Short-Term Variability of Solar Power

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Solar Power International:
Making High Penetration Possible

Energy Analysis Department

BERKELEY LAB

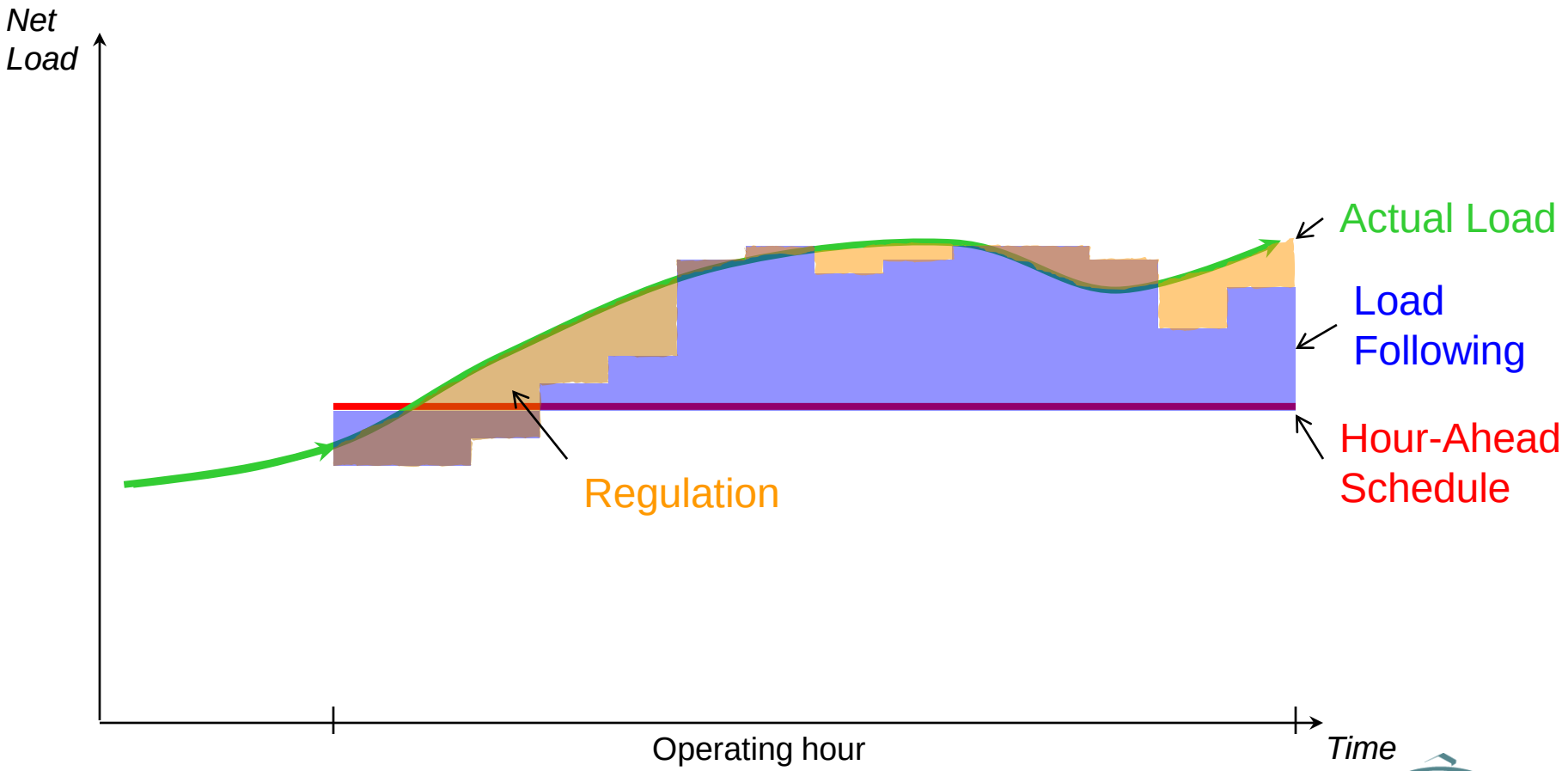
Short-Term Variability of Solar Power

- Rapid deployment of photovoltaics (PV) and concentrating solar power (CSP) in the U.S.
- Limited of understanding of operational integration of solar into wholesale electric power markets
- Concern about variability, strategies to manage variability, and costs to manage that variability
- Preliminary research indicates that geographic diversity smoothes variability of solar
- Additional solar production data is needed to verify benefits of diversity and quantify costs to manage remaining variability

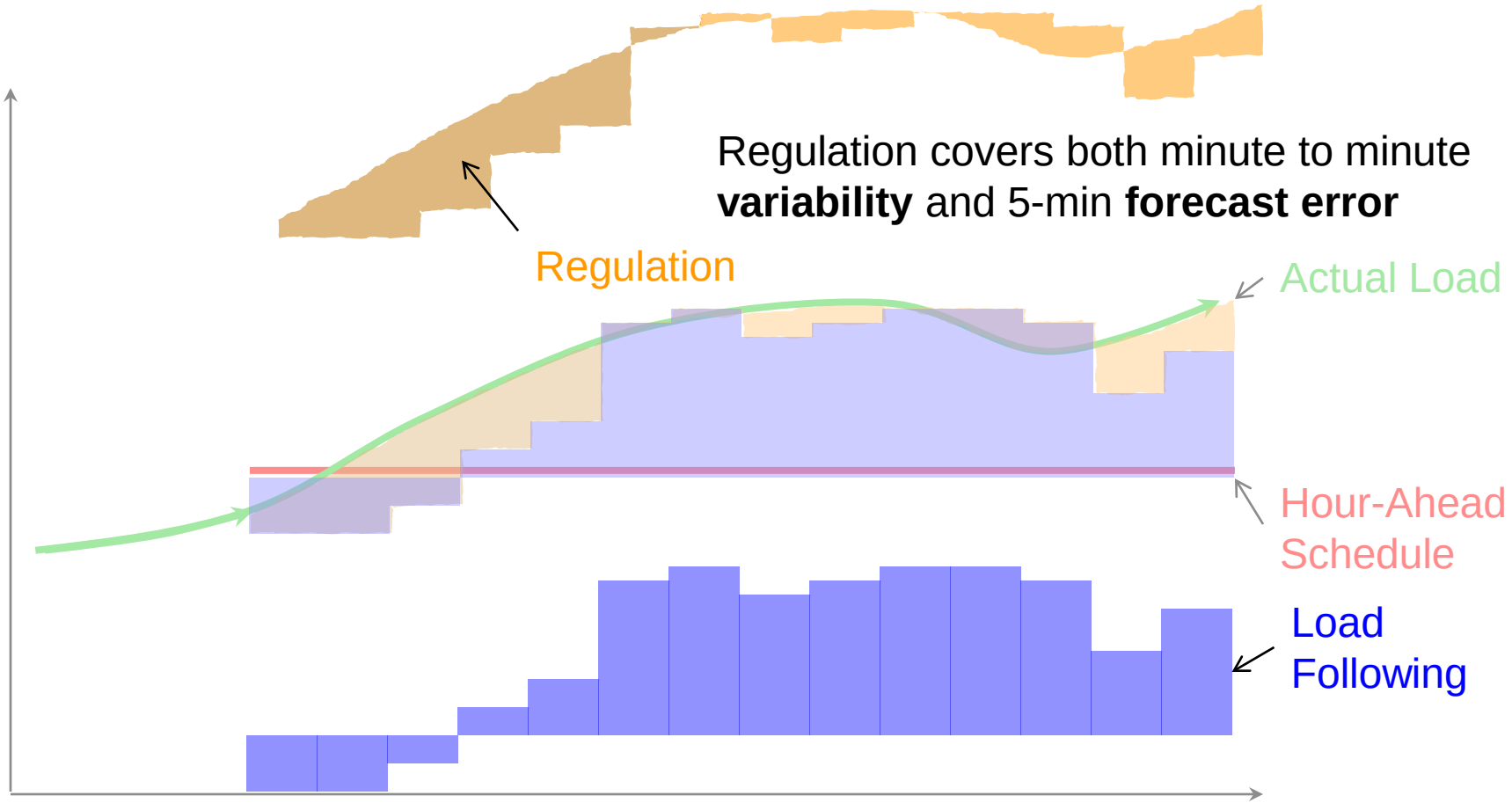
Where Will Solar Be Deployed By 2020?

- Large quantities in high-quality, low-impact solar resource regions
  - CA Renewable Energy Transmission Initiative (RETI)
  - Western Renewable Energy Zone Initiative (WREZ)
  - Proposals for 50 - 500 MW utility-scale solar plants
- "Distributed wholesale" on the distribution grid
  - Utility-owned and/or independent power producer
- Distributed, behind-the-meter installations on residential and commercial rooftops
  - California Solar Initiative (CSI), Self-Generation Incentive Program (SGIP)
  - Other state and utility incentive programs

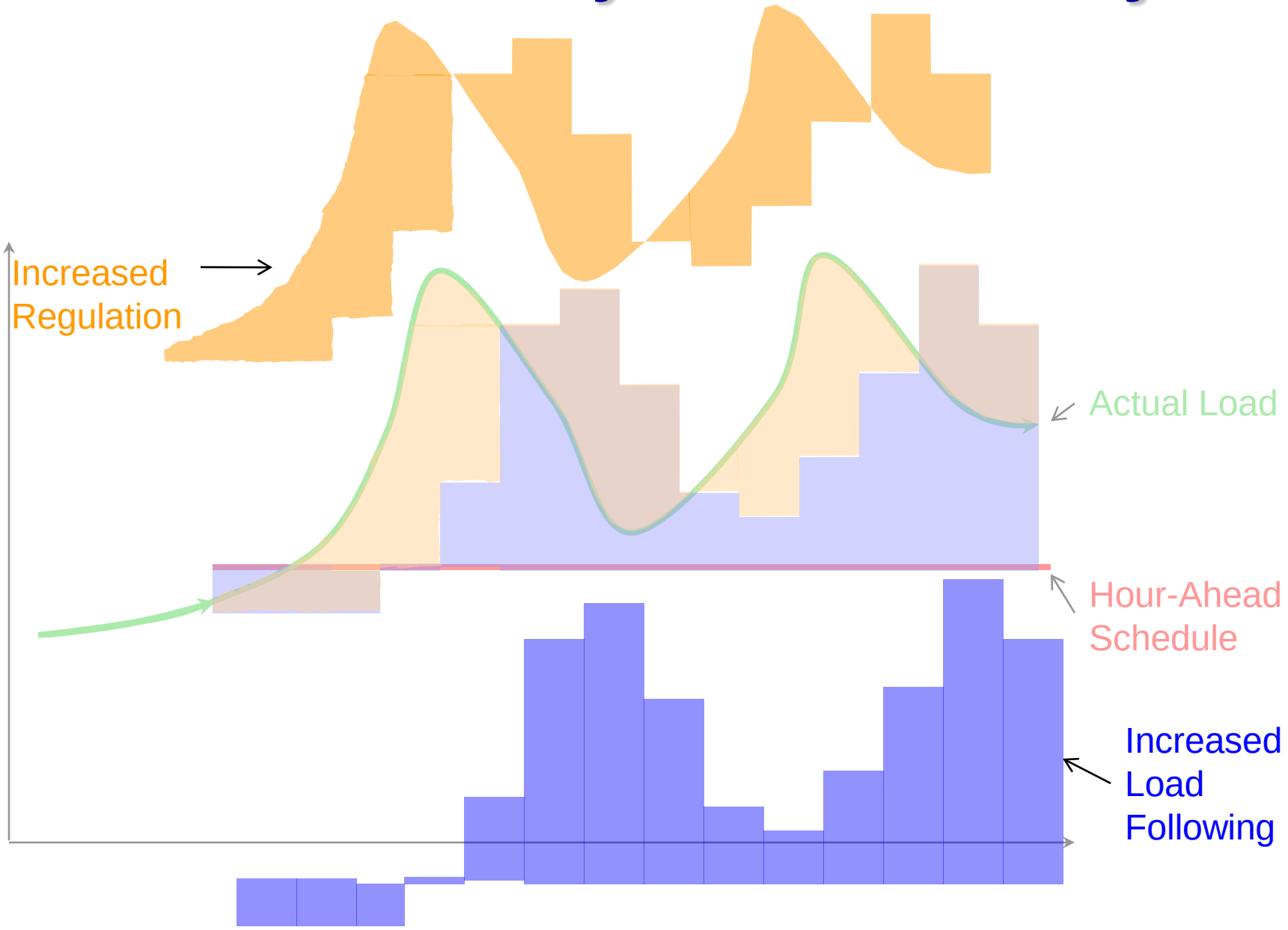
Example of CAISO Operations



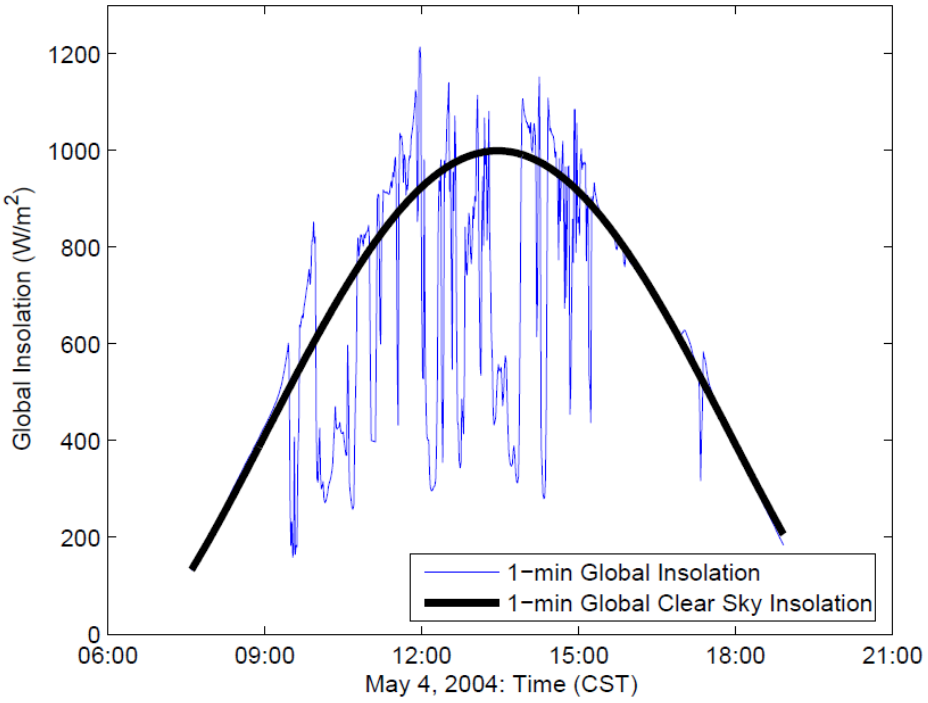
Example of CAISO

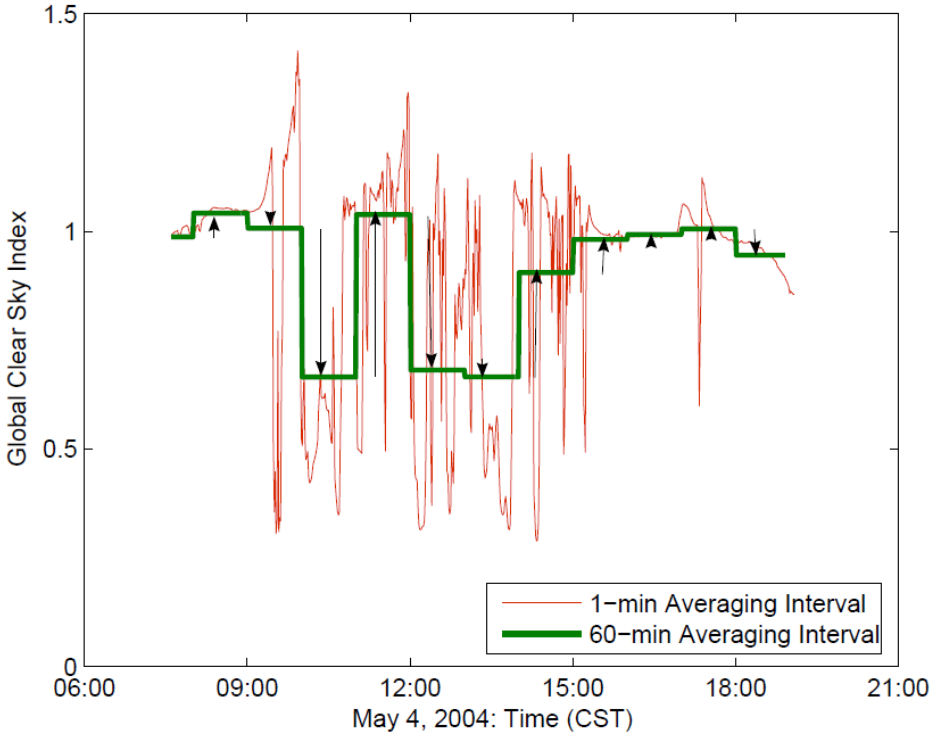


Increased Variability and Uncertainty



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

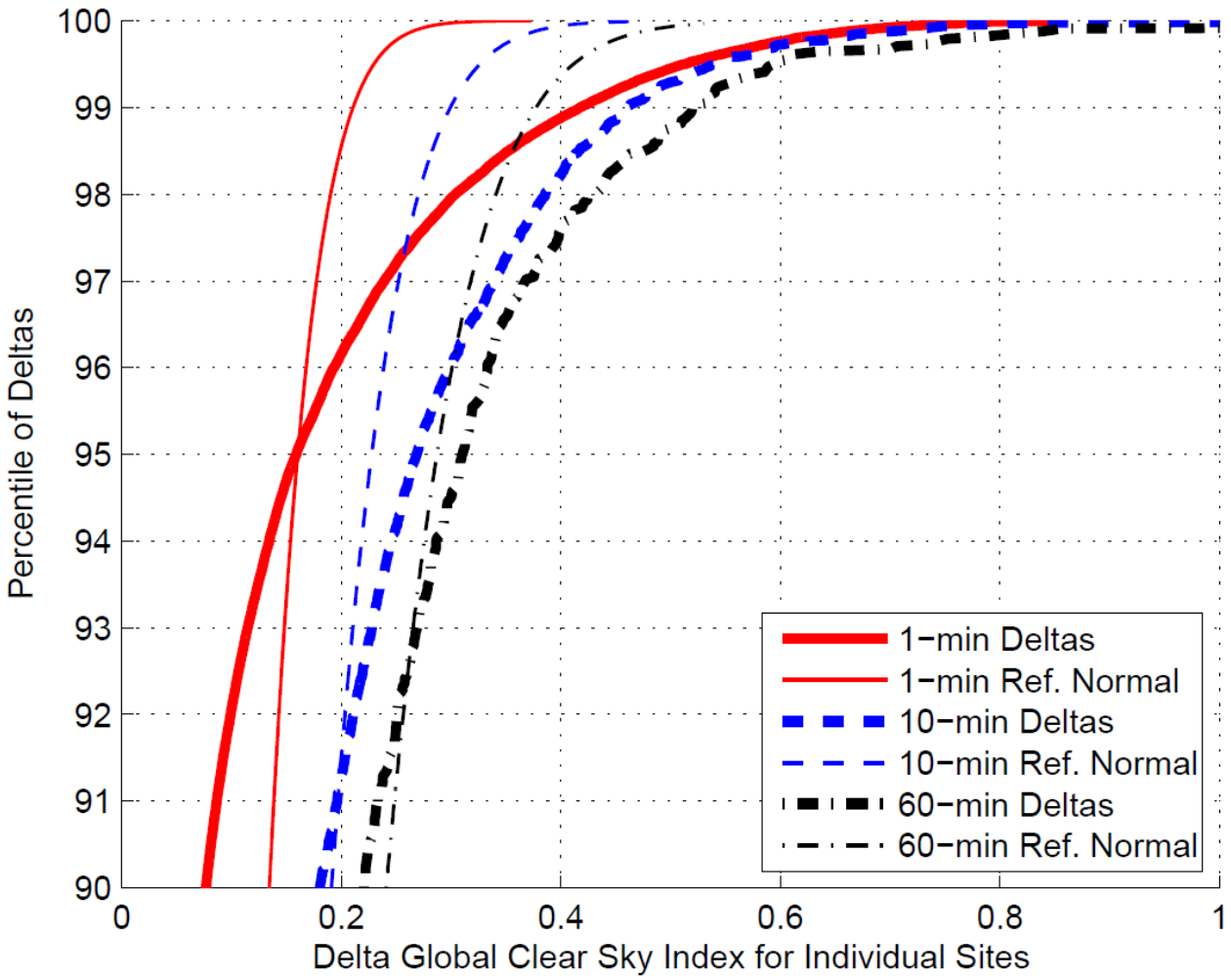




Deltas: Step change from one averaging interval to the next

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.

Integration Studies Need to Consider *Aggregate* Variability and Uncertainty of Solar

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

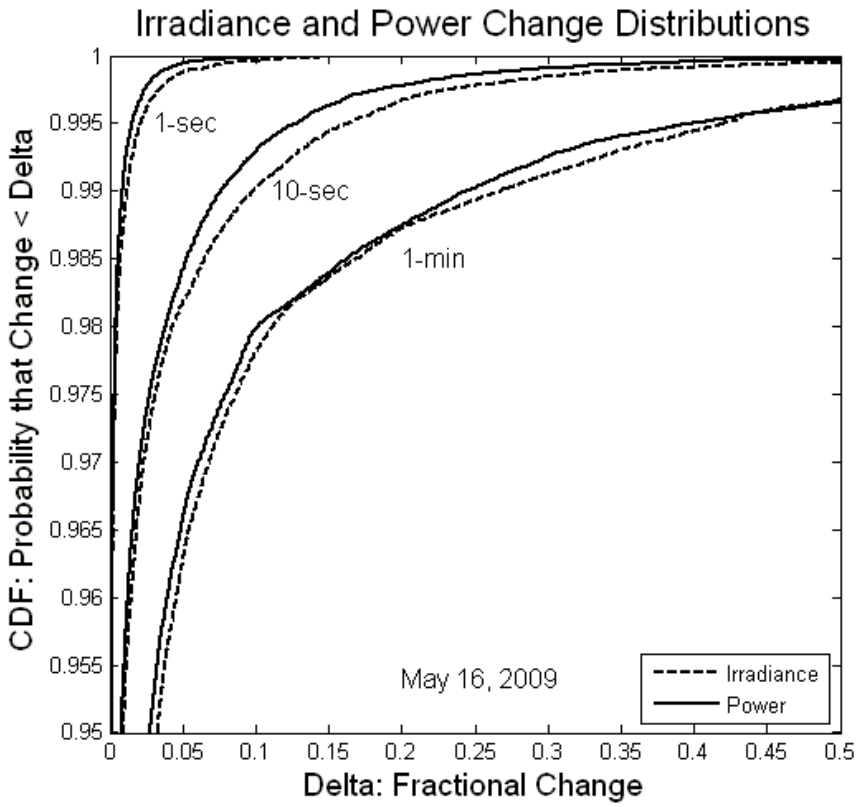
- NERC stated that "PV installations can change output by +/- 70% in a time frame of two to ten minutes, many times per day."
- Numerous academic studies between 1980 – 1996 suggested potential limits to increasing PV penetration due to rapid fluctuations in PV output

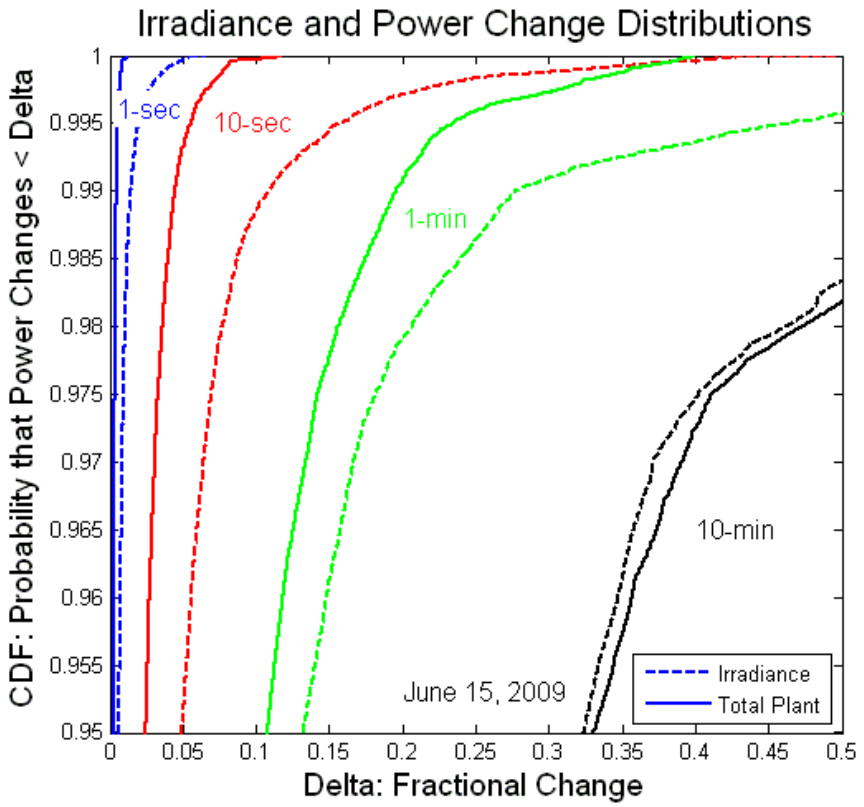
Many previous studies did not adequately consider the benefits of geographic diversity in project sites - studies need to consider the impact of geographic diversity in smoothing the aggregate output of several PV plants

Short-term variability and uncertainty of solar is reduced by geographic smoothing:

- Within individual plants
- Between plants in the same cities
- Between plants within the same balancing authority

Smoothing Occurs Within PV plants

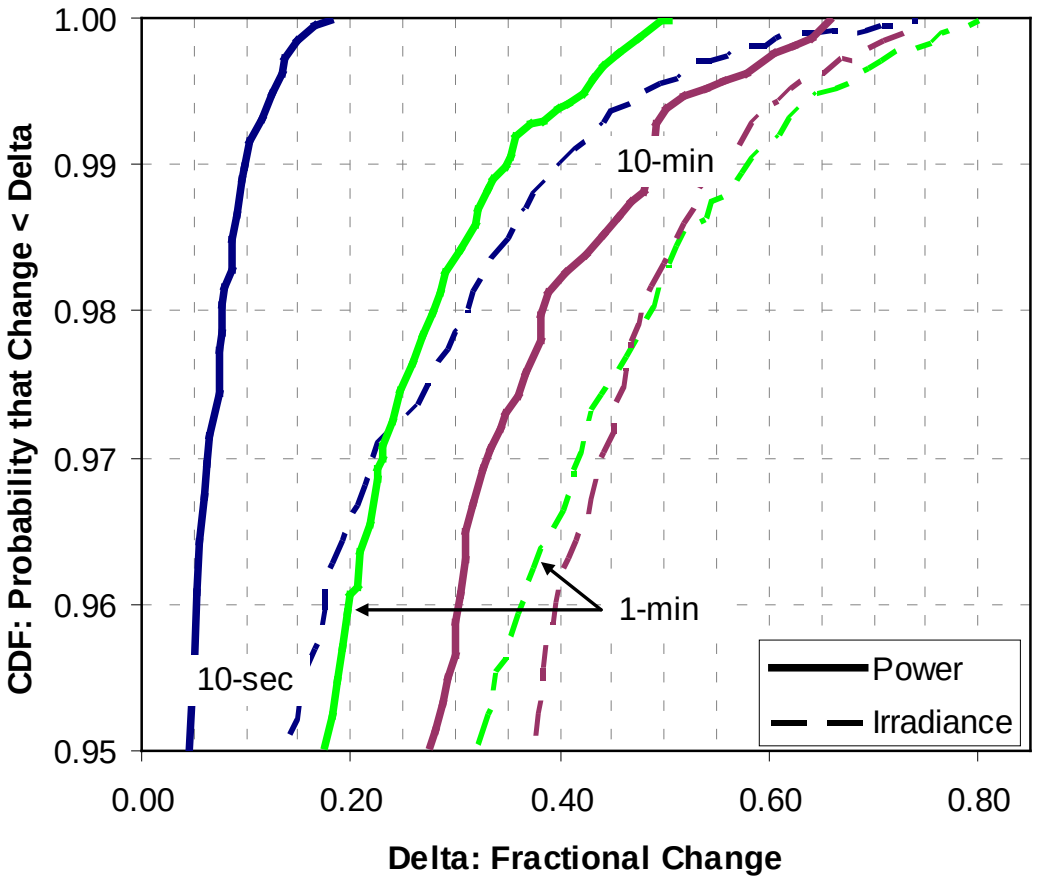




Cumulative distributions of changes in irradiance and PV power during a single day from a 30-kW PV system (left) and a multi-MW PV system (right). Variability observed in single point measurements (irradiance) is reduced in PV plant output (power/ total plant)

Source: Joshua Stein, Sandia National Laboratories, adapted from presentation at the 2009 PV Variability Workshop

Smoothing Occurs Within PV Plants

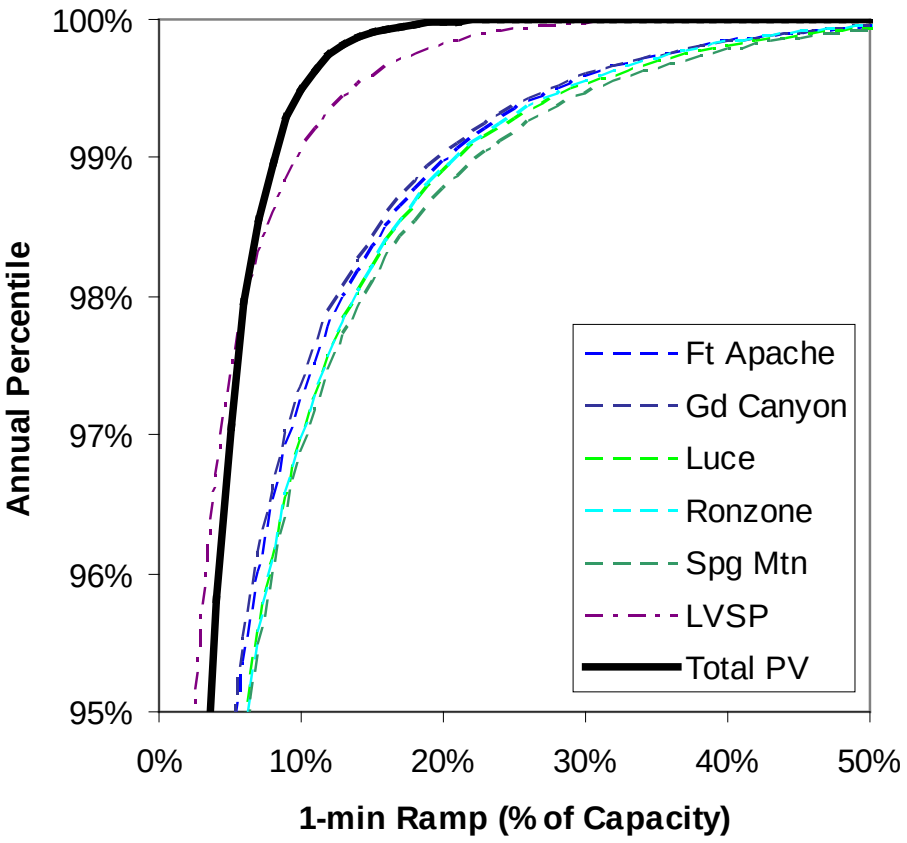


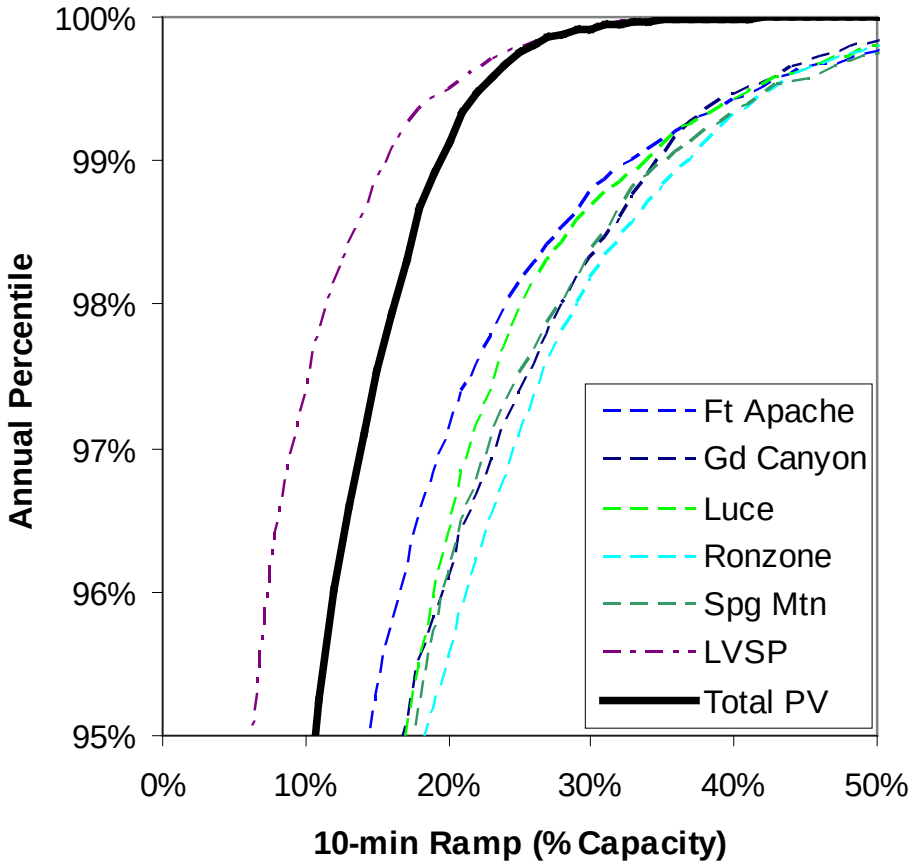
Cumulative distributions of changes in irradiance and PV power during a highly variable day for a 13.2-MW system

Time Scale	Maximum Change in Insolation	Maximum Change in PV Plant Output
10-sec	75%	20%
1-min	80%	50%
10-min	75%	65%

Source: Carl Lenox, SunPower Corporation, adapted from presentation at 2009 PV Variability Workshop

Smoothing Occurs Between Separate PV Plants in the Same Urban Region

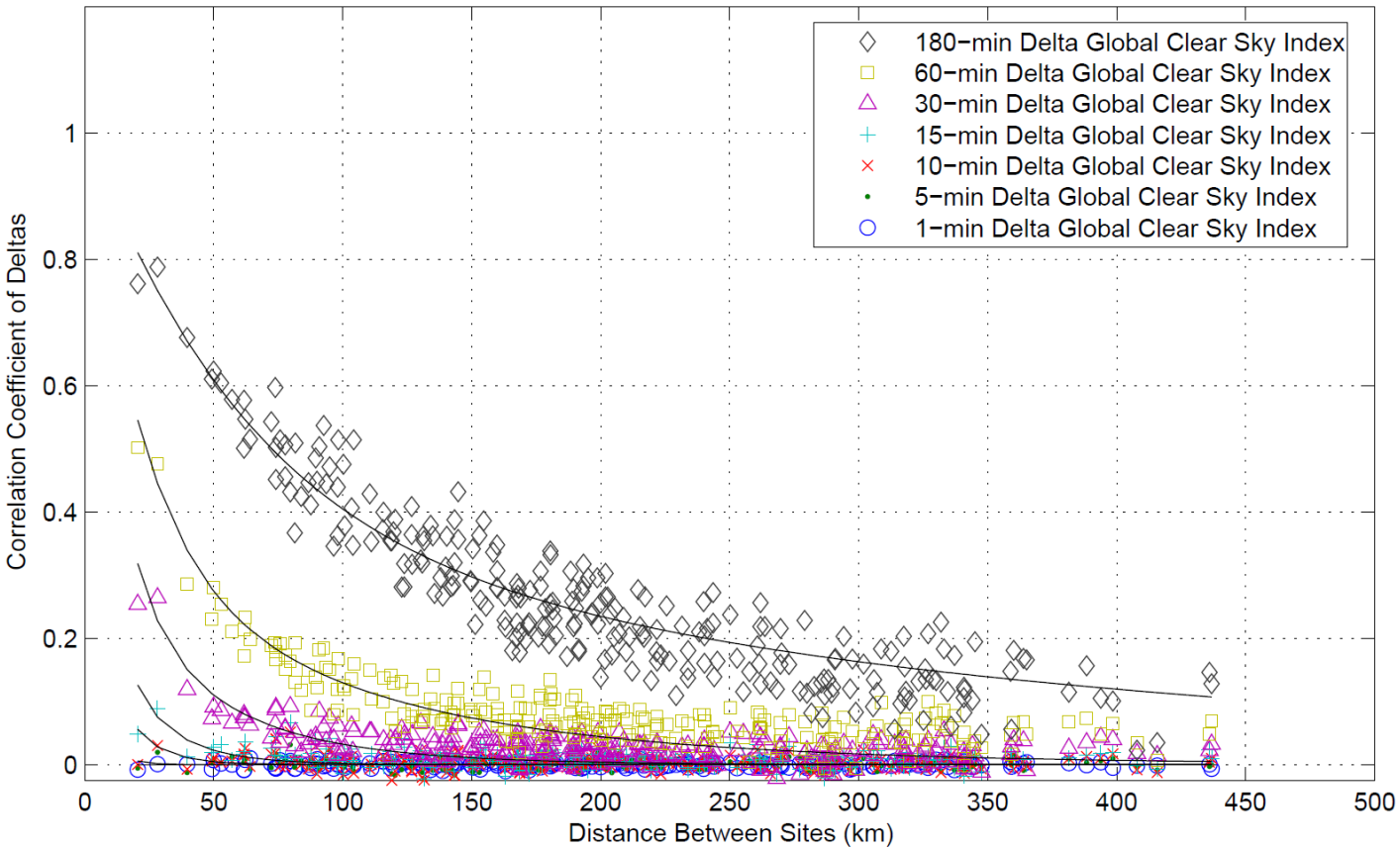




Aggregating the output of six individual PV plants within a ~200 square kilometer area in Las Vegas decreases relative variability for both 1-min and 10-min ramps

Source: Yih-huei Wan, NREL, adapted from presentation at the 2009 PV Variability Workshop

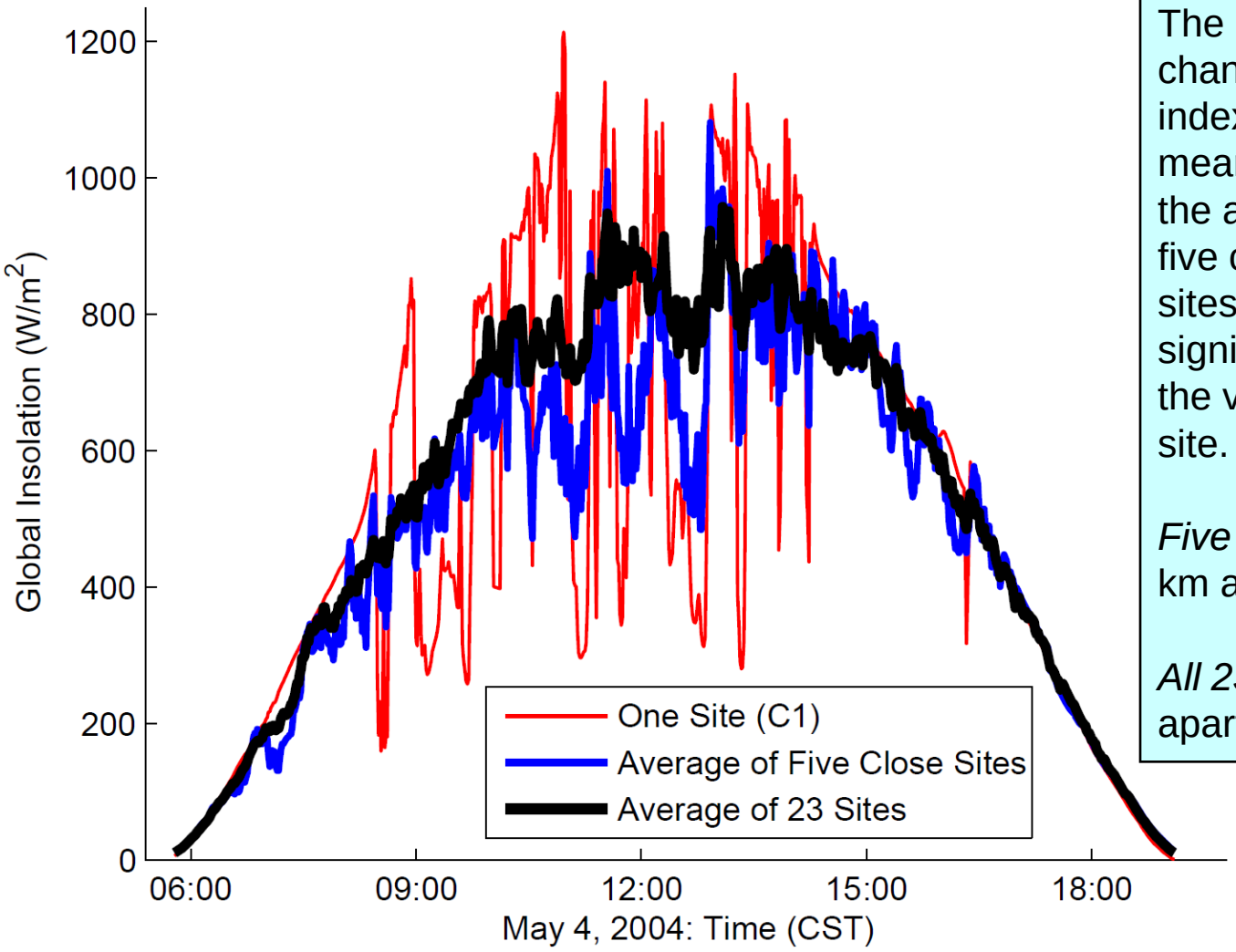
Short Time Scale Changes in Insolation Are Uncorrelated Between Sites



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

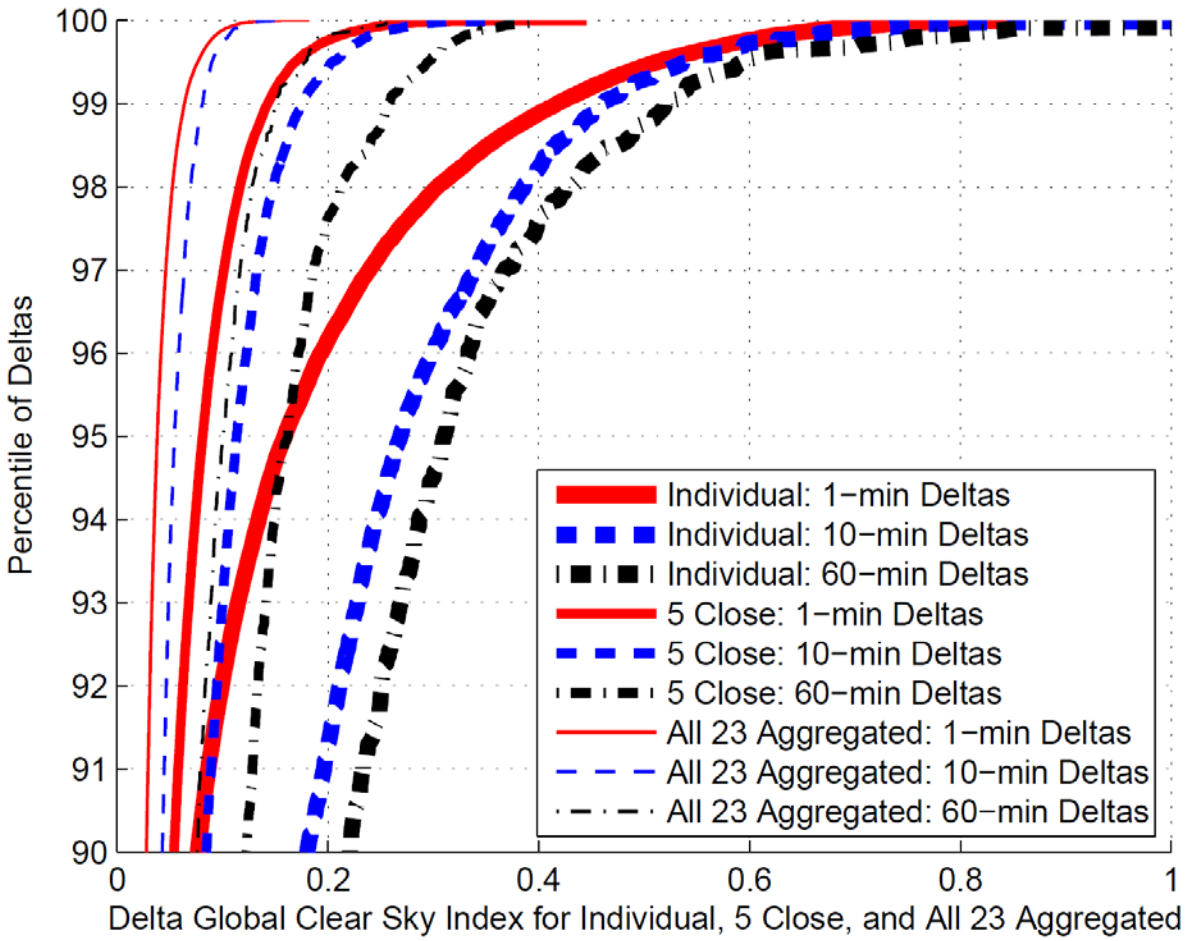


The lack of correlation in changes in the clear sky index over short time scales means that the variability of the aggregated data from the five closest sites and all 23 sites in the SGP network is significantly smoother than the variability of an individual site.

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

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

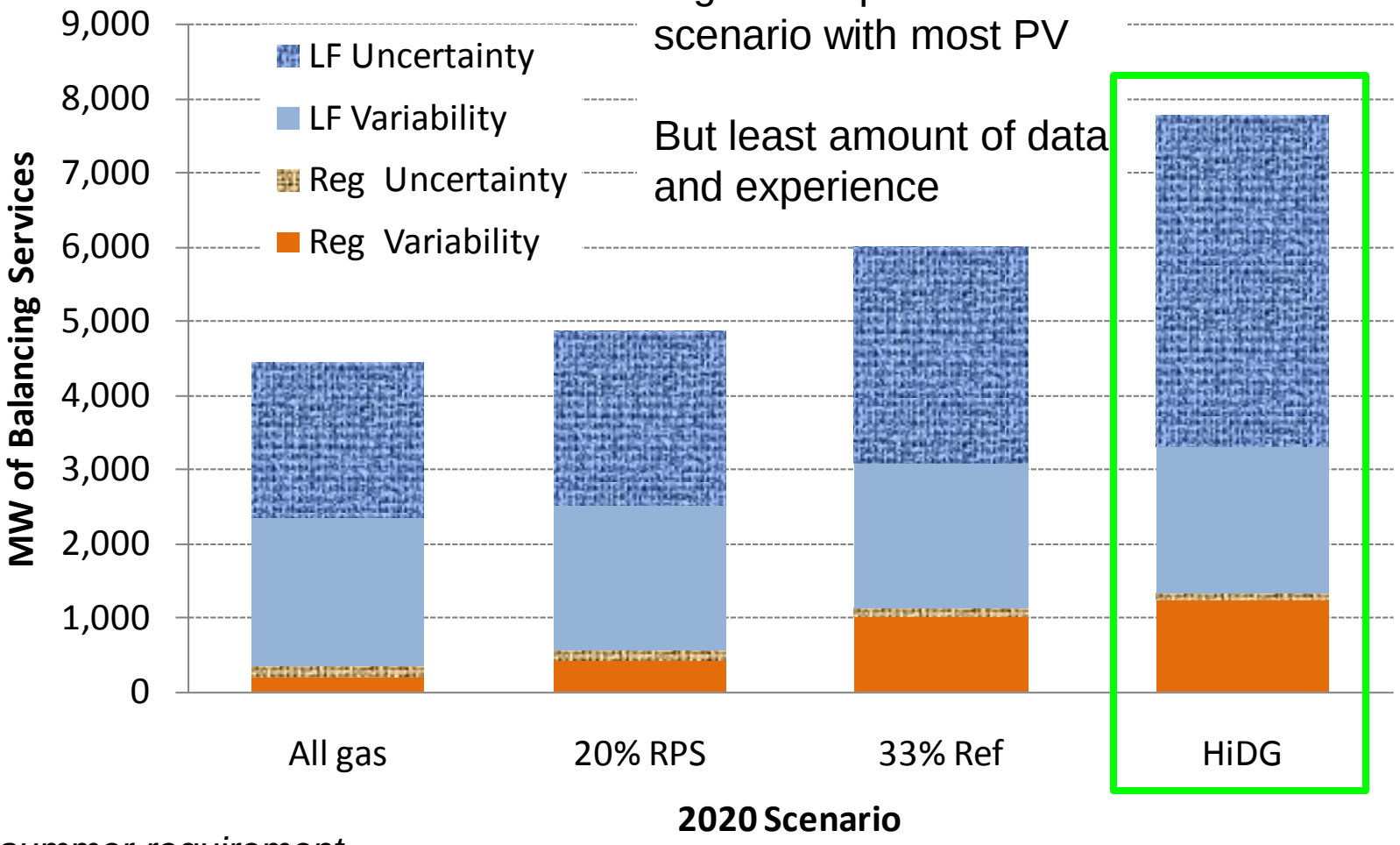
Cost estimates are developed using simple approximations and are only meant to illustrate relative changes in cost

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

CAISO 33% RPS Preliminary Analysis

Highest requirements in scenario with most PV

But least amount of data and experience



Maximum summer requirement with improved forecasting

Source: CAISO presentation to CPUC Aug 24. 2010

Future Research

- **Data and models to understand aggregate variability and uncertainty**
  - Regional differences in variability and correlation with distance between sites
  - Better models of “within-plant” smoothing
    - Need data from multiple regions of the U.S.
    - 1-min (or shorter) time-synchronized insolation or PV production data from multiple sites in regions with potential for high PV penetrations
- **Is it valuable to increase distance between solar sites to get more diversity?**
  - Depends on where solar would otherwise be deployed
  - Benefits of spreading sites out more should be compared to costs:
    - Lower solar resource quality?
    - Forgone economies of scale?
    - Additional transmission capacity and losses?

For more information...

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