Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power

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Short-Term Variability of Solar Power: Presentation Outline

1. **Motivation and Scope**
2. **Data and Approach**
3. **Results**
    a) Characteristics of Short-Term Variability at a Single Site
    b) Aggregate Variability from Geographically Dispersed Sites
    c) Comparison of Wind and Solar Variability from Similarly Sited Plants
    d) Potential Cost of Increased Balancing Reserves to Manage Variability
4. **Conclusions and Future Research**

Project Overview

Motivation: Concern that rapid fluctuations in photovoltaic plant (PV) output are a potential roadblock to PV integration

- NERC stated that "PV installations can change output by +/- 70% in a time frame of two to ten minutes, many times per day."
- Numerous academic studies between 1980 – 1996 suggested potential limits to increasing PV penetration due to rapid fluctuations in PV output

Many previous studies did not adequately consider the benefits of geographic diversity in project sites - studies need to consider the impact of geographic diversity in smoothing the aggregate output of several PV plants

Scope: Assess short-term variability of PV due to clouds for individual and aggregated sites (and compare it to variability of similarly sited wind plants)

- *To what degree does short-term solar variability over various timescales decline with geographic distance and number of PV sites?*
- *How much does geographic smoothing reduce the potential costs of additional balancing reserves to manage short-term PV variability? How do the possible costs of those reserves compare to the reserve costs for wind energy?*

Data and Approach

- Use time-synchronized data from multiple insolation sensors to develop relationships between:
  - Time-scale of variability in clear sky index (e.g., 1 min, 5 min, 60 min)
  - 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 with additional balancing reserves
- Data source: Southern Great Plains network in Atmospheric Radiation Measurement (ARM) program (Oklahoma and Kansas)
  - One year of data (from 2004) with a time resolution of 1-min
  - 23 time-synchronized solar insolation sites (20-450 km spacing)
  - 10 time-synchronized 10-m wind anemometers (40-450 km spacing)
- Focus on point-source insolation-based clear sky index, not on absolute insolation levels and not on actual PV plant output (smoothing within individual PV project sites not considered, leading to overstatement of variability at individual sites at under 10 min time steps)

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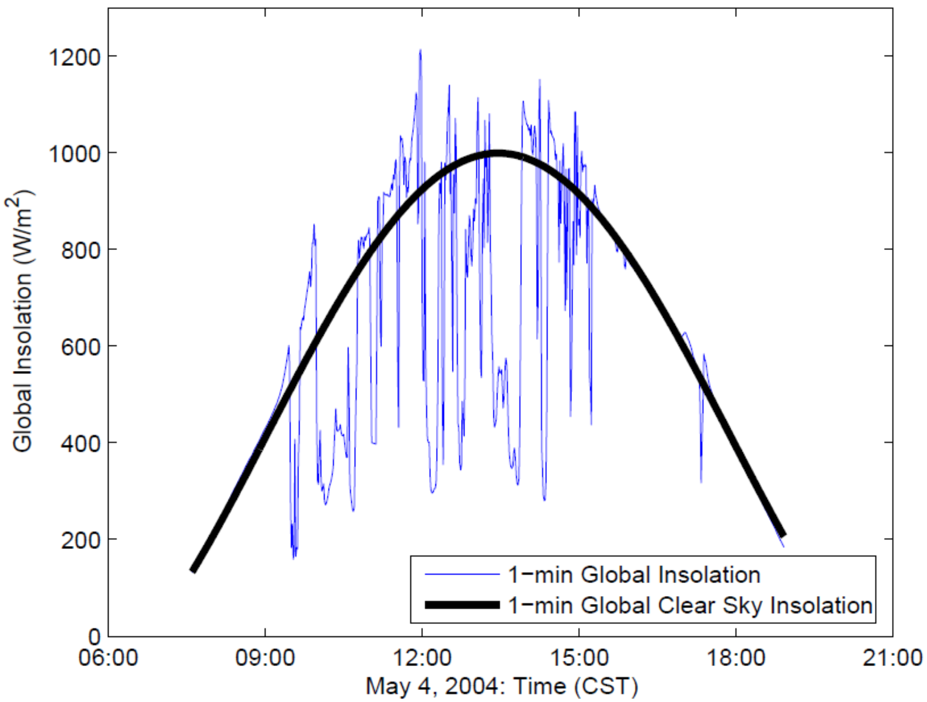
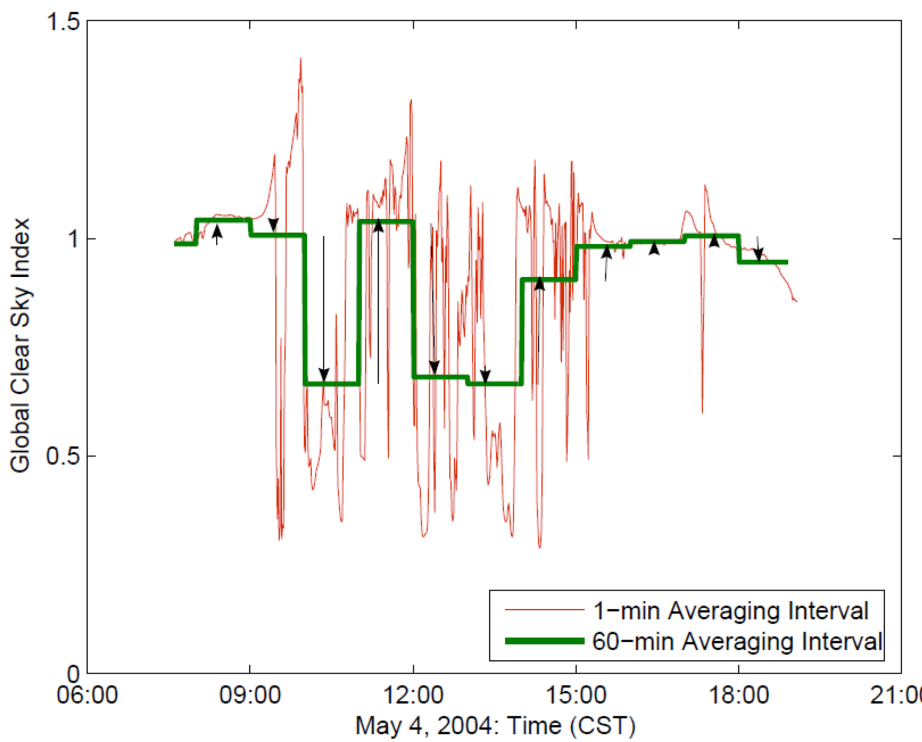
Clouds Can Produce Rapid Ramps in Solar Insolation at a Single Point

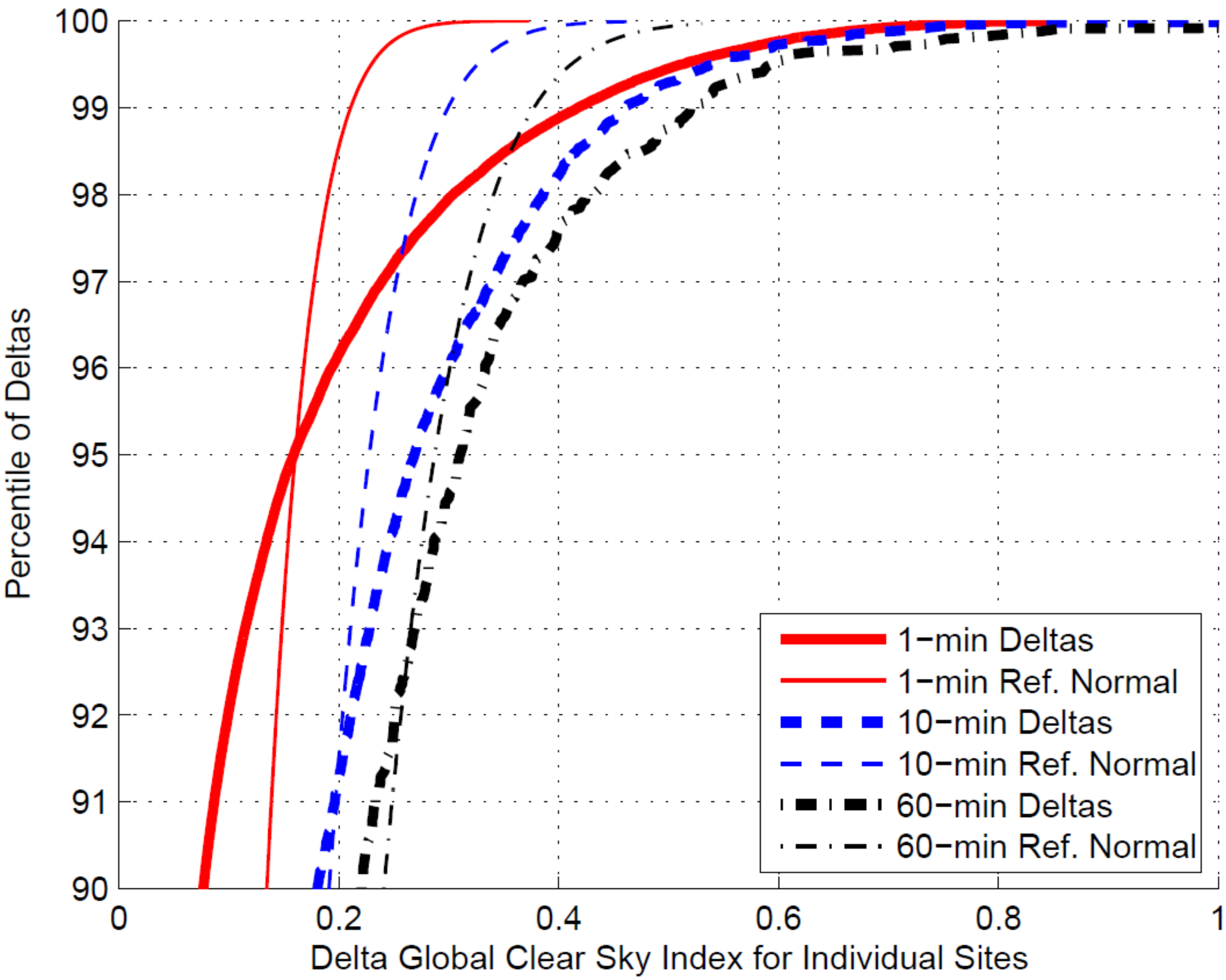




Deltas: Step change from one averaging interval to the next

Clear Sky Index: Ratio of measured insolation to clear sky solar insolation (index focuses on impacts of clouds, removing deterministic effect of position of sun)

Extreme Changes at Individual Sites Are Frequent Relative to a Normal Distribution



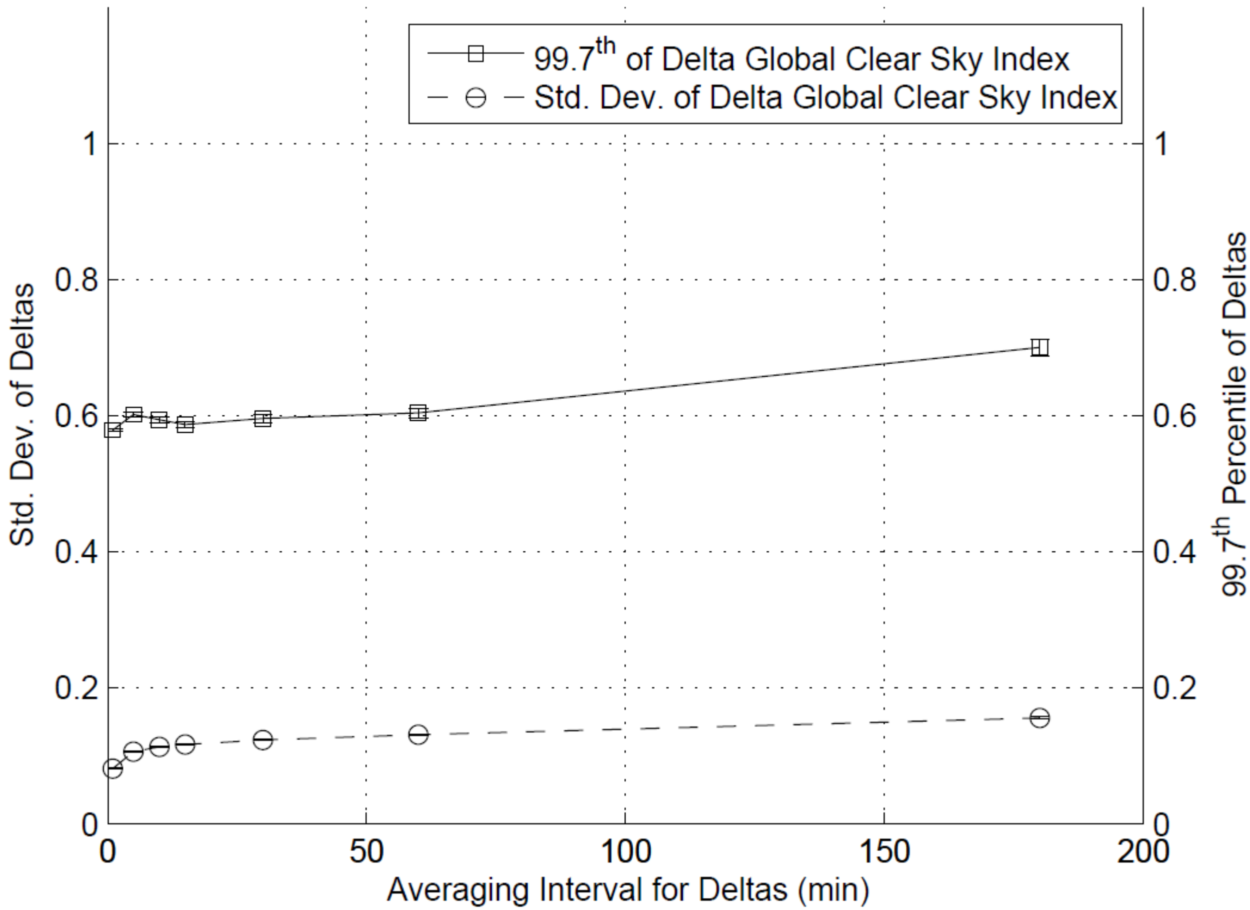
Cumulative Distributions:

The value on the y-axis indicates the fraction of the deltas that are below the level indicated on the x-axis.

For example, 99% of 1-min step changes in the clear sky index are smaller than 0.4.

Thin lines indicate a normal cumulative distribution with the same standard deviation.

Characterize Short-Term Variability of Clear Sky Index with Standard Deviation and 99.7th Percentile of Deltas



Characterize variability over different time-scales:

- The standard deviation of the deltas, and
- The 99.7th percentile of the deltas

Focus on deltas of clear sky index

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

99.7th percentile of deltas substantially above 3 standard deviations because deltas are not normally distributed

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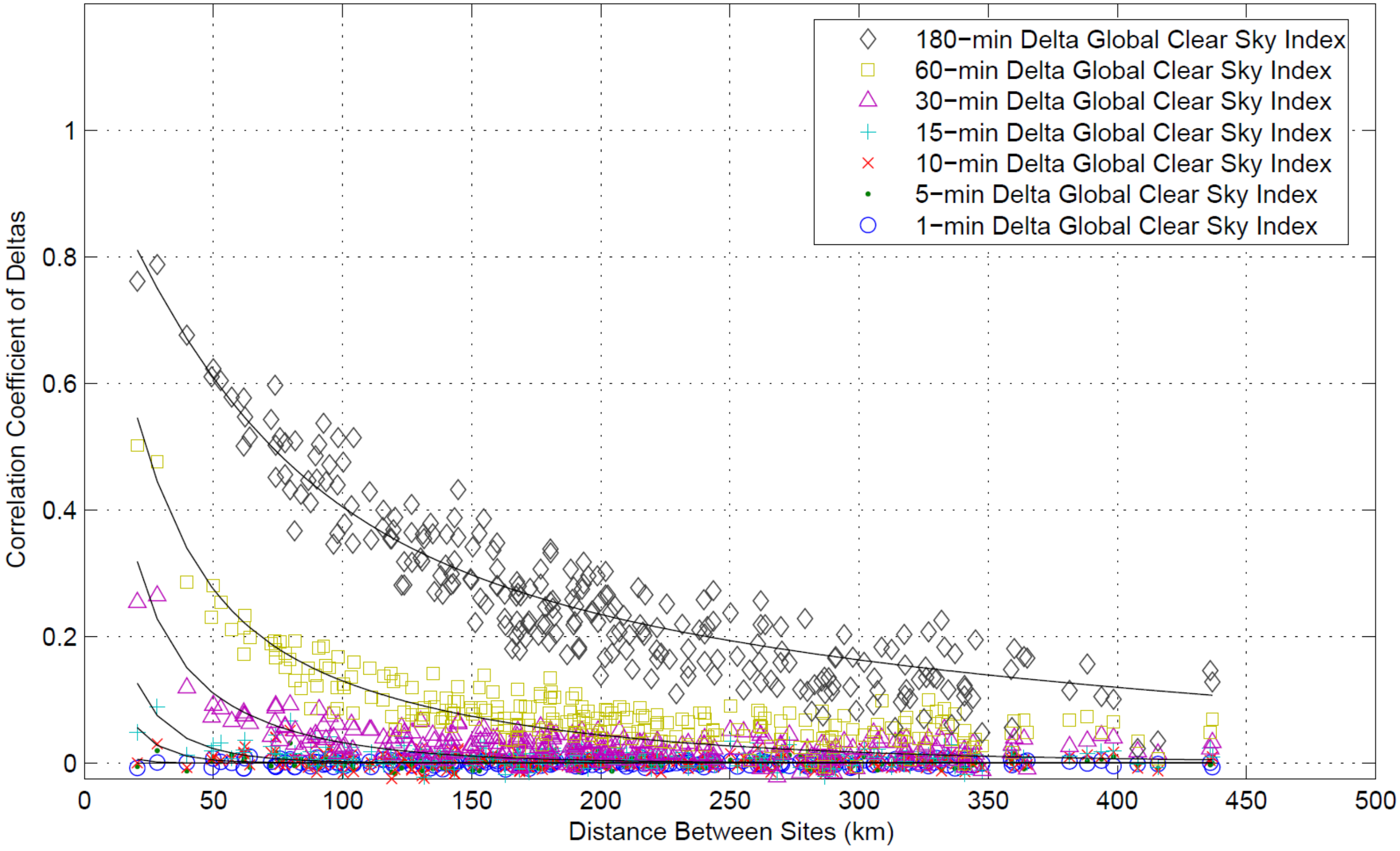
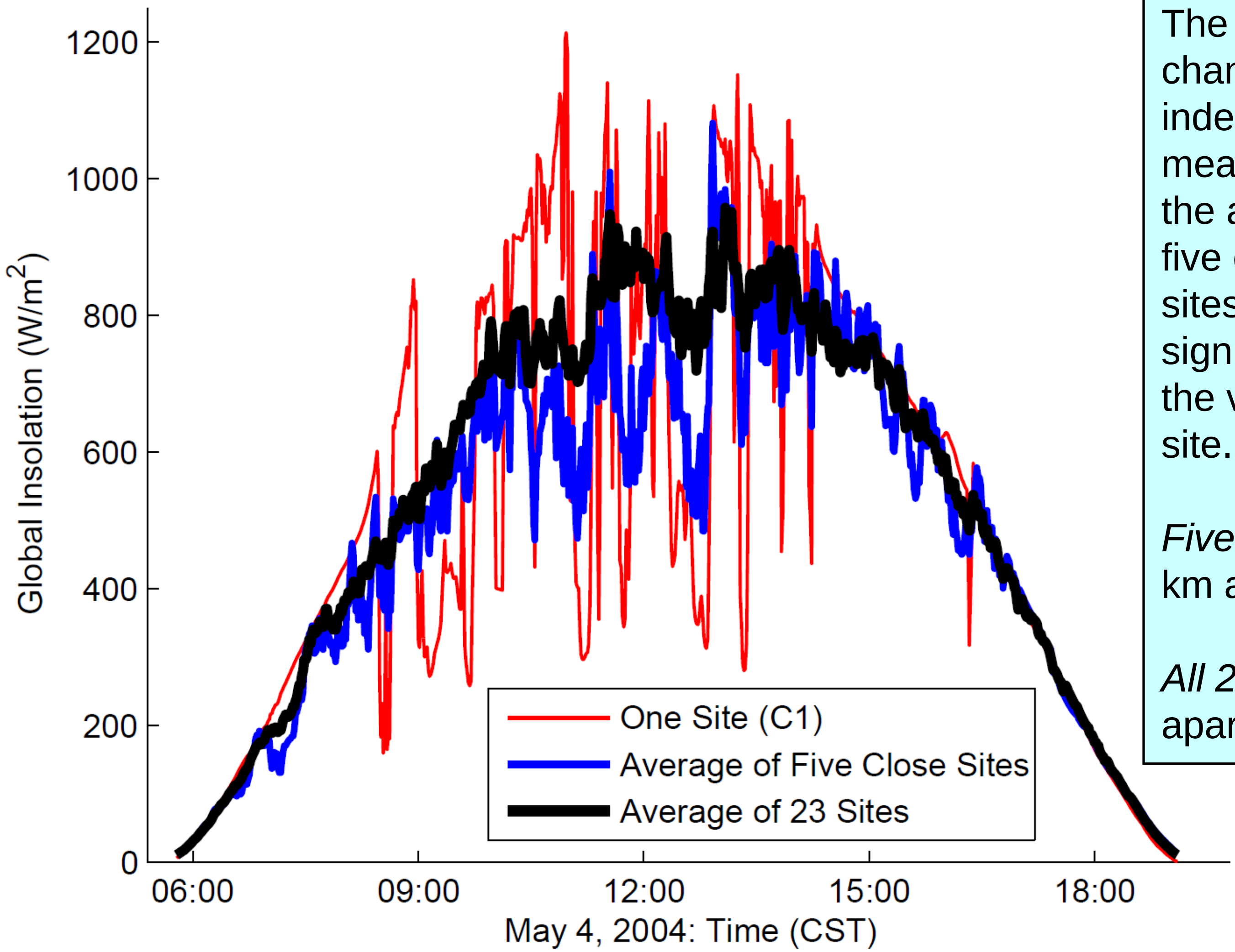
Short Time Scale Changes in Insolation Are Uncorrelated Between Sites in Sample



Points represent correlation coefficient of step changes in the clear sky index between pairs of sites at different distances from one another.

Changes in the clear sky index for sites even as close as 20 km apart are uncorrelated for 1-min and 5-min deltas.

Aggregate Variability of Multiple Sites Is Significantly Smoother than Individual Sites

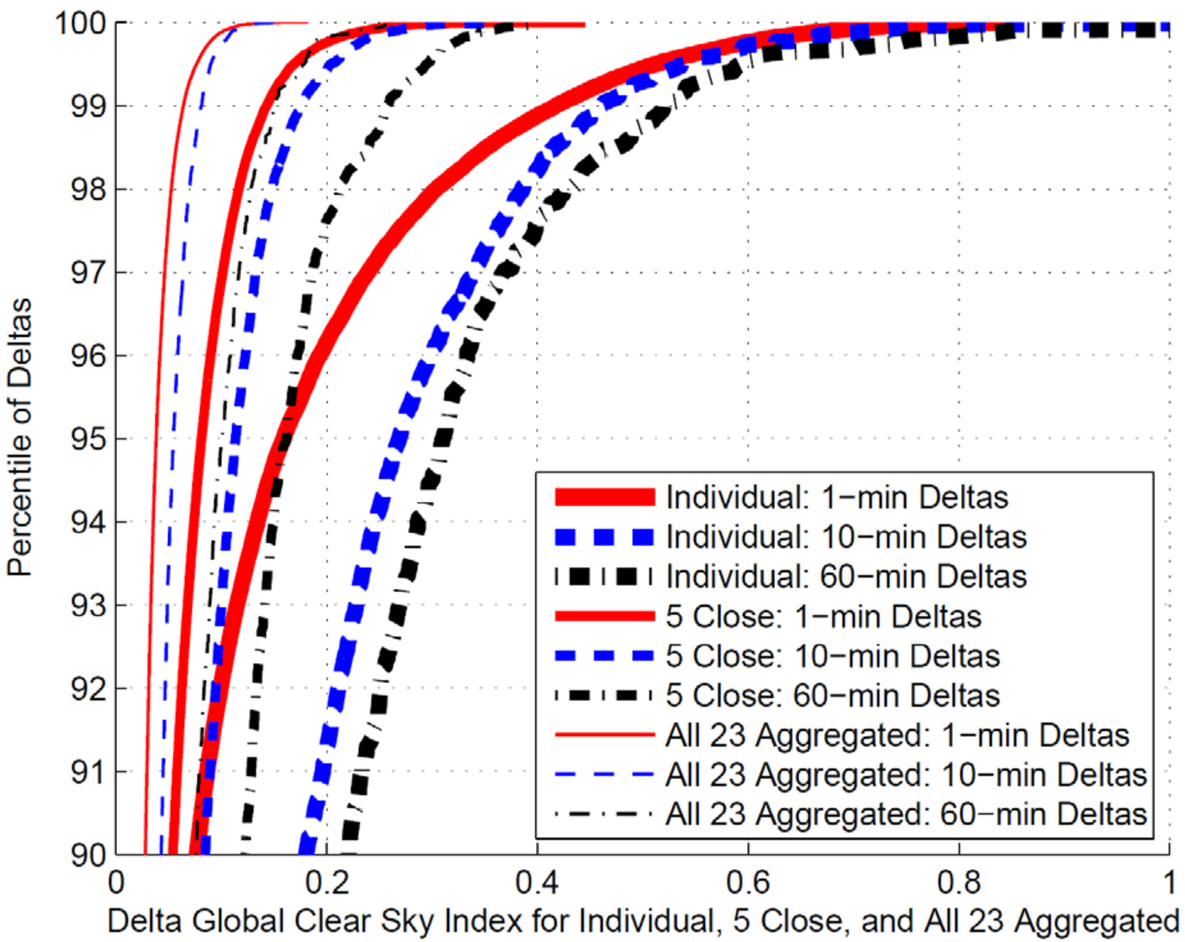


The lack of correlation in changes in the clear sky index over short time scales means that the variability of the aggregated data from the five closest sites and all 23 sites in the SGP network is significantly smoother than the variability of an individual site.

Five closest sites: 50 – 170 km apart

All 23 sites: 20 – 440 km apart

Aggregate Variability of Multiple Sites Is Significantly Smoother than Individual Sites



The most extreme changes in the aggregate clear sky index (represented by the 99.7th percentile) are only a fraction of the changes observed at an individual site.

Smoothing benefit especially significant for short time scale variability

99.7th Percentile of Deltas	1-min	10-min	60-min
Individual	0.58	0.59	0.60
Five Close	0.19	0.23	0.31
All 23 Sites	0.09	0.10	0.19

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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 (standard deviation of deltas) for a time-scale *t* at system level for *N* sites
- $\Delta\sigma^t_{k1}$: Variability of clear sky index k_1 at a single site
- ρ^t: Correlation coefficient of deltas in clear sky index between two sites
- If all sites are uncorrelated ($\rho^t = 0$), average variability is ***1/√(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

Similarly Sited and Geographically Distributed Wind and Solar Have Similar Variability Within Data Sample; Benefits of Geographic Diversity for Solar Apparent

Used relationships from previous slide and variability and correlation data to estimate aggregate variability of similarly sited wind and solar.

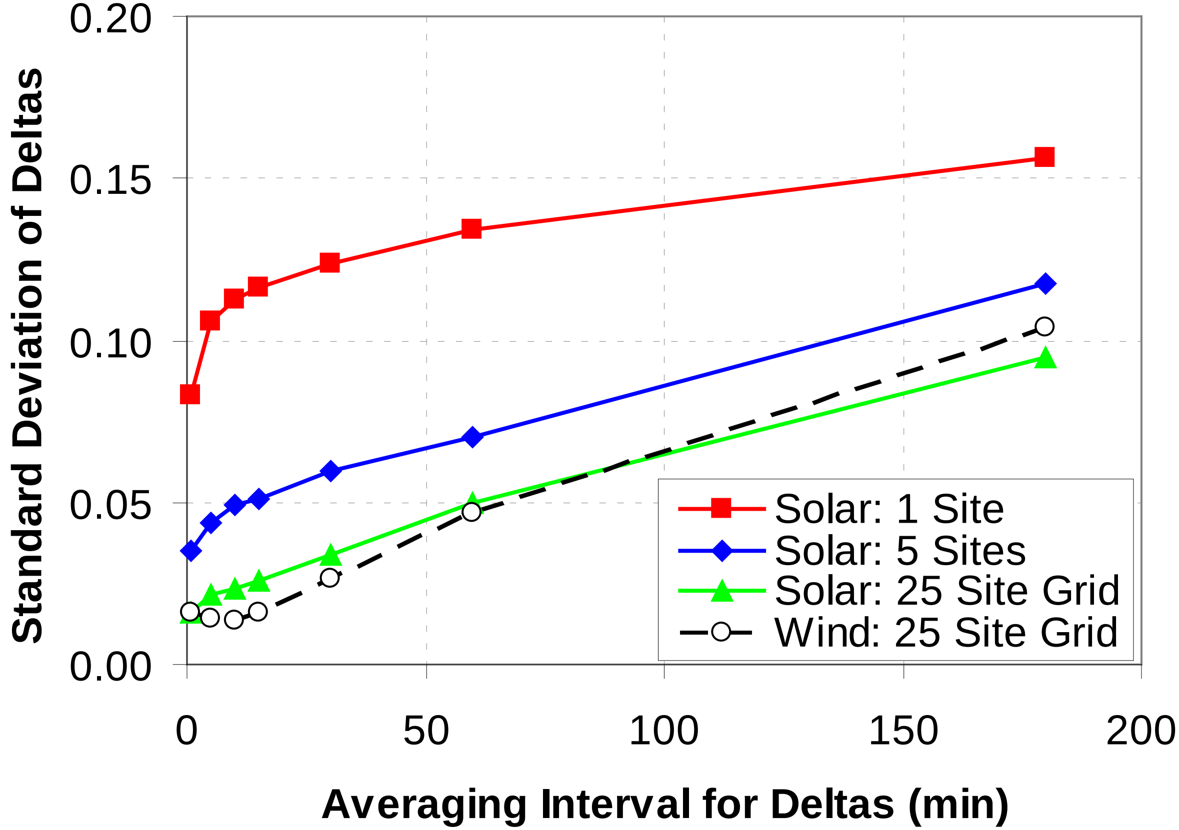
5 close sites

~ 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, and additional smoothing will occur for both wind and solar over short-time scales within individual PV project sites. These results therefore overstate variability of plants below ~10-min time scale

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Costs to Manage Short-Term Variability: Key Assumptions

- Short-term variability is managed by increasing balancing reserves at the power system level (as opposed to plant level)
- Balancing reserves are assumed to increase to manage variability over three time scales:
  - 1-min deltas ~ NERC Control Performance 1 (CPS1) standard
  - 10-min deltas ~ NERC Control Performance 2 (CPS2) standard
  - 60-min deltas ~ Hourly schedules for transfers between balancing authorities
- Following Grubb (1991): Cost of balancing reserves is due to:
  - Part-load efficiency penalty for spinning plants (assumed to be 15%)
  - Use of high-cost energy from quick-start standing plants when standing reserves are deployed (applicable to 60-min deltas only)
- Used average variability characteristics of a generic load data set with solar and wind variability from current study data set to estimate increase in balancing reserve costs due to increased variability from both solar and wind; see paper for full details on approach

Costs to Manage Short-Term Variability of Solar Dramatically Impacted By Geographic Diversity; Costs Similar to Wind for Diverse Sites

Time Scale	Increased Balancing 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	$16.7	$4.8	$1.2	$0.9	$0.8
10-min Deltas	$17.3	$4.4	$1.0	$0.2	$0.7
60-min Deltas	$5.0	$1.6	$0.6	$0.5	$0.5
Total Cost	**$39.0**	**$10.8**	**$2.7**	**$1.6**	**$1.9**

These costs address only short-term variability and do not include many other costs and benefits associated with solar and wind

Cost estimates are developed using simple approximations and are only meant to illustrate <u>relative</u> changes in cost

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

<u>Why are solar and wind costs comparable?</u>

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

Reserves assumed to be held at same level all year for wind

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Conclusions

- Step-changes or "deltas" in solar insolation over short time scales can be severe at individual insolation measurement sites
- The distribution of deltas at individual sites are "fat-tailed" relative to a normal distribution: the probability of severe events exceeds the probability of extreme events from a normal distribution with the same standard deviation
- Scaling the output of an individual PV plant to represent increasing levels of solar penetration leads to a significant estimated increase in the cost of balancing reserves
- As is well known for wind, however, accounting for the potential for geographic diversity can significantly reduce:
    - the magnitude of extreme step changes in output
    - the resources required to accommodate short-term variability
    - the potential cost of additional balancing reserves
- The cost of accommodating the short-term variability of similarly sited and geographically diverse wind and solar plants is expected to be comparable in the Southern Great Plains region

Future Research

- **Variability of actual PV plants will differ from solar insolation:**
  - Need data and models to understand “within-plant” smoothing
  - PV module orientation/tracking, inverter trips, and effect of temperature on PV plant efficiency may affect short-term variability
- **Regional differences in variability and correlation as a function of distance between sites:**
  - Present study focused on only one region of the U.S. (Oklahoma and Kansas)
  - Need 1-min time-synchronized insolation or PV production data from multiple sites in other regions with potential for high PV penetrations
- **Smoothing benefits of geographic diversity could be compared to potential additional costs to achieve diversity:**
  - Lower solar resource quality
  - Forgone economies of scale
  - Additional transmission capacity and losses

For more information...

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Download the full report:

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