Spatial and Temporal Scales of Solar Variability: Implications for Grid Integration of Utility-Scale Photovoltaic Plants

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BERKELEY LAB

Presentation Overview

- Motivation
- Data and Approach
- Characterizing Variability at a Single Site
- Characterizing Temporal and Spatial Scales of Diversity
- Variability at the System Level
- Estimating the Costs of Managing Short-term Variability
- Impact of Geographic Diversity on the Costs of Managing Short-time scale PV Variability

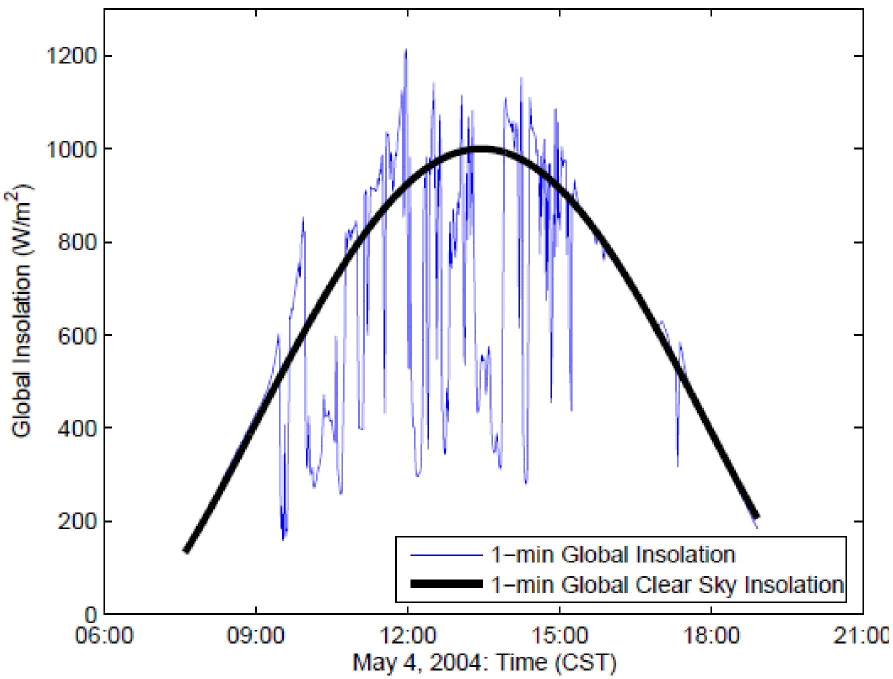
Concern that Rapid Fluctuations in PV Output Are a Potential Roadblock to PV Integration

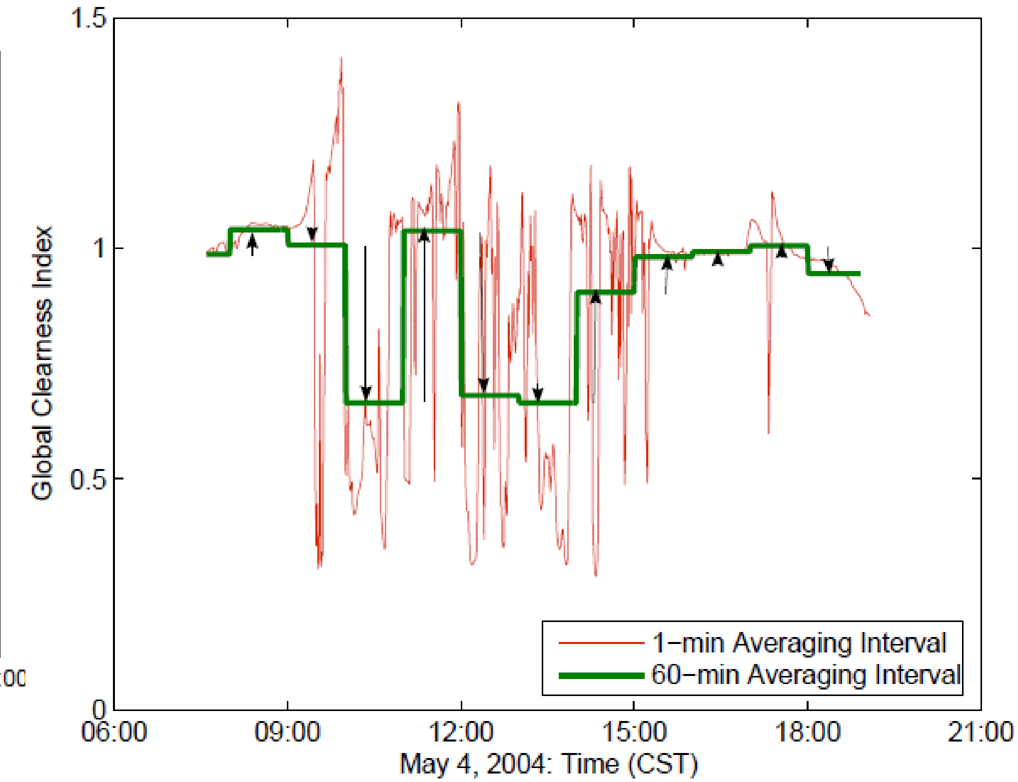
- NERC Integrating Variable Generation Task Force: "*…PV installations can change output by +/- 70% in a time frame of two to ten minutes, many times per day. Therefore, these plants should consider incorporating the ability to manage ramp rates and/or curtail power output.*"
- Numerous academic studies between 1980 – 1996 suggested potential limits to increasing PV penetration due to inability or high cost of operating conventional generation to respond to rapid fluctuations in PV
- Many of these concerns/studies lack detailed consideration of the effect of geographic diversity in smoothing aggregate output of several PV plants
  - Cloud models, anecdotal evidence, and increasingly available actual plant output suggests geographic diversity will play an important role in mitigating rapid fluctuations at the system level, as is already well known for wind energy

Data and Approach

- Use time-synchronized data from multiple sensors to develop relationships between:
  - Time-scale of variability
  - Variability at one site; variability of aggregate of multiple sites
  - Number of sites and geographic orientation of sites
- Apply similar approach to solar and wind data in the same region
- Estimate the potential implications of geographic diversity on the cost of managing variability
  - Use 'back-of-the-envelope' estimation applied similarly to wind and solar
- Data source: Southern Great Plains in ARM – 1-min data from 2004
  - 23 time-synchronized solar insolation sites (20-450 km spacing)
  - 14 time-synchronized 10-m wind anemometers (40-450 km)

Clouds Can Produce Rapid Ramps in Solar Insolation at a Single Point





Deltas: Step change from one averaging interval to the next

Clearness Index: Ratio of clear-sky solar insolation to measured insolation

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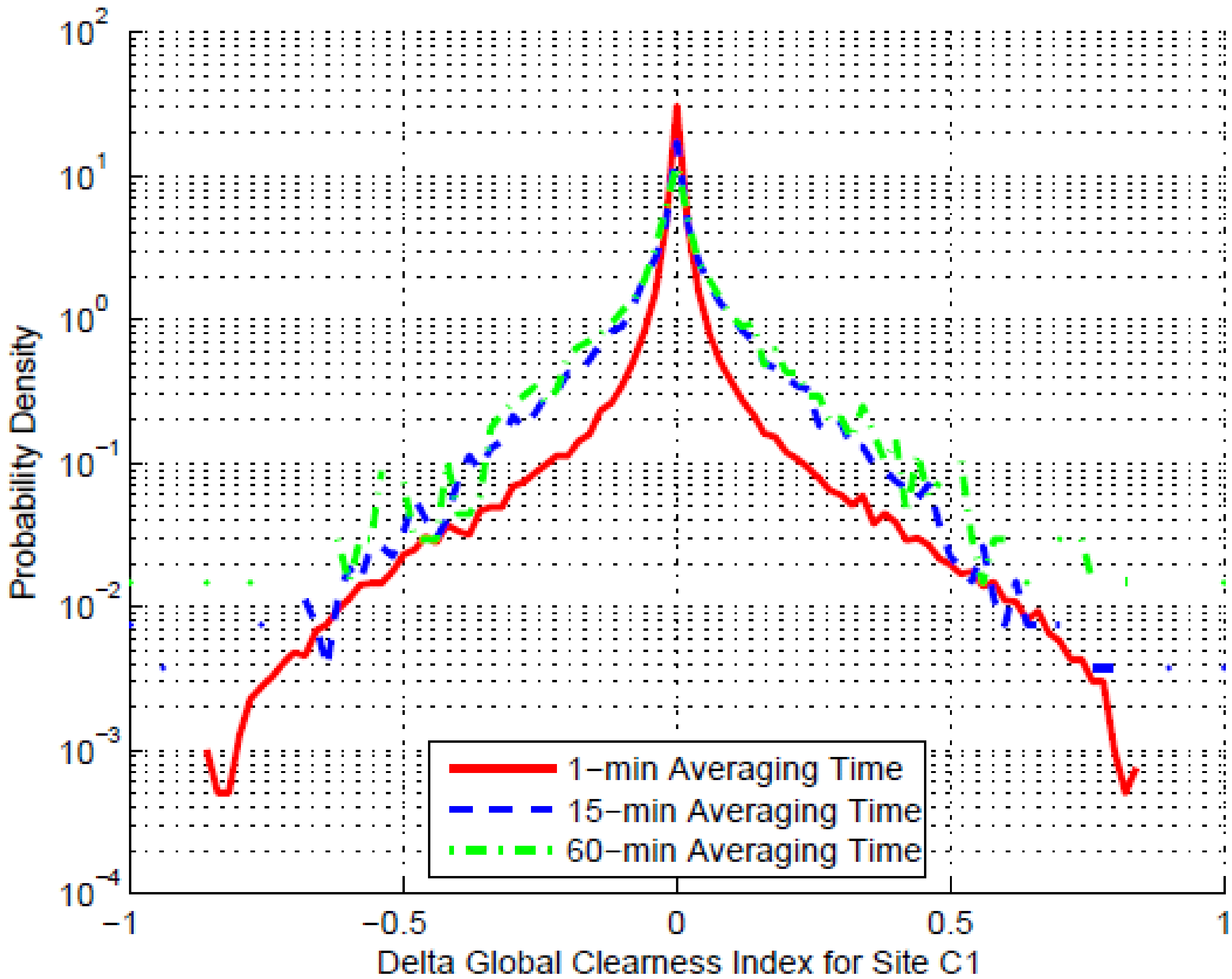
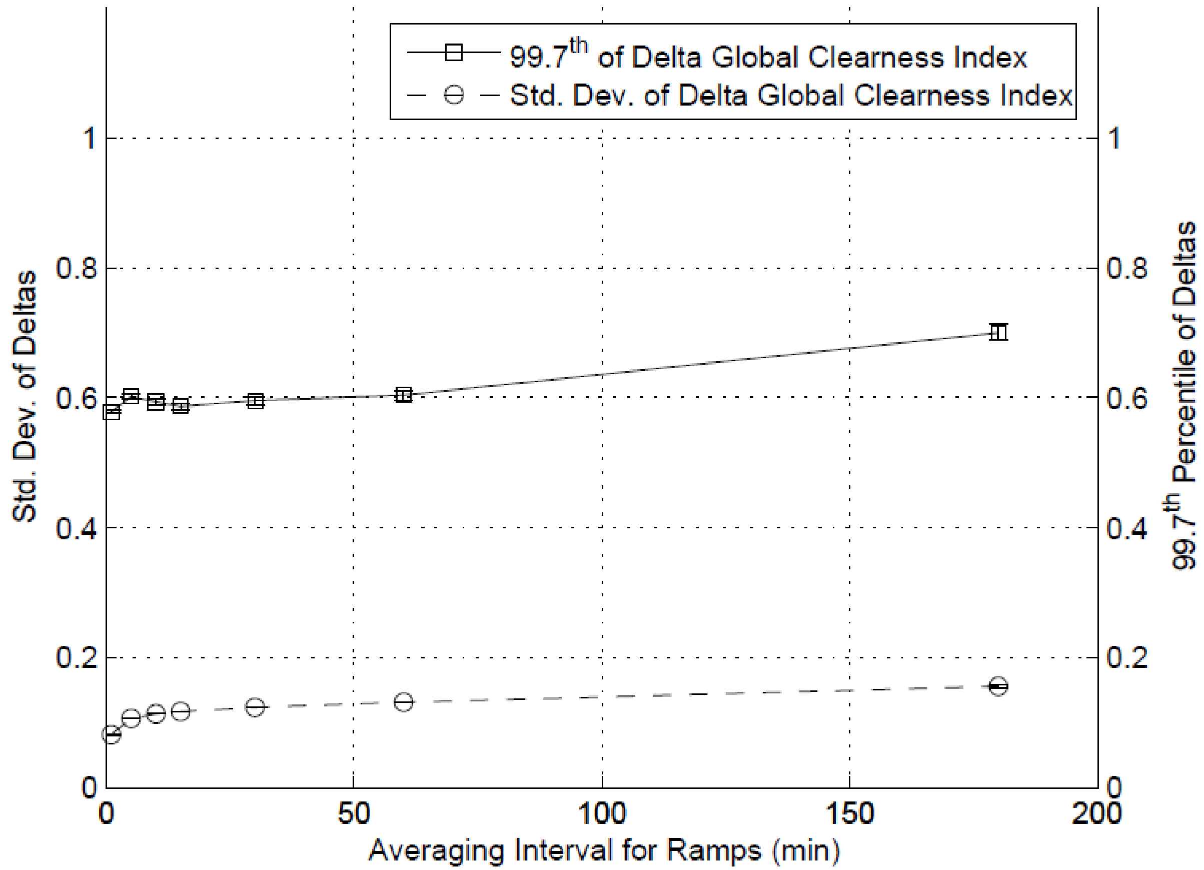


Variability Metric is Standard Deviation and 99.7th Percentile of Deltas

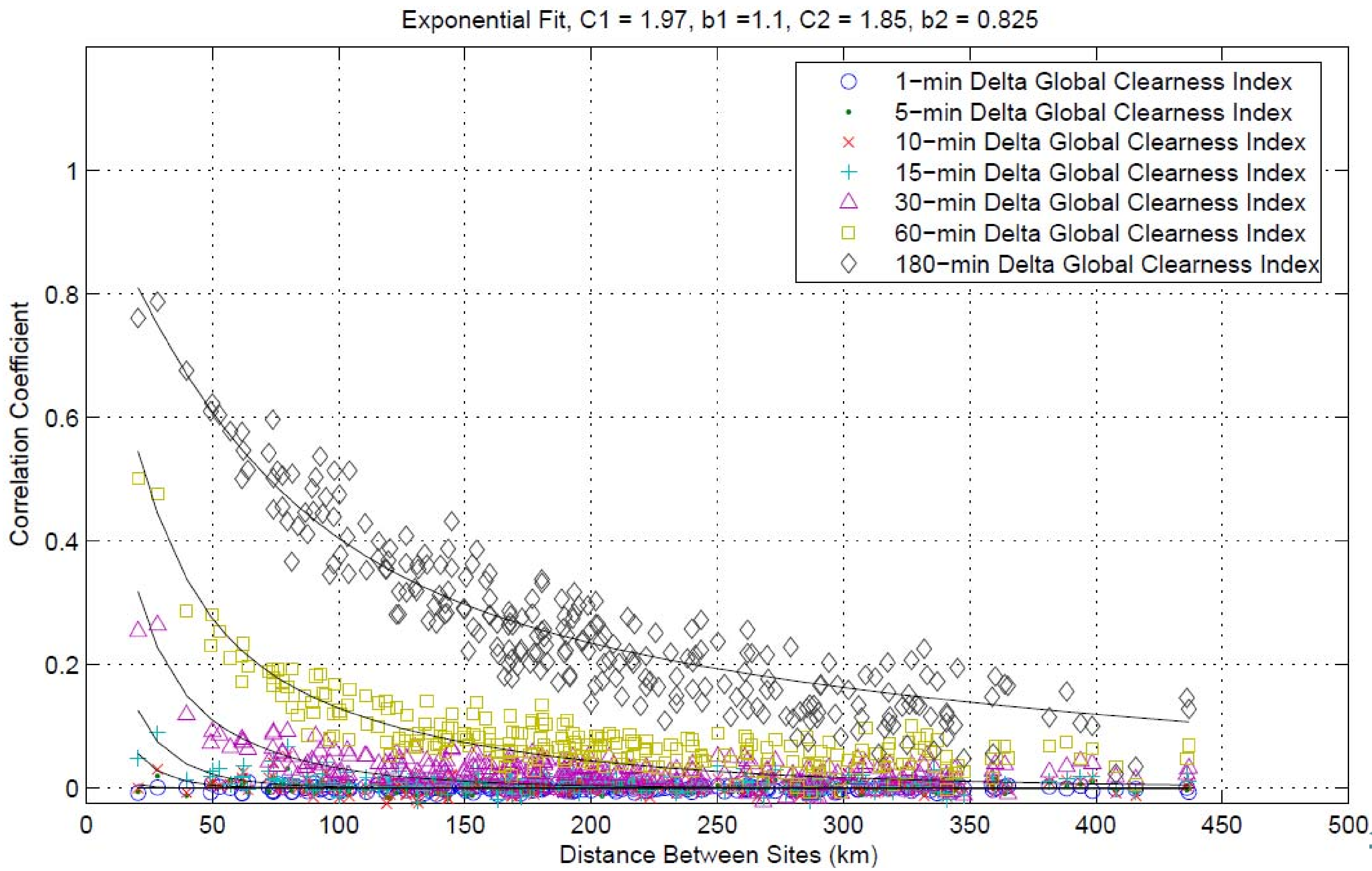


Characterize variability over different time-scales as:

(1) The standard deviation of the deltas
(2) The 99.7th percentile of the deltas

Extreme changes are observed from one hour to the next (60-min deltas) and even one minute to the next (1-min deltas)

Short Time-Scale *Changes* in Insolation are Uncorrelated Between Sites



Temporal and Spatial Scales of Diversity Can be Used to Predict Variability at System Level

$$\frac{\left(\Delta\sigma_k^{\bar{t}}/N\right)}{\Delta\sigma_{k_1}^{\bar{t}}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\rho^{\bar{t}}\left(\Delta k_i^{\bar{t}}, \Delta k_j^{\bar{t}}\right)}$$

- $(\Delta\sigma^t_k/N)$: Average variability for a time-scale *t* at system level for *N* sites
- $\Delta\sigma^t_1$: Variability at a single site
- ρ^t: Correlation coefficient of step-changes in clearness index between two sites
- If all sites are uncorrelated ($\rho^t = 0$), average variability is ***1/sqrt(N)*** times the variability at a single site
- If all sites are perfectly correlated ($\rho^t = 1$), average variability is ***equal*** to the variability at a single site

Diversity Within a Control Area Will Significantly Smooth Rapid Ramps

Ramps at a single site can be severe, but diversity between sites can mitigate ramps.

Similarly sited wind and solar appear to have similar variability

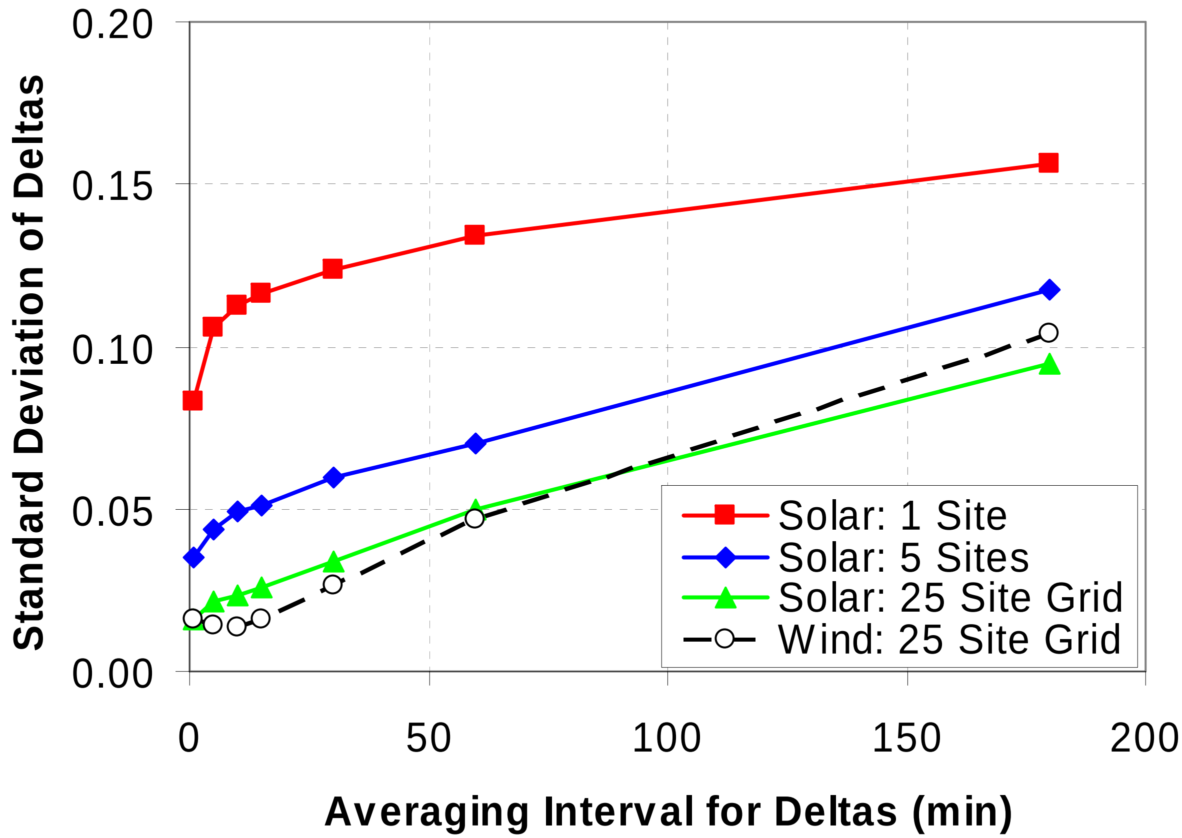
5 close sites

~ 7,000 sq. km

25 site grid

5 X 5 Site array with 40 km spacing between sites

~ 40,000 sq. km



Caveat: Each site is based on a single point measurement, additional smoothing will occur for both wind and solar over short-time scales within individual sites. These results overstate variability of plants below ~10-min time scale

Costs to Manage Short-term Variability: Assumptions

- Short-term variability is managed by increasing reserves at the power system level (as opposed to plant level)
- Reserves are increased to manage variability over three time scales:
  - Regulation (1-min deltas)
  - Load Following (5-min deltas)
  - Operating Reserve Margin (60-min deltas)
- Grubb (1991): Cost of reserves is due to:
  - Part-load efficiency penalty for spinning plants (assumed to be 15%)
  - Use-of high cost energy from quick-start standing plant when standing reserves are deployed (applicable to 60-min deltas only)
- Used characteristics of MISO load and assumptions made in 2006 MISO Wind Integration Study to estimate increase in reserve costs due to increased variability from solar and wind

Integration Costs of Solar Dramatically Impacted By Geographic Diversity, and May Be Less than for Comparably Sited Wind

Time Scale	Increased Reserve Costs ($/MWh)				
	Reserves Constant Throughout Year				Reserves Change with Position of Sun
	Solar			Wind	Solar
	1 Site	5 Sites	25 Site Grid		
1-min Deltas (Regulation)	$14.7	$5.0	$1.6	$1.1	$0.2
5-min Deltas (Load Following)	$7.0	$2.1	$0.7	$0.2	$0.1
60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)	$5.2	$2.2	$1.3	$0.8	$0.2
Total Cost	**$26.9**	**$9.3**	**$3.5**	**$2.1**	**$0.5**

Example costs based on 10% penetration of solar or wind on capacity basis

Why are solar costs lower?

Reserves can be held in proportion to clear-sky insolation for solar

Reserves are held at the same level all year for wind

Integration costs include unit-commitment costs which are not considered here

Preliminary Conclusions

- Variability in solar insolation at a single site can be severe. Scaling a single point measurement of insolation leads to projections of high costs to manage PV variability
- 1-min to 10-min step changes in solar insolation for sites as close as 20 km apart, however, are uncorrelated
- Aggregation of multiple sites at the system level leads to significant smoothing of ramps, particularly over short time-scales
- Costs to manage short-term PV variability from multiple sites aggregated to the system level may be similar to the modest costs to mange short-term variability of wind

Acknowledgements

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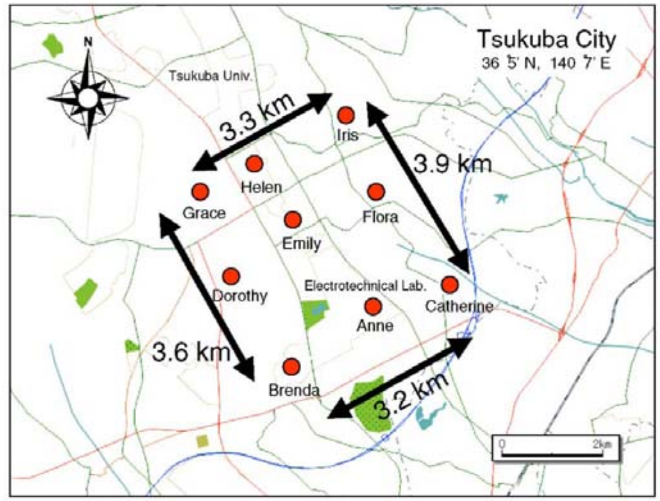
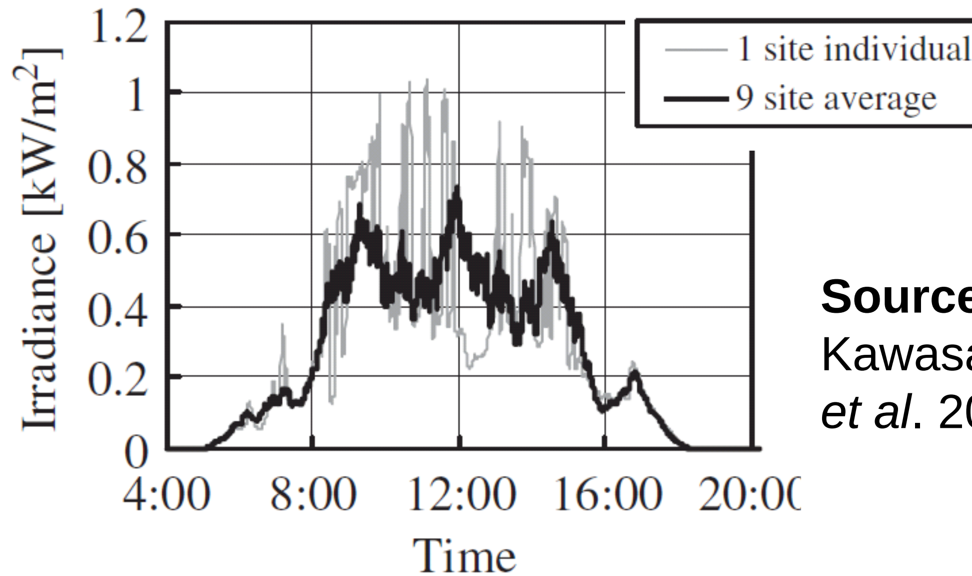
Backup Slides

Next Steps

- Characterize temporal and spatial scales of geographic diversity in high-solar regions
- Estimate the degree to which smoothing occurs at the plant level; compare within-plant smoothing to wind
- Perform more detailed studies of reserve costs using production cost models and time-synchronized PV and load data



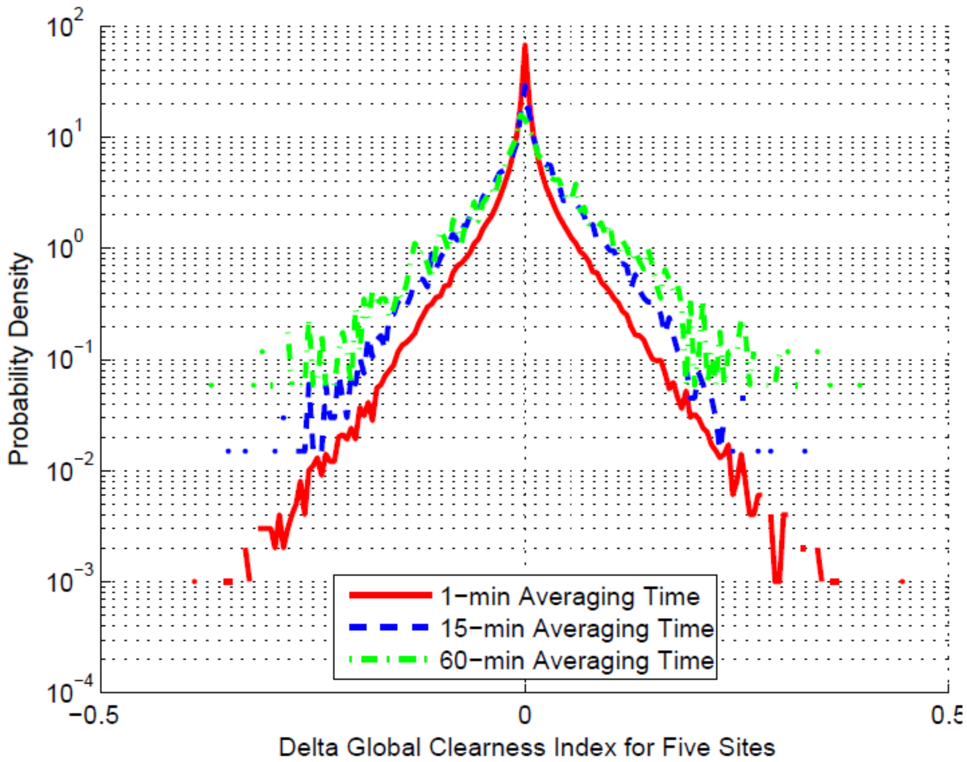
12.25 sq. km = 3025 acres ~ 350 MW PV plant

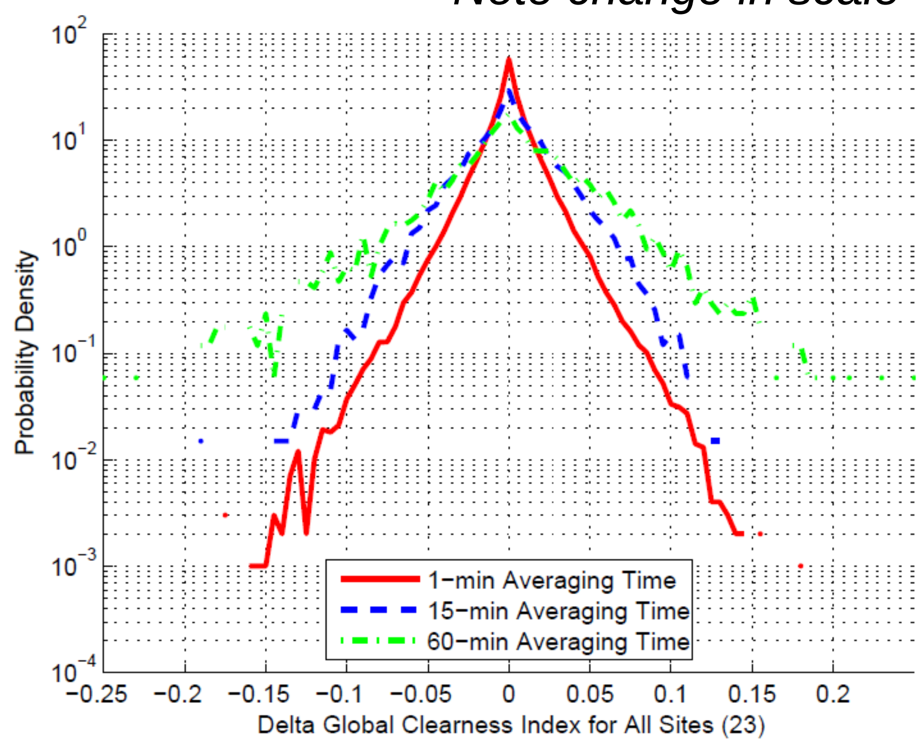


Source: Kawasaki *et al*. 2006.

Variations are Smoother for Aggregate of Multiple Sites Compared to a Single Site

Note change in scale

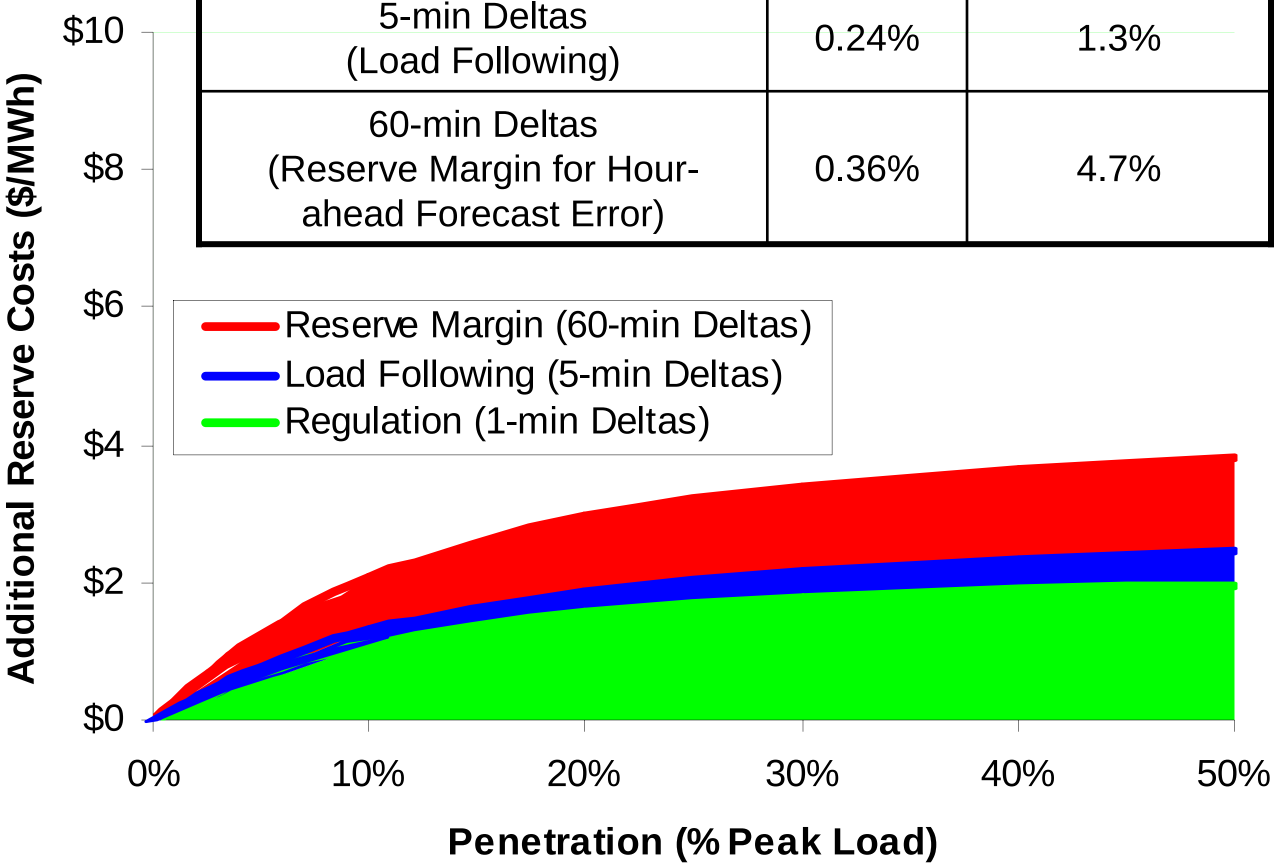




- Deltas are relatively smaller with more sites; aggregation is particularly effective for shorter time-scales
- Shape of distribution of deltas becomes less “fat-tailed”

Costs to Manage Short-term Variability: Simple Example for Wind

Time-Scale	Load (% Peak)	Wind (% Nameplate)
1-min Deltas (Regulation)	0.13%	1.7%
5-min Deltas (Load Following)	0.24%	1.3%
60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)	0.36%	4.7%



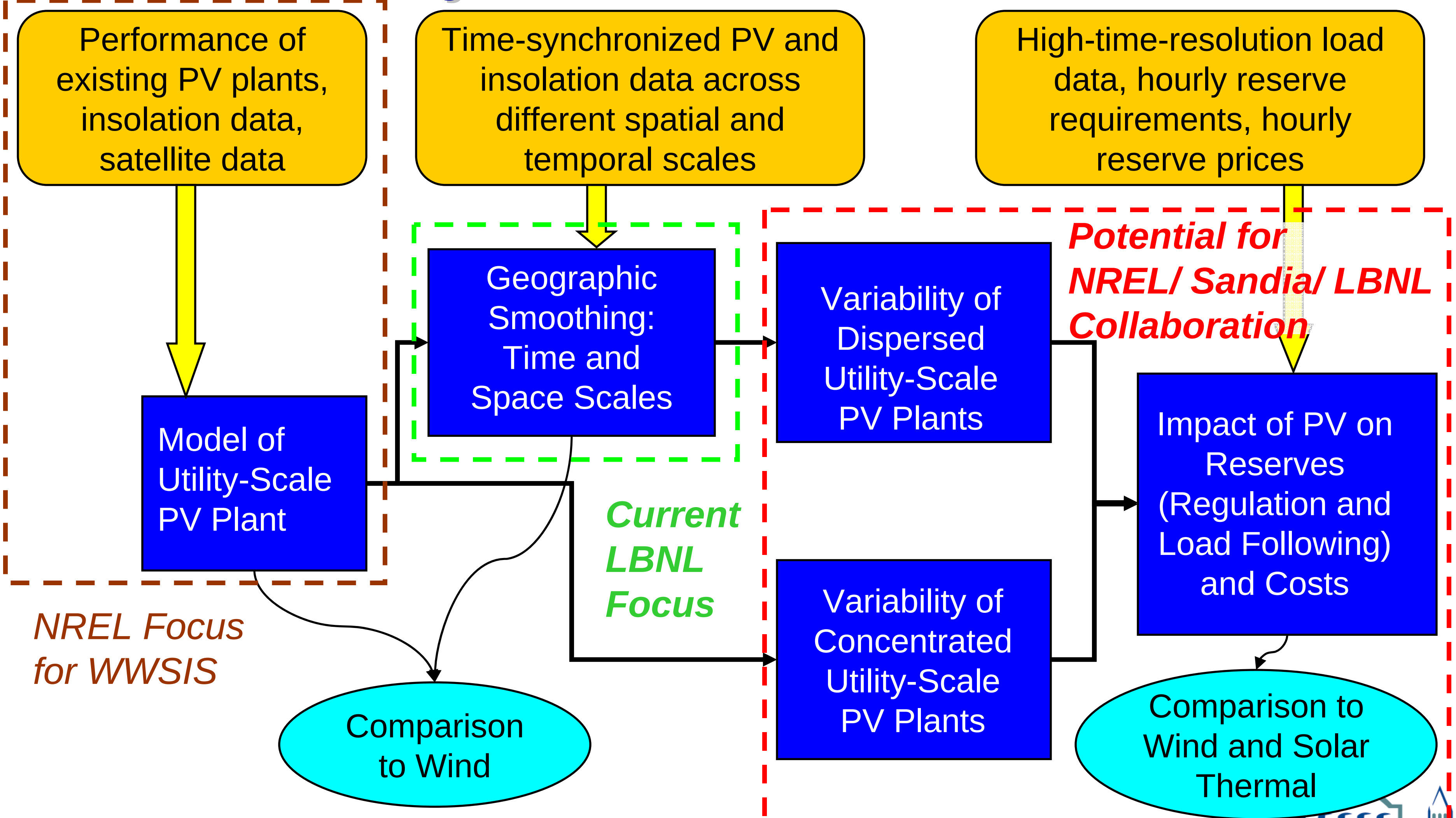
Analysis Relies on Many Simplifying Assumptions:

Reserves are constant throughout year for both load and net-load

One type of plant provides spinning reserve throughout year (marginal cost at full load = $55/MWh)

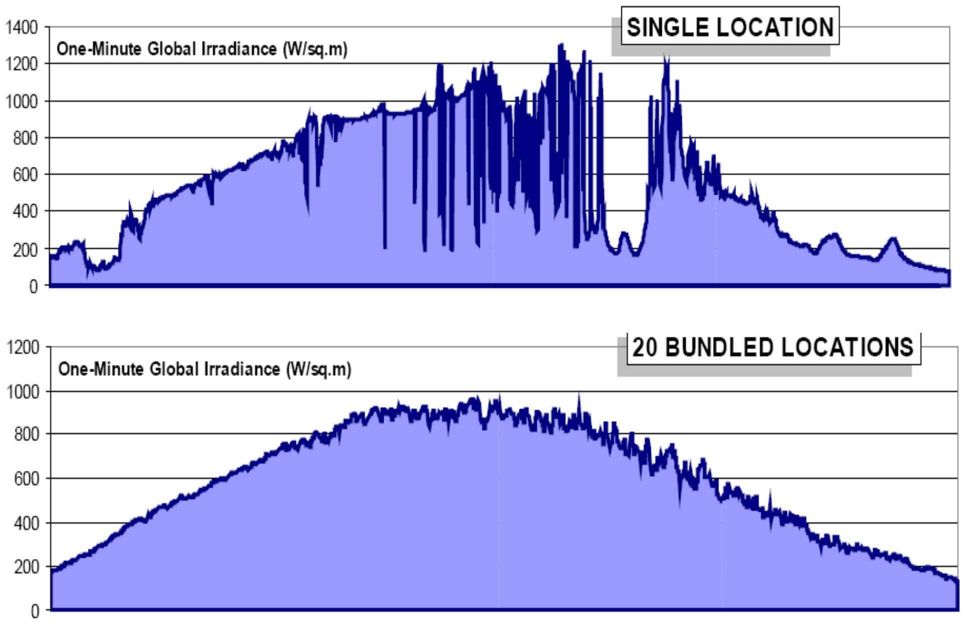
One type of plant provides standing reserve (marginal cost = $85/MWh, no start-up cost)

Broad Sketch of Research Required to Assess the Operational Integration Impacts of Utility-Scale Photovoltaic Plants



Geographic Diversity Smoothes Rapid Variations in Output

Information about the benefits of geographic diversity need to be incorporated into the analysis of utility-scale PV grid integration impacts



Source: Hoff et al. 2008

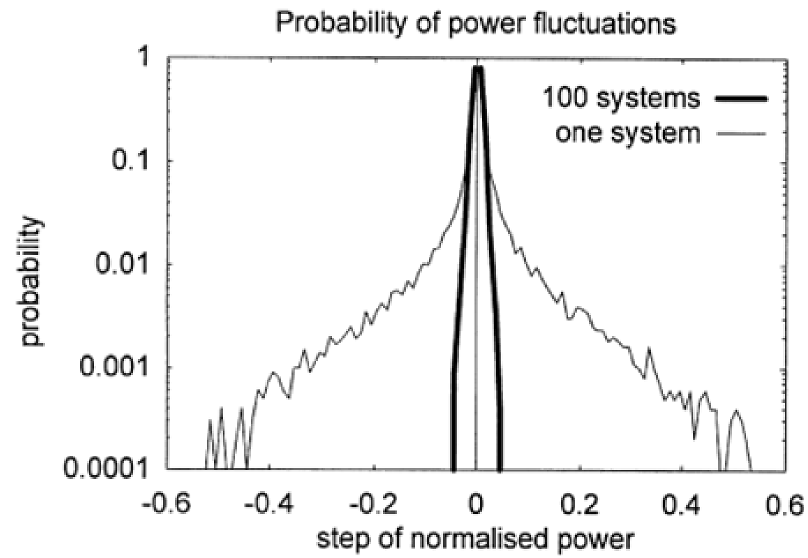


Fig. 5. The time series of both the power generation of an individual PV system and of the combined systems are scanned for differential power steps. For instance, a probability at the normalised power of delta $P/P_{\text{inst.}} = 0.2$ means that in the investigated period ($P/P_{\text{inst.}} > 0$) power differences of 20% of the installed power have occurred between two time steps with this probability. Positive values indicate an increase in power, negative values a decrease. The time resolution is 5 min, the class width of the normalised power levels is 0.01.

Source: Weimken et al. 2001

Temporal and Spatial Scales for Correlation of Changes in Wind Power are Well Understood

*Correlation of changes in **wind power** output is a function of distance and time-scale. 5-min variations in wind plants over 20 km apart are statistically uncorrelated.*

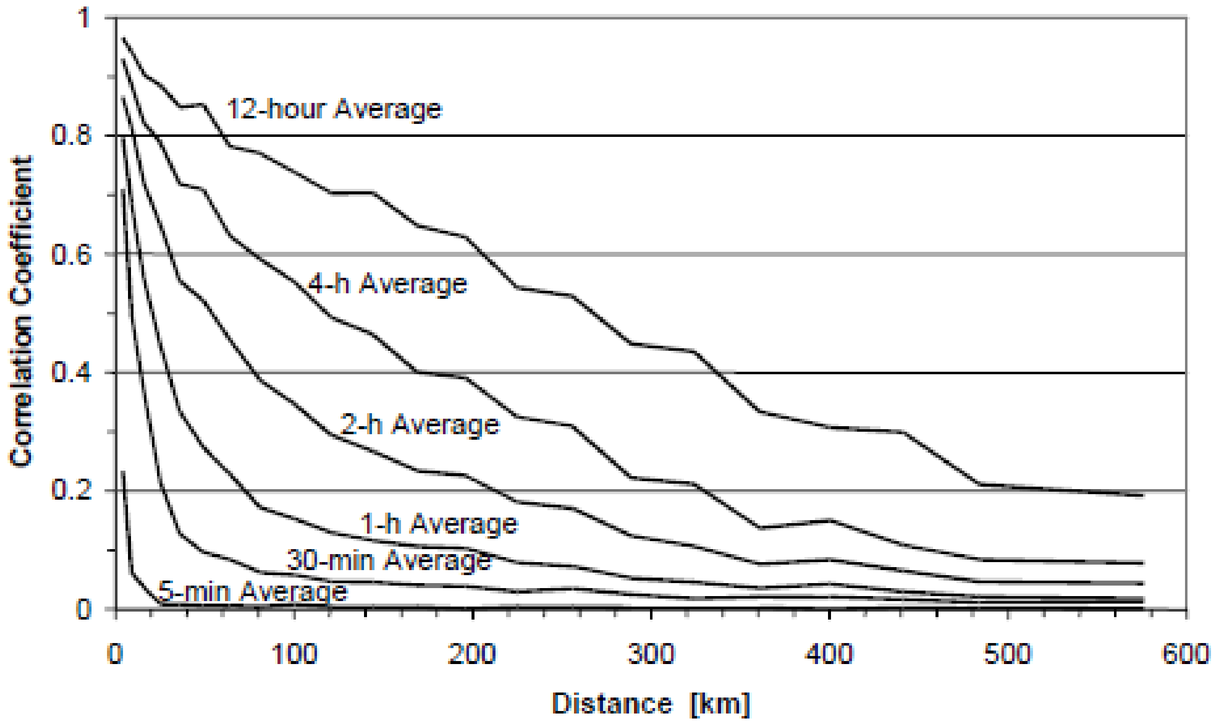
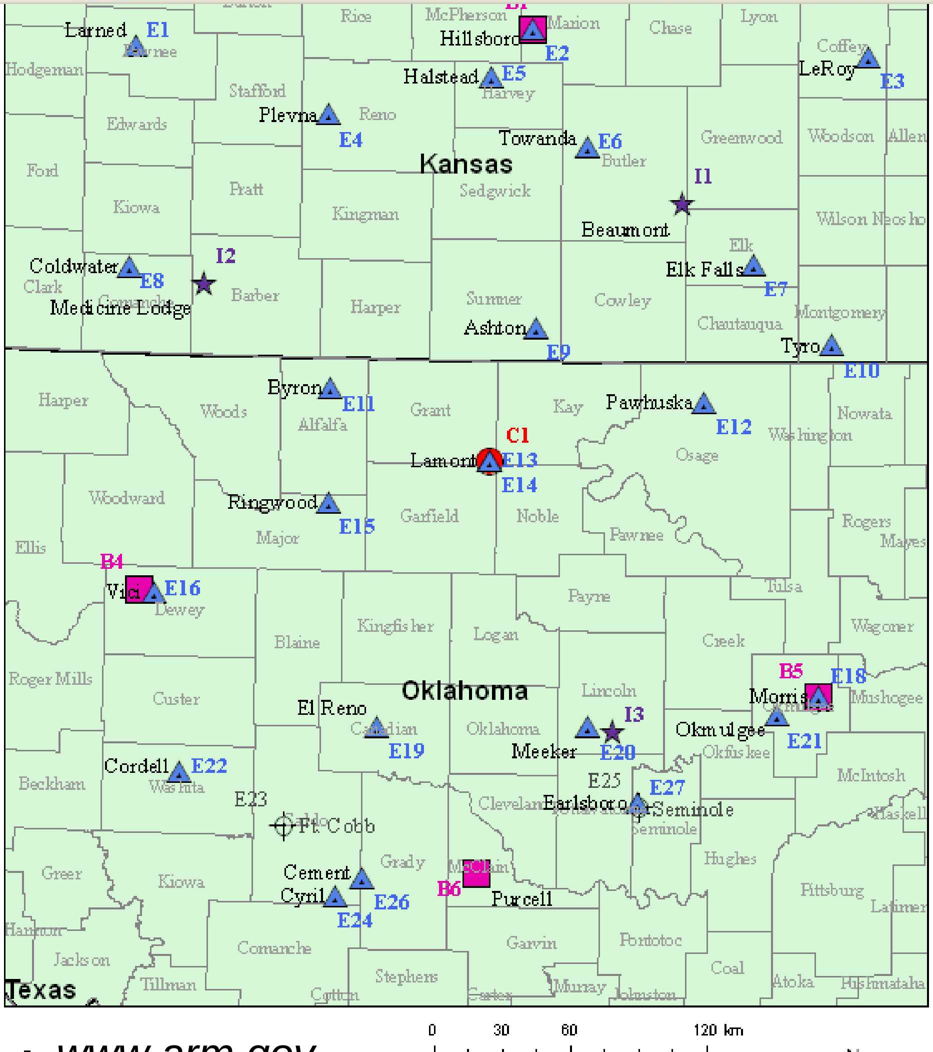


Figure 7. Correlation coefficient of Δp for different average times over the distance

Source: Ernst, Wan, and Kirby 1999

Analysis of Temporal and Spatial Scales of Geographic Diversity: ARM Program



- Use 1-min data from 2004 to estimate correlation coefficient for changes in:
  - global insolation,
  - direct insolation, and
  - clearness index*

  between pairs of stations in the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) Program.
- Calculate histograms of changes in solar insolation over different time-steps for a single site (C1) and all 23 available sites (C1 & E1-27 excl. E-14 & E-26)

Clearness Index: Ratio of measured insolation to "clear sky" insolation (i.e. insolation in absence of clouds). SGP data includes clear sky insolation

- *www.arm.gov*

Diversity Decreases Probability of Large Swings in Solar Insolation for Multiple Sites

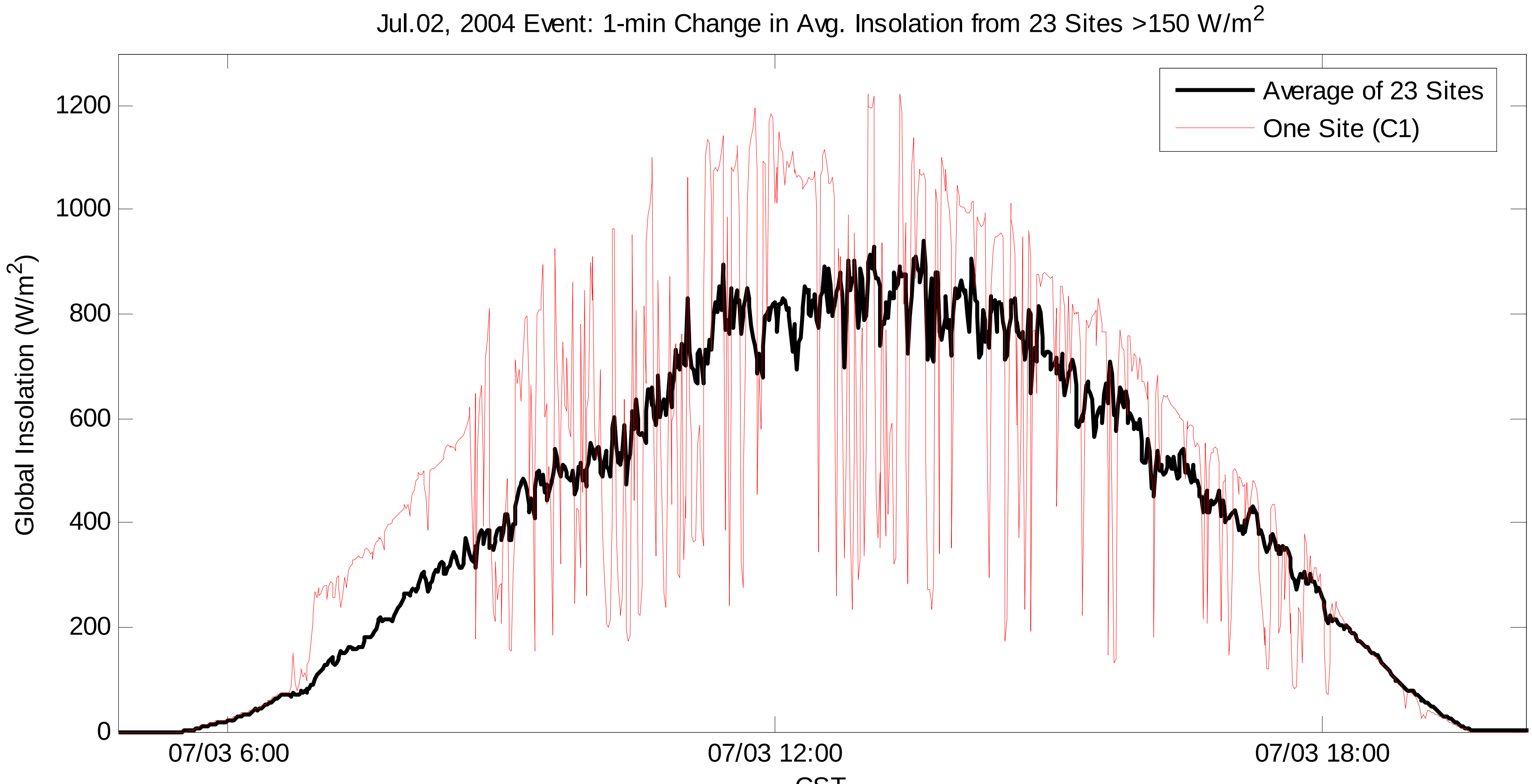


Chart shows a day in 2004 with one of the most extreme 1-min changes in global solar insolation simultaneously measured at all 23 sites

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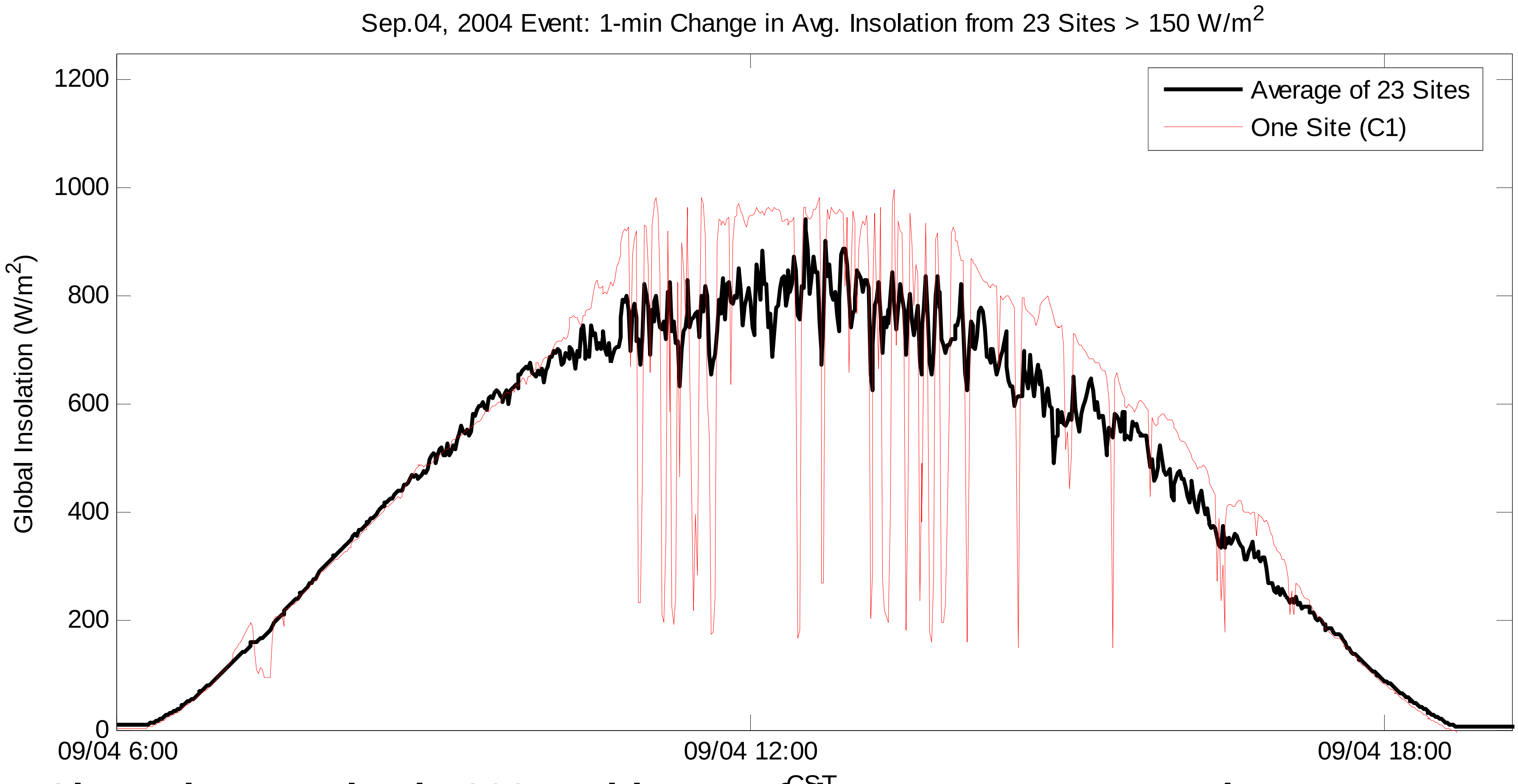

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