



Characterization of short-term PV variability for large PV systems

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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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





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.**



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)

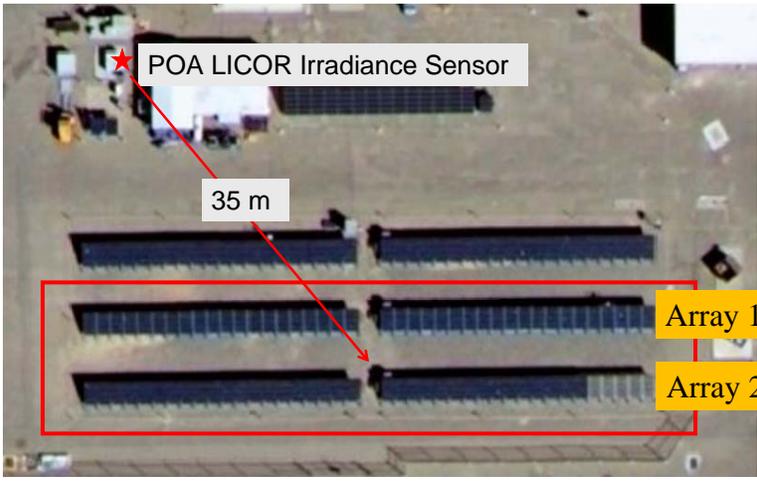


Part 1

- The difference between irradiance and PV output power...



Sandia 30 kW Array (1-Sec Data)

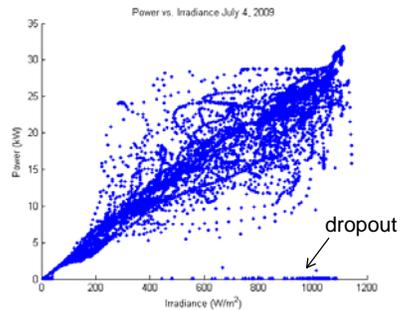
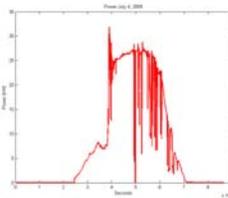
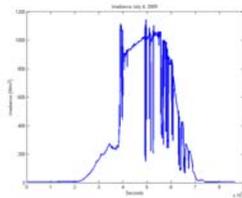


30 kW latitude tilt array



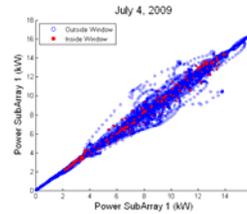
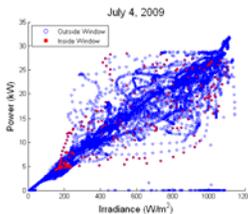
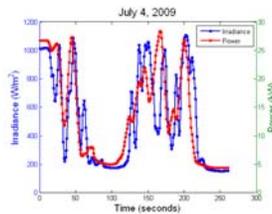
Difference Between Irradiance and PV Power

- 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



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).

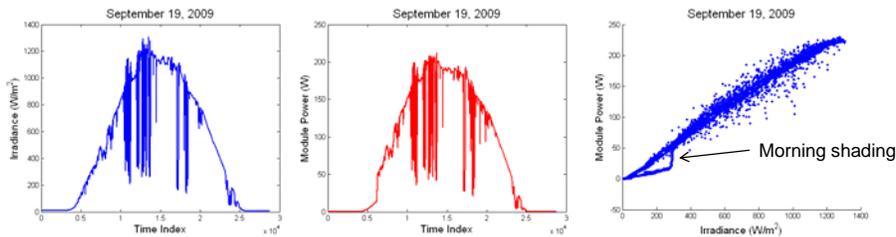


- Sandia is developing a wireless 1-sec irradiance sensor network
 - Deployments in: Albuquerque, NM, Lanai, HI, and other sites in the near future



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



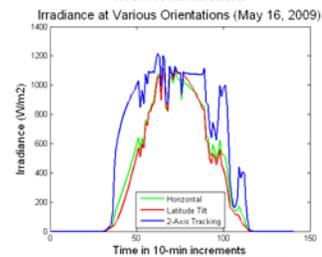
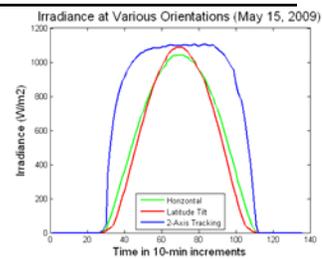
- Scatter indicates that inverter causes some of the variation between irradiance and A/C power.

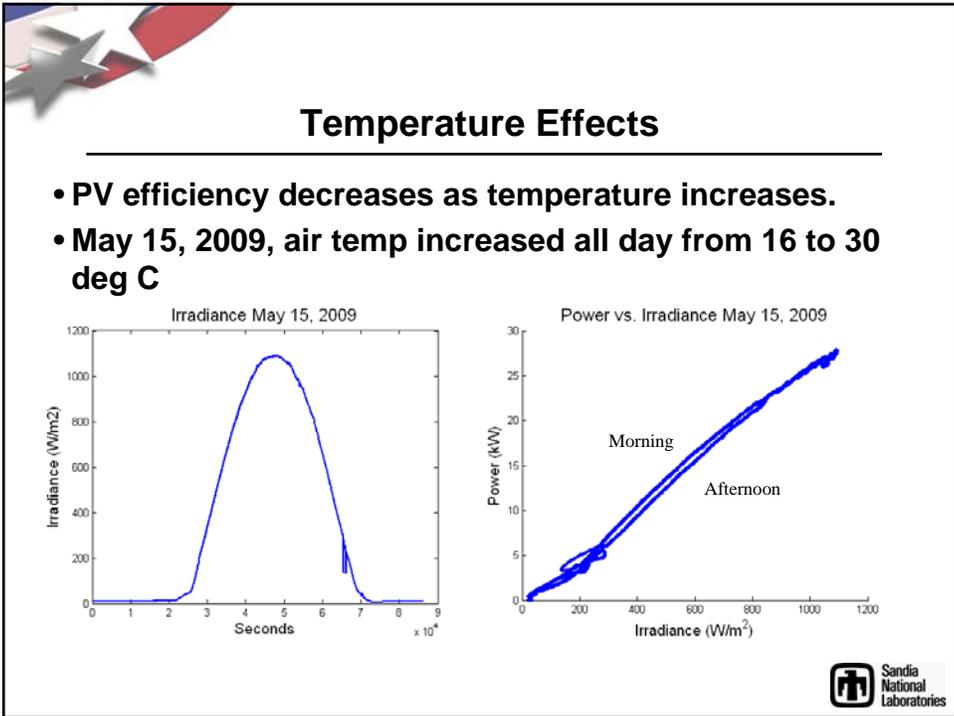
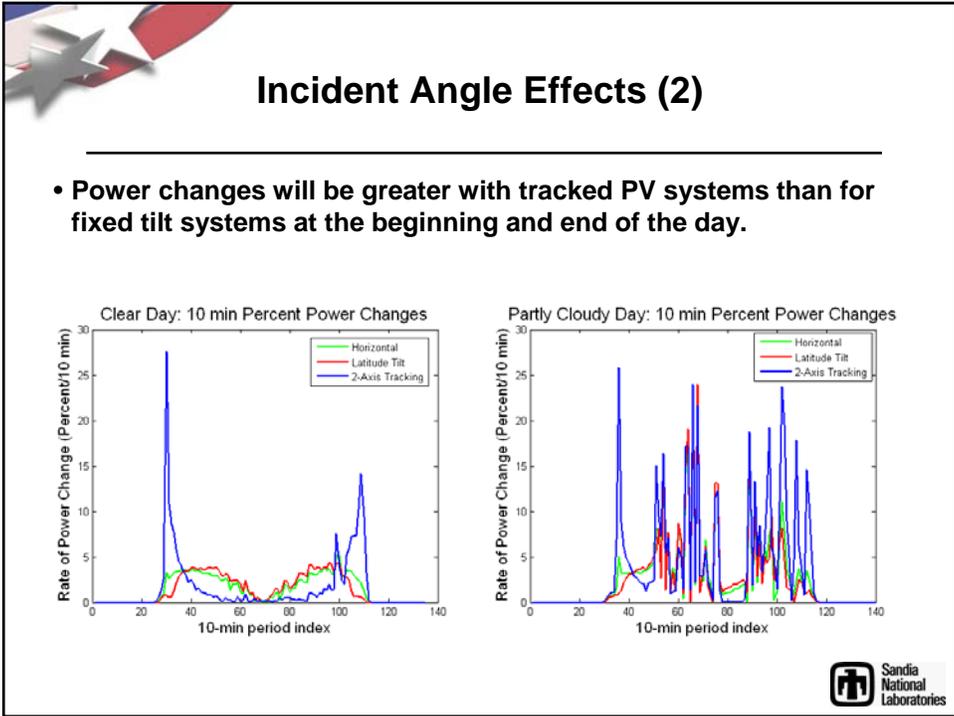
Module located 5 m from irradiance sensor (2-sec data frequency).



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.







Part 2

- Measures of variability...



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)
- Step Changes: $P_t - P_{t+k}$, where t is time (1 to nt) and k is fixed time interval
- Ramping Rates:
 - 1) rate of change of moving average
 - 2) least squares linear regression slope of $P_t \rightarrow t+k$



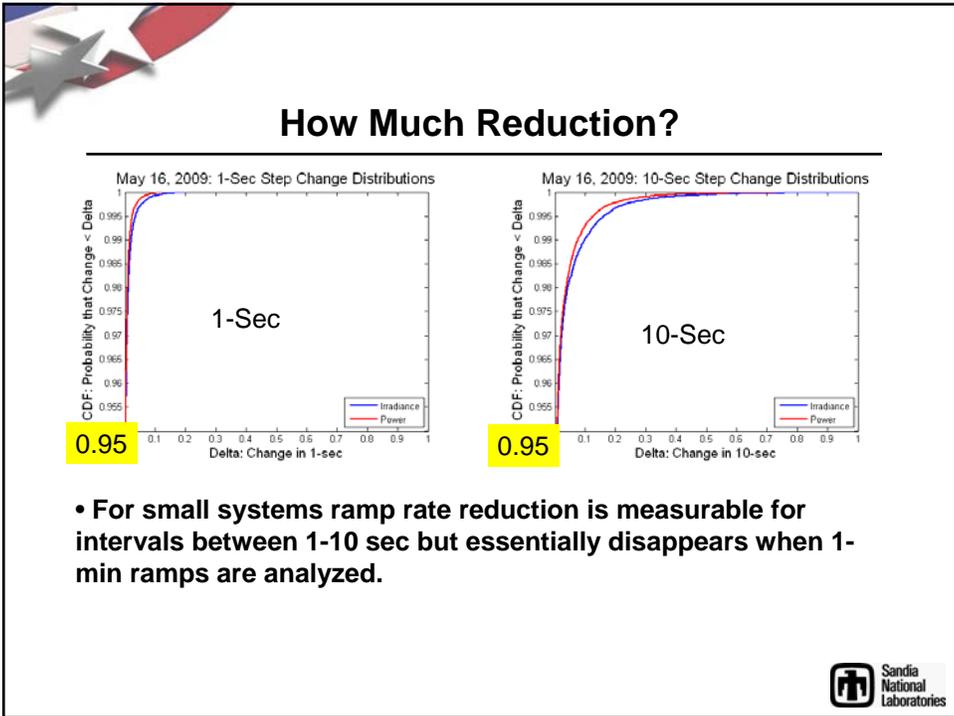
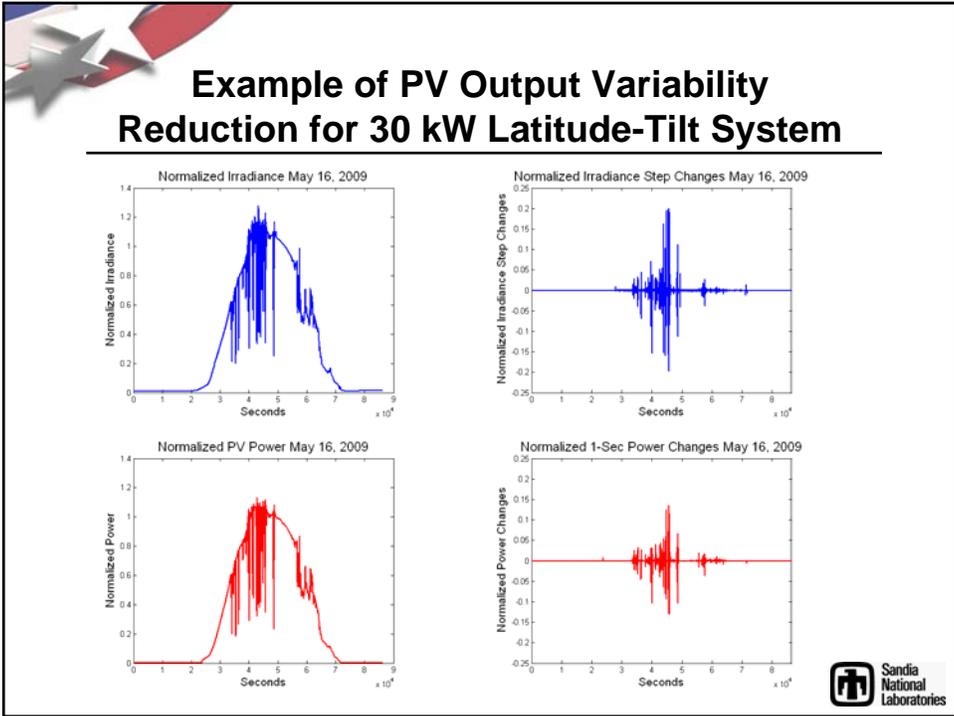
Steps for Characterizing Variability

- **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.)**



Part 3

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





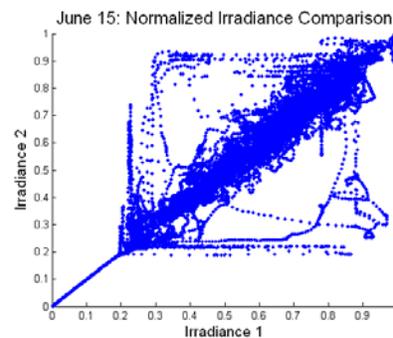
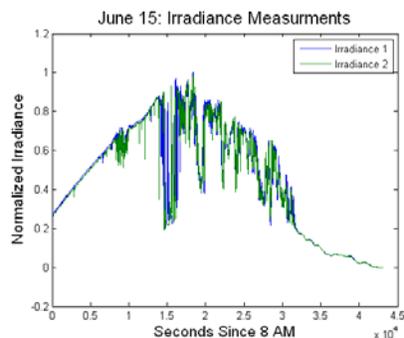
Variability Analysis of Large PV Plant Output

- 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 kW)
 - Half of plant's inverters (multi MW)
 - Total plant output (multi MW x 2)

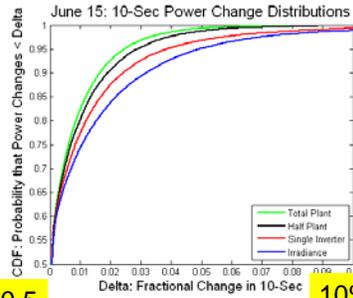


Irradiance Measurements

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

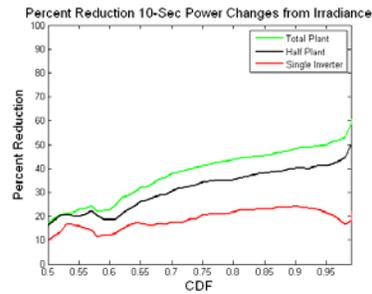


10-Sec Changes



0.5

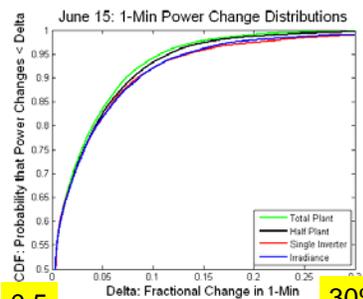
10%



- 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

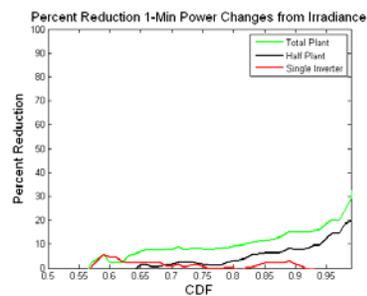


1-Min Changes



0.5

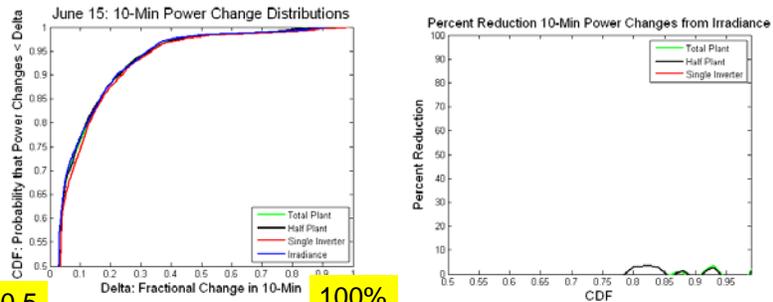
30%



- 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



10-Min Changes



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

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.