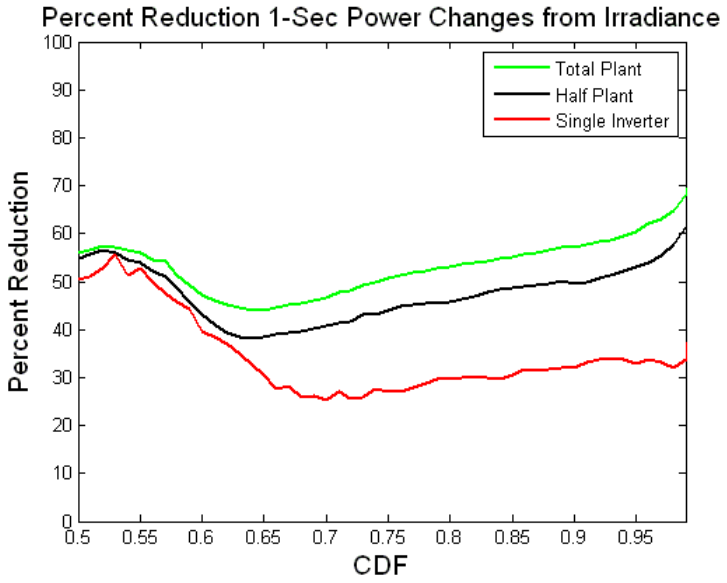

1%

- **1-Sec power variability relative to irradiance decreases as a function of unit size.**
- **Single Inverter = ~30% reduction of large ramps**
- **Total Plant = >60% reduction of large ramps**

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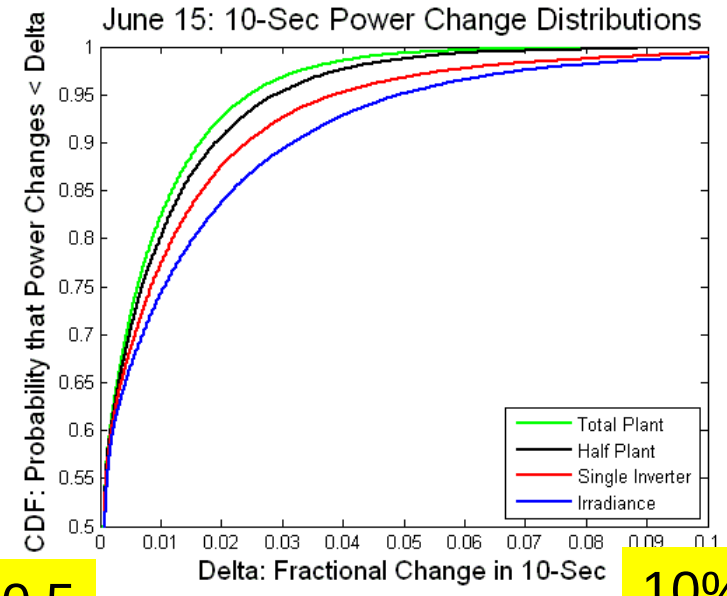
10-Sec Changes



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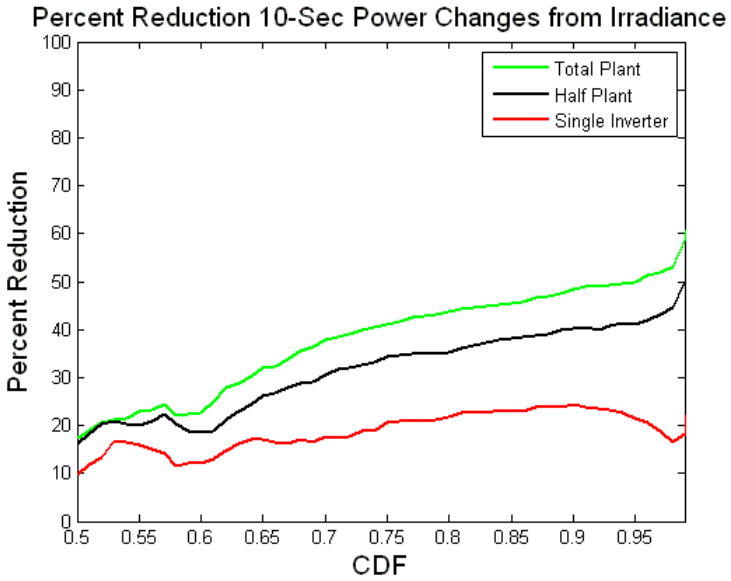

10%

- **10-Sec power variability relative to irradiance decreases as a function of unit size.**
- **Single Inverter = ~20% reduction of large ramps**
- **Total Plant = >40% reduction of large ramps**

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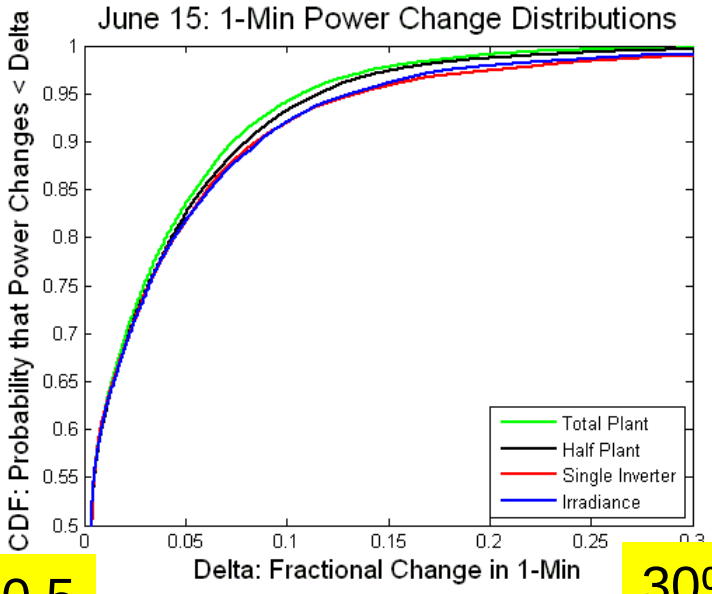
1-Min Changes



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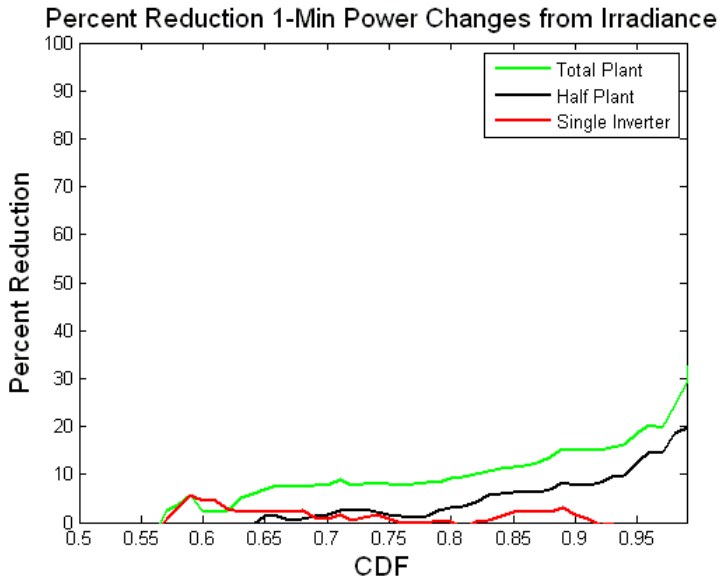

30%

- **At 1-Min, variability difference between unit sizes is not as significant as for shorter time intervals.**
- **Single Inverter = ~5% reduction of large ramps**
- **Total Plant = >10% reduction of large ramps**

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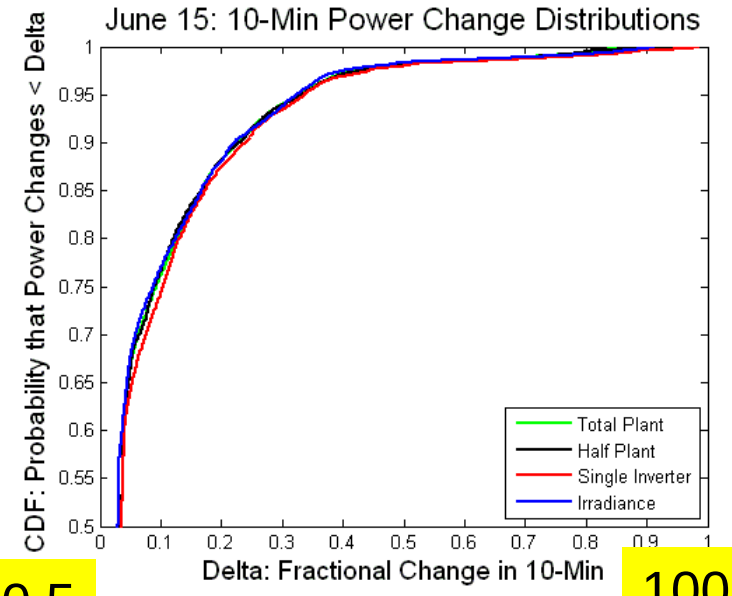
10-Min Changes



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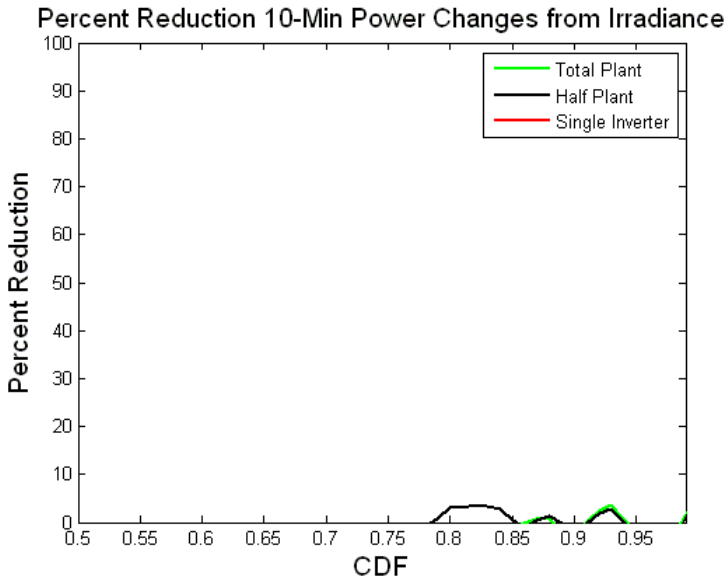

100%

- **10-min power variability is not influenced by unit size and is essentially equivalent to 10-min irradiance variability.**

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Summary

- **Variability of PV power output is not a simple linear function of variability in plane-of-array point irradiance, especially on partly cloudy days.**
- **Preliminary results suggest that >10 min variability of multi-MW PV plants can be approximated by the variability of point irradiance averaged over a similar time window.**
- **Short term (<10 min) variability is influenced by the size of the plant, with variability decreasing with increasing size.**

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