

The SunPower logo is displayed in white text on a black background. To the right of the logo is a graphic of a solar panel, consisting of a grid of dark grey rectangular cells with a lighter grey border, set against a dark grey background. A vertical yellow bar is located on the far right edge of the panel graphic.

SUNPOWER™

Variability In A Large-Scale PV Installation

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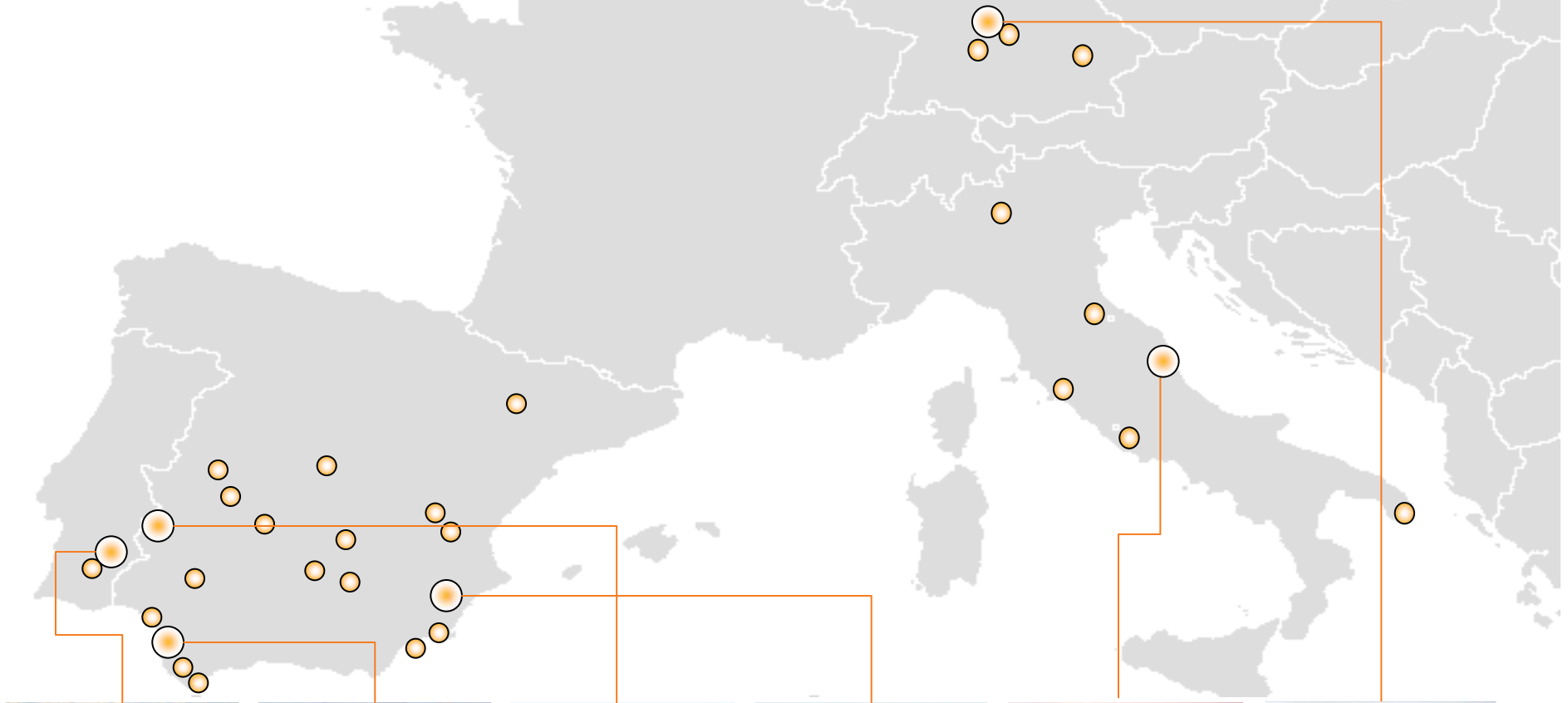
October 7, 2009



Established and Proven Technology Innovator

- Incorporated in 1985
- Publicly traded company: NASDAQ
- 4,000 employees, 100 % solar
- 25 years of R&D, 85 patents
- Manufacturing U.S., Philippines, Malaysia
- Diversified portfolio: residential, commercial, power plant & utility
- World record cell efficiency: 23.4%
- 500 systems over 4 continents
- Over 400 MW installed worldwide

Over 200 MW of power plants installed in Europe



Serpa, Portugal
11 MW



Isla Mayor, Spain
8 MW



Olivenza, Spain
18 MW



Jumilla, Spain
23 MW



Tolentino, Italy
7 MW

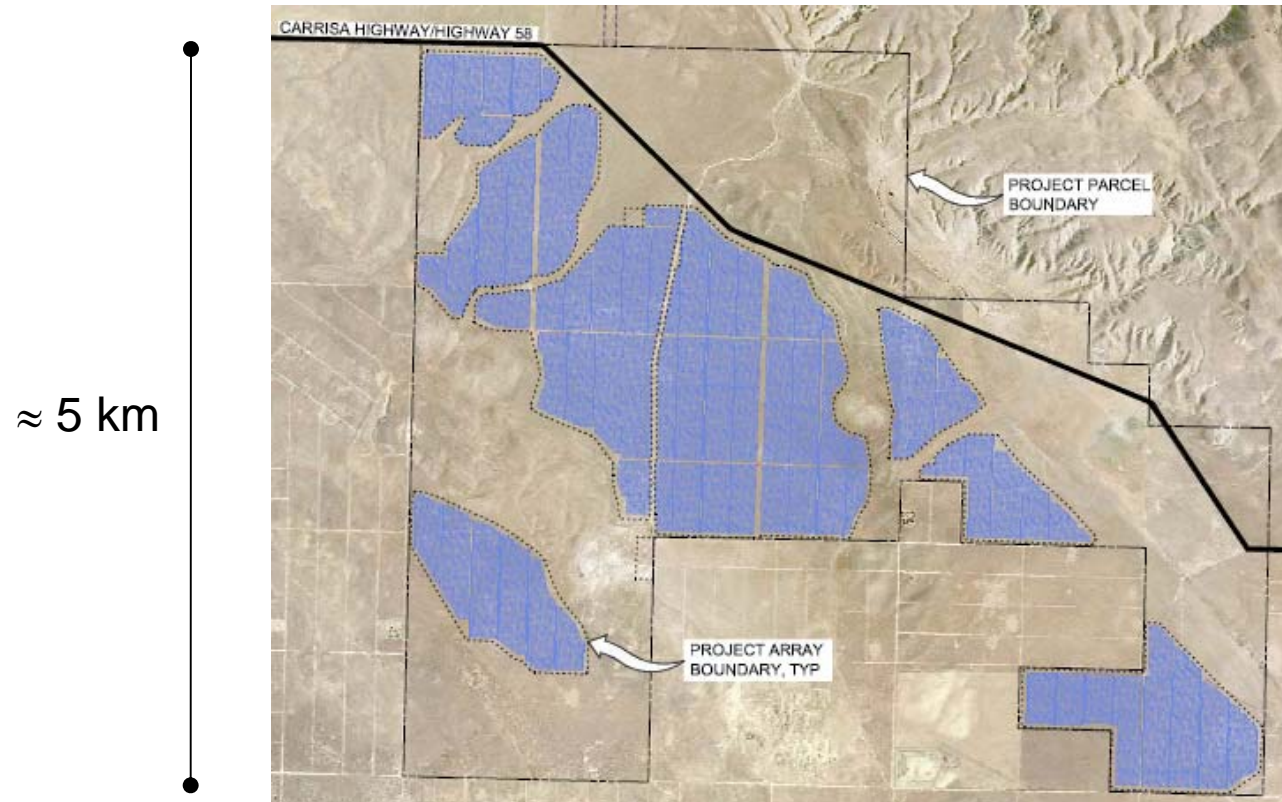


Muehlhausen, Germany, 6 MW

FPL Desoto 25 MW SunPower T0 Tracker



SPWR's California Valley Solar Ranch – 210 MW



Preliminary Plant Layout *

* 2010 Projected Construction Start

Today's Presentation

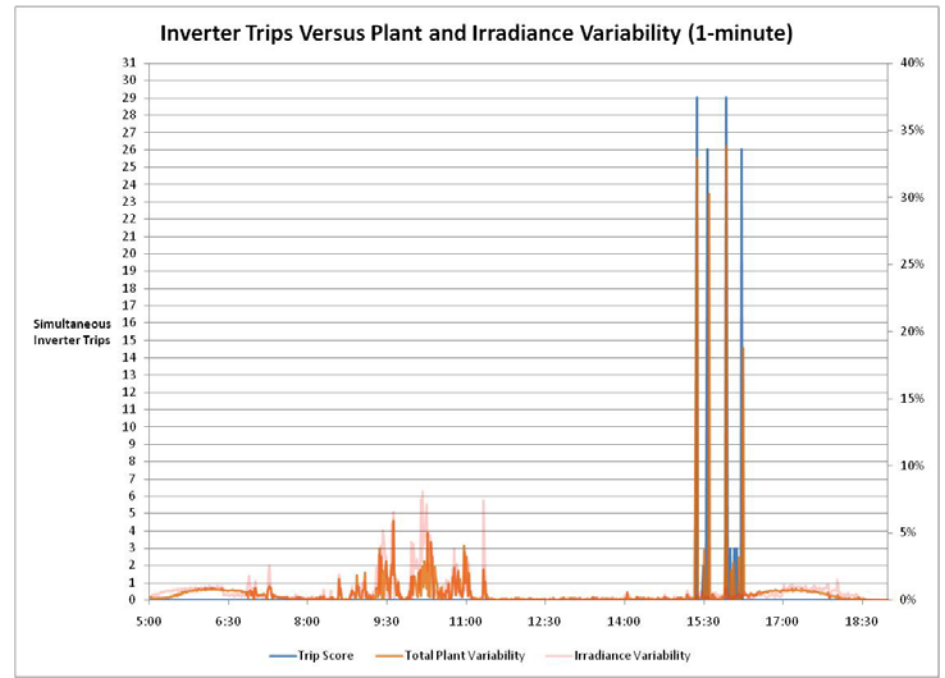
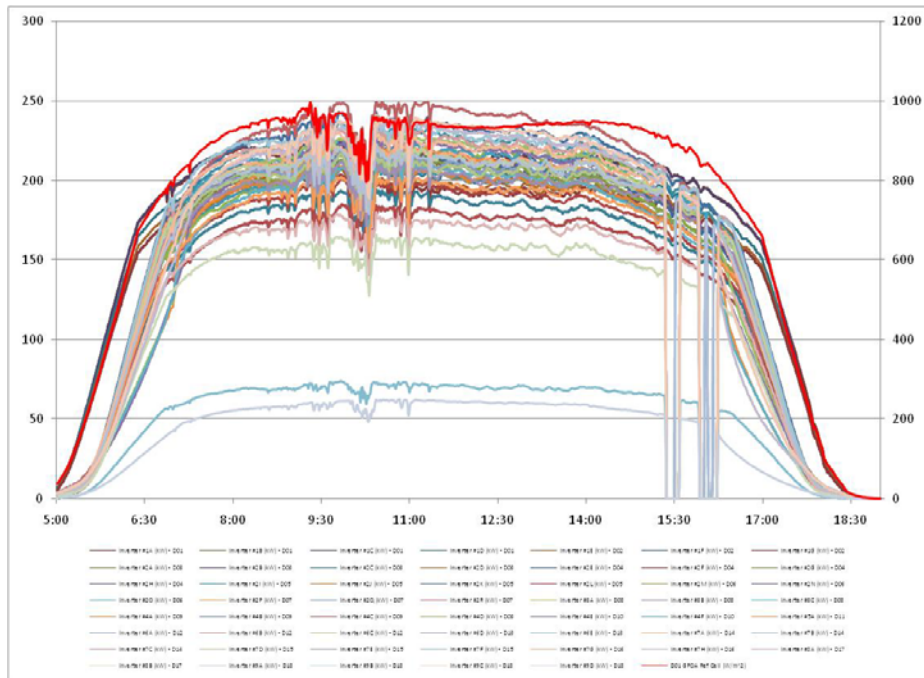
- Based on 1-second resolution data from ~13 MW (AC) site in Nevada
- Data is at the inverter level (typically 250 kW), time synchronized
- Dates from 5/11 – 9/7/2009 – 120 days
- We consider these results to be preliminary – more to be done!

Questions For Today

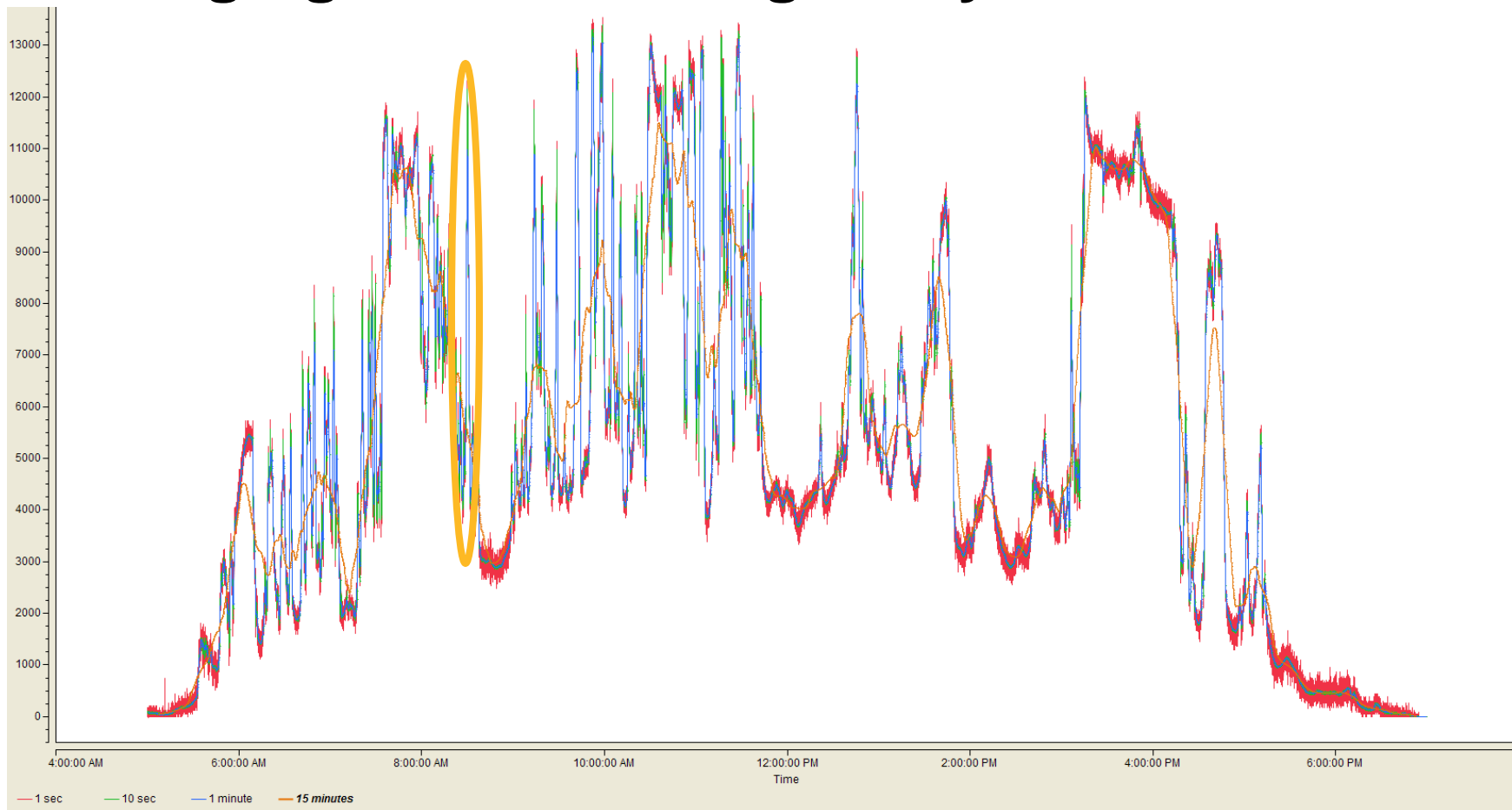
- **What are useful interval(s) for data collection?**
- **How frequently do large changes in output occur?**
- **How does variability change with scale, and over different intervals?**

An Important Note

- This site uses typical UL Listed commercial inverters, IEEE 1547 compliant
- Multiple, simultaneous inverter trips cause the largest short-duration changes in output (1-sec and 10-sec).
- The signature of these trips indicate they are most likely due to anti-islanding – operating as designed.
- Consistent LVRT requirements and implementation should significantly mitigate this issue.
- This cause of variability is excluded from most of the analysis – noted where included.



Averaging Interval – Single Day

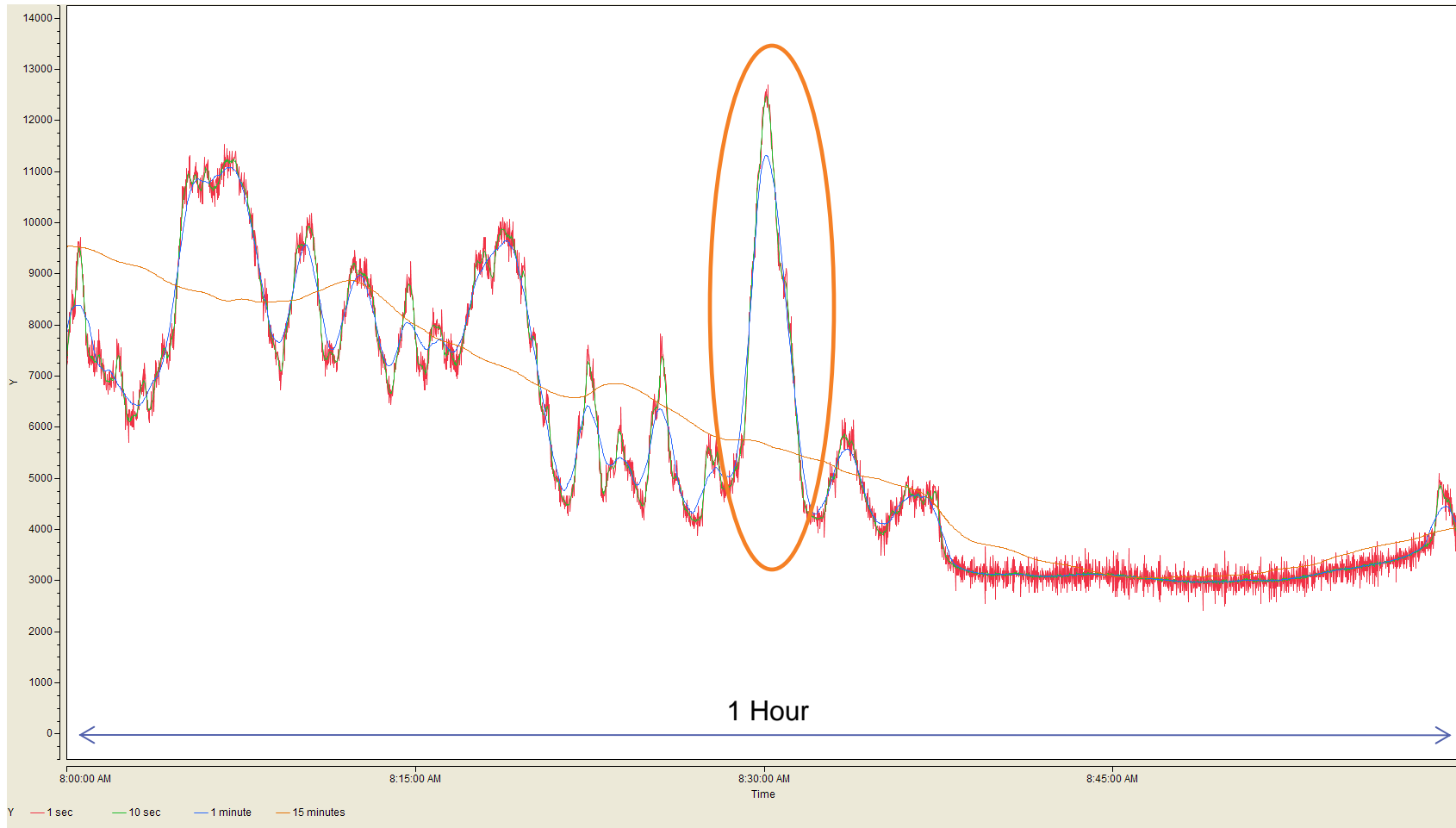


Day with highest 10-sec maximum variability

Red = 1 sec, Green = 10 sec, Blue = 1 minute, Orange = 15 min

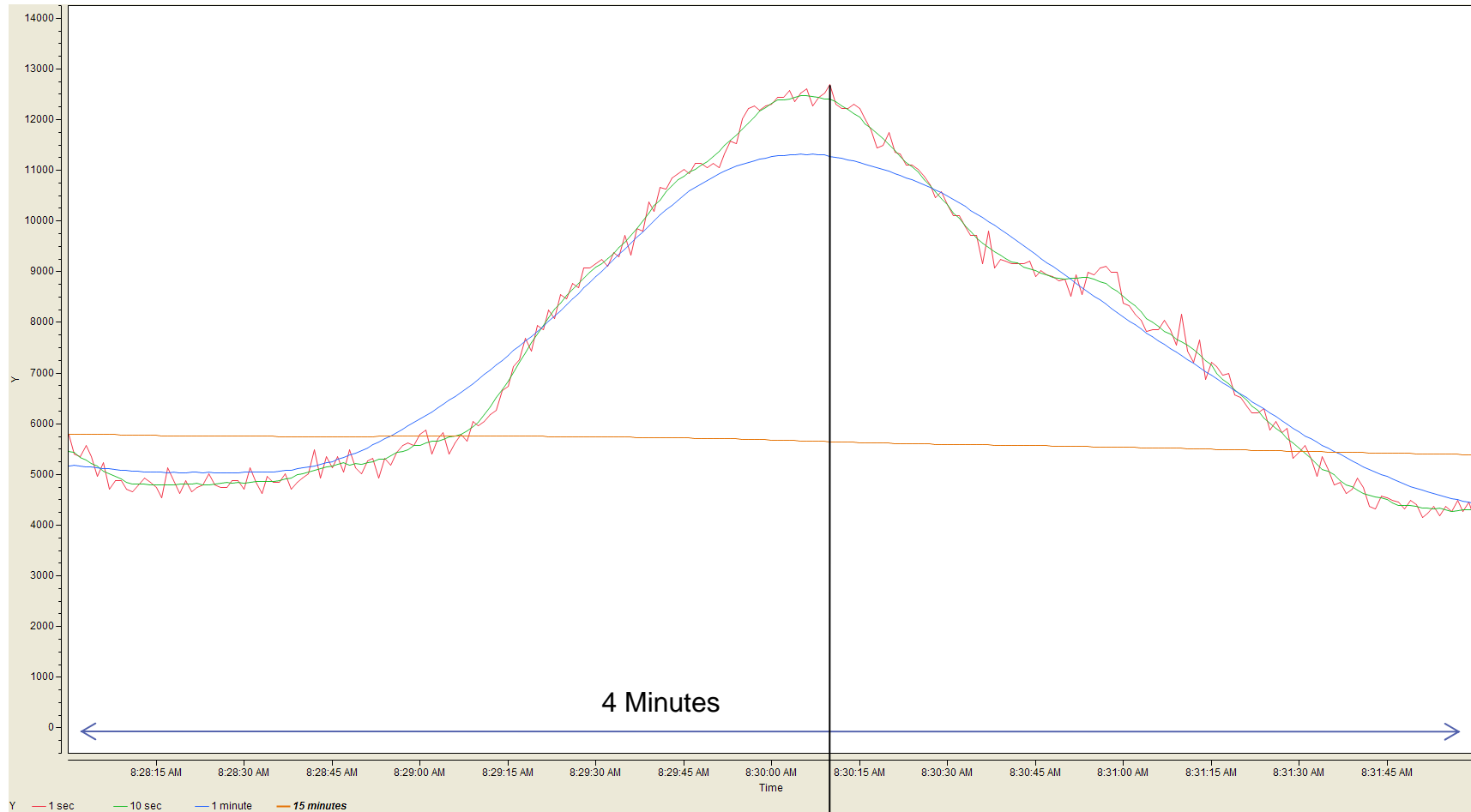
Except for 1 sec data, all are centered moving averages.

Averaging Interval – Single Day



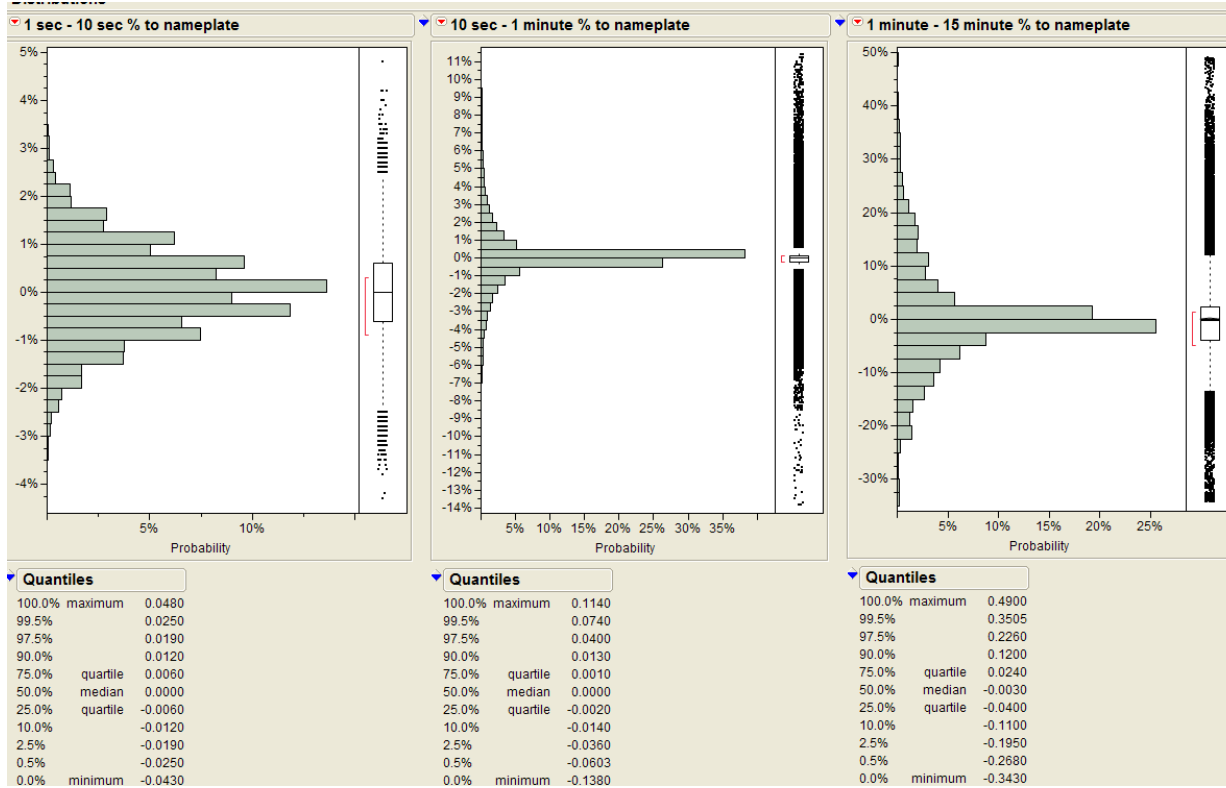
Noise in 1-second data is a data acquisition artifact (pulse meter)

Averaging Interval – Single Day



- 1 minute data captures 80% of deviation from the long term trend even in this very extreme event.
- 10 second data captures 97% of deviation.
- 1 second data deviation from 10-second trend is at least partially pulse count noise.

Averaging Interval – Highest Variability Day



Distributions show the difference between the shorter interval data, and the longer interval trend.

| Interval to Trend | 95% within | All |
|-------------------|------------|--------------|
| 1 sec to 10 sec | +/- 2% | +/- 5% |
| 10 sec to 1 min | +/- 4% | +11% / -14% |
| 1 min to 15 min | +/- 20% | + 50% / -34% |

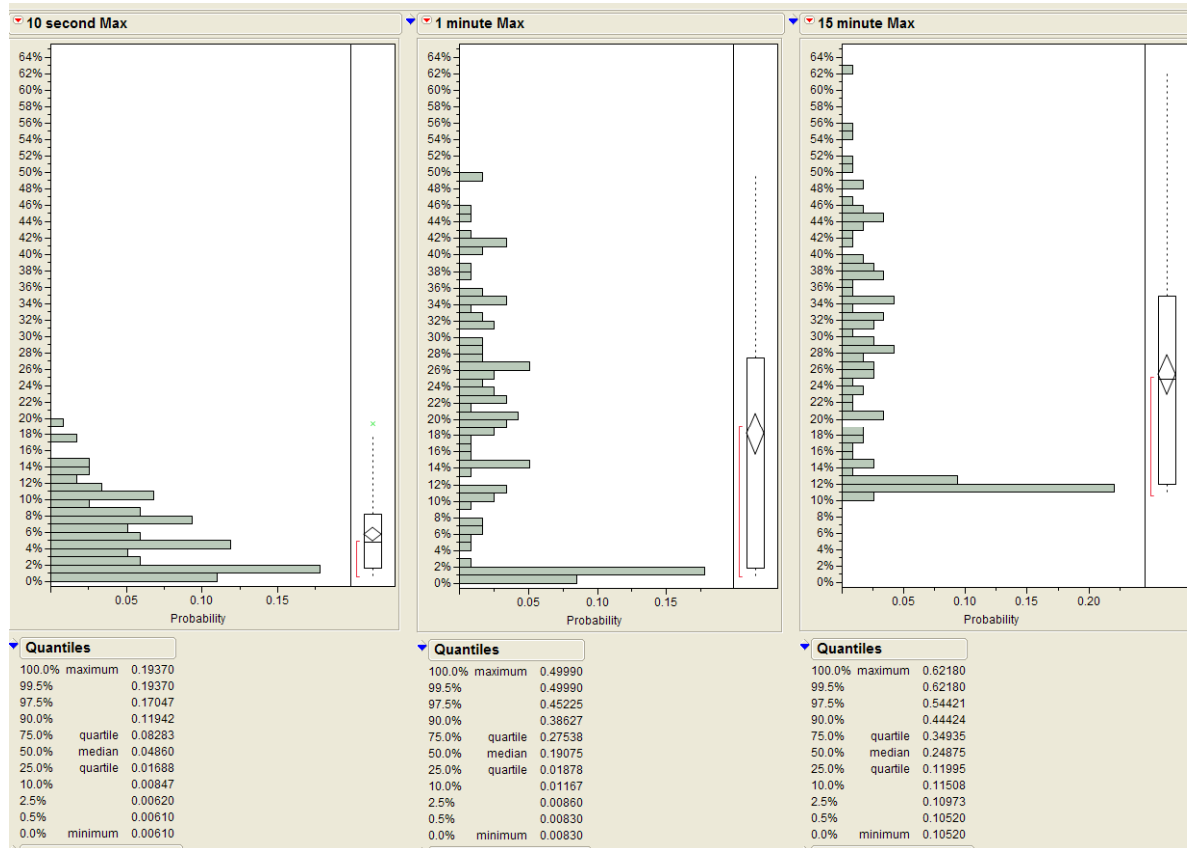
Data Intervals - Conclusion

- One second resolution data may not be required to characterize variability of 10 MW+ plants.
- One minute data is very useful for some purposes since it is much easier to handle and analyze, but it seems to underestimate variability in extreme events.
- Use of ten-second data is recommended where it is important that short-term transients are captured completely.
- Ten second data does not adequately characterize rapid changes in irradiance measured at a single point. This also likely holds for smaller PV arrays which can be approximated as a point.
- 15 minute data misses large, short interval transients.

Future Work:

- Verify relationship between 1 sec and 10 sec data at large PV site with better data acquisition.
- Extend this type of analysis to more days – not just one, extreme day.
- Data interval selection should comprehend what is relevant to system operations. In other words, do transients that last 1 second matter? 10 seconds? 1 minute?

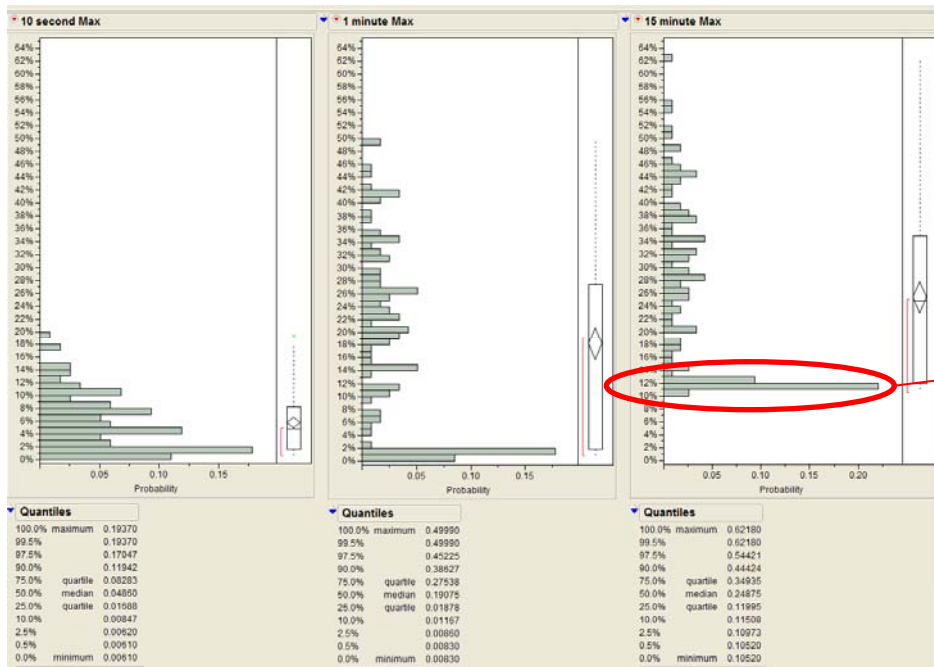
Distribution of Maximum Variability



This shows the distribution of the **largest** absolute change between periods as % of AC nameplate, on a given day, for all days analyzed.

For 10-second data, the data point for a day is the single largest change between the 4320 intervals in that day.

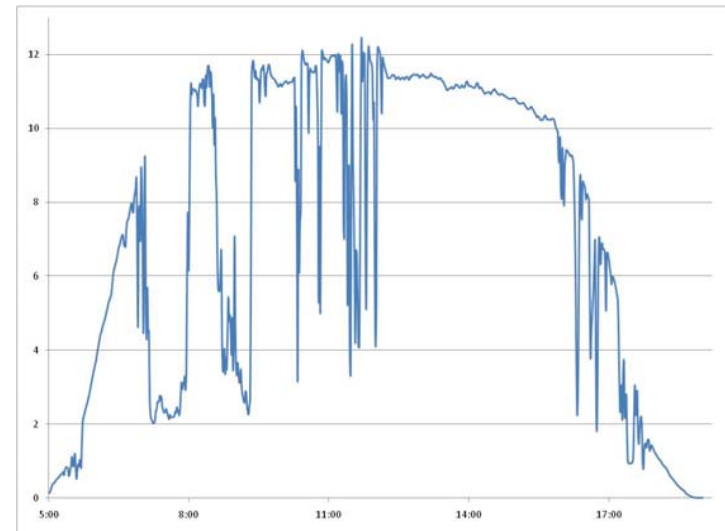
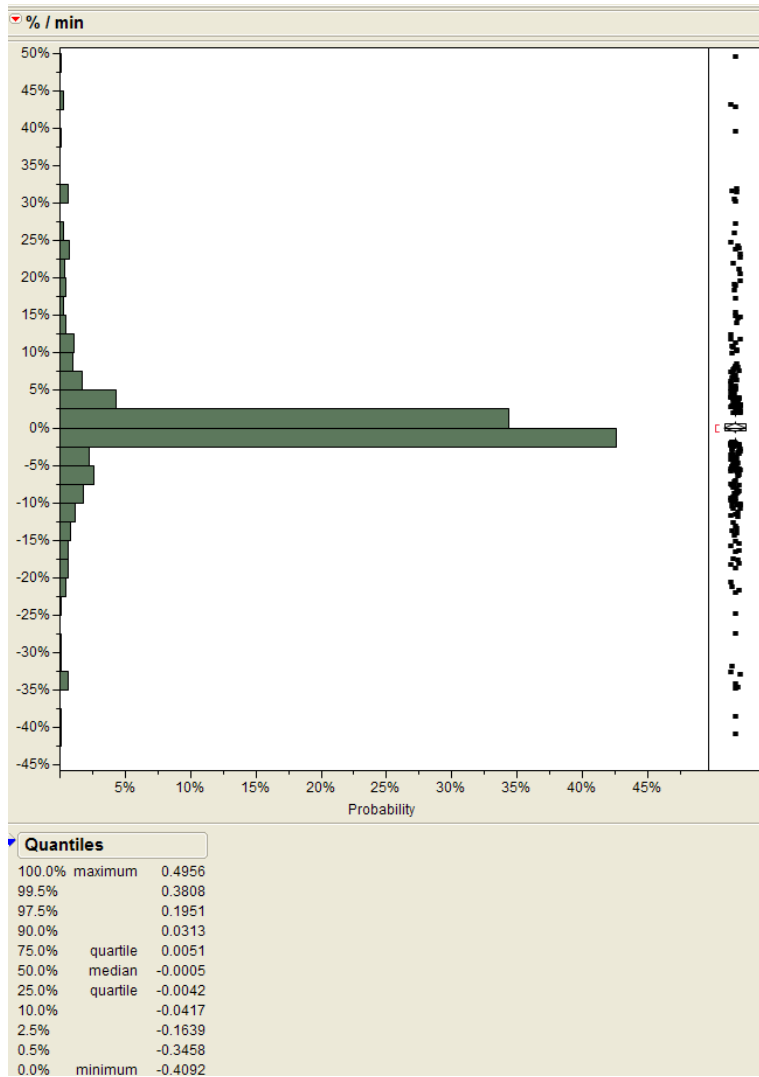
Distribution of Maximum Variability – All Days



Note floor on 15 minute data. 10-13% in 15 minutes is max change on a clear day – driven by sunrise or sunset.

| Averaging Interval | 90% of days (108 days) | 10% of days (12 days) |
|--------------------|--------------------------------|-----------------------|
| 10 second max | < 12% (1.2% / sec, sustained) | 12% - 19% |
| 1 minute max | < 39% (0.65% / sec, sustained) | 39% - 50% |
| 15 minute max | < 44% (2.9% / min, sustained) | 44% - 62% |

Distribution Within A Highly Variable Day



Day with largest 1-minute interval change

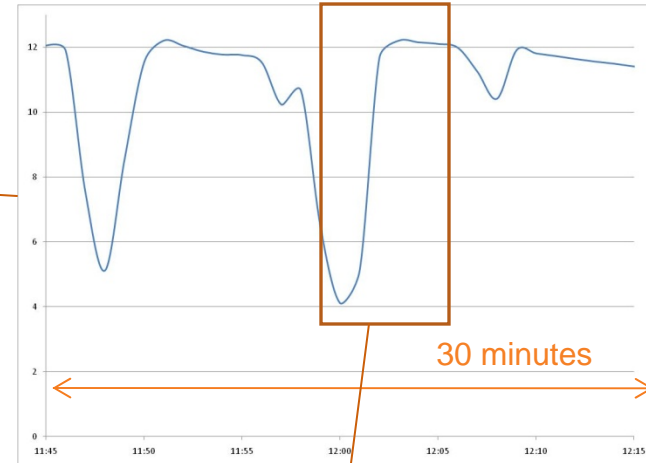
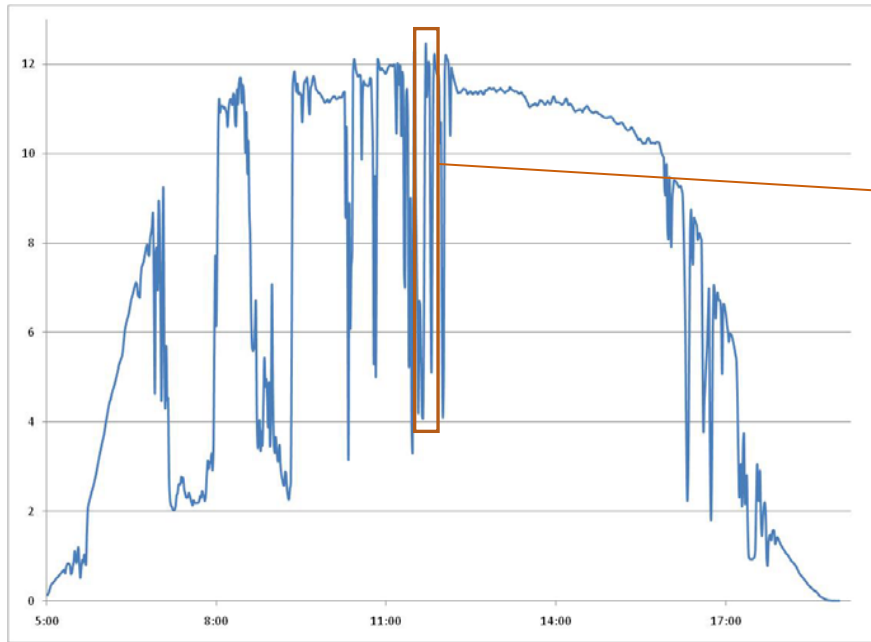
Prob. of change between 1-min intervals

80% of all intervals between -4% & +3%

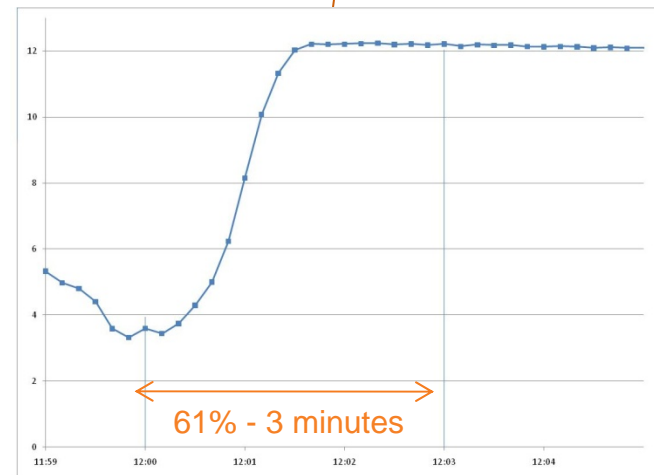
95% of all intervals between -16% & +20%

99% of all intervals between -35% & +38%

Maximum Variability Snapshot



50% / minute



Peak 1-minute change (12:01 – 12:02) of all days
(1 of 100,800 intervals)

A Few Points:

- A “spiky looking” graph can be misleading.

Even large, rapid changes occur over a minute or two, not in “a second” as has been stated.

Not readily apparent from visual inspection of a plot spanning 12 hours!

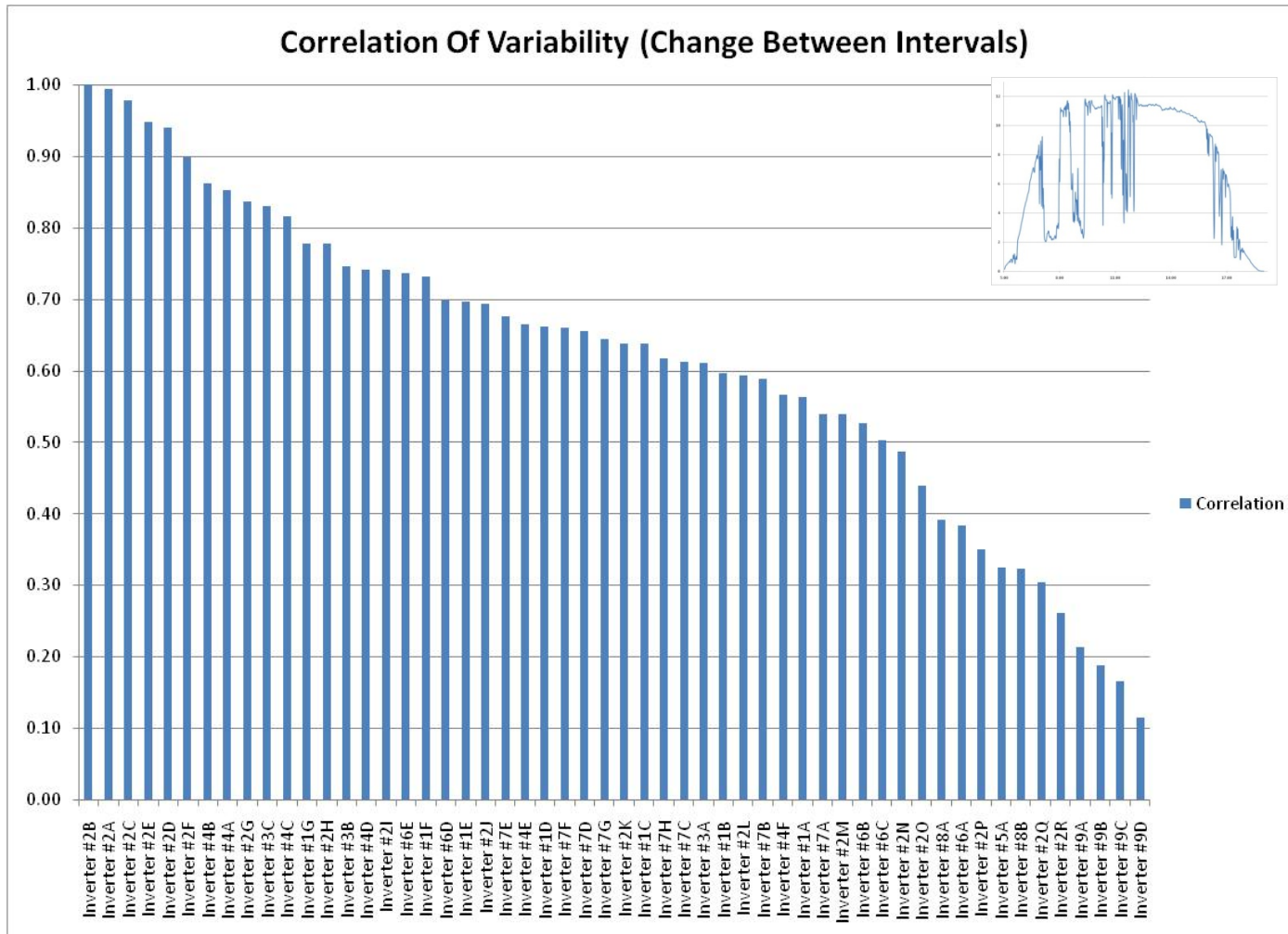
- **No operational issues:** the utility has investigated, and has not found, any operational issues related to this site.
- **This system is “high penetration”** relative to the distribution system capacity (as defined by DOE, “high penetration” PV is >30% peak on peak).

Variability Occurrence - Conclusions

- Approximately 1/3 of days are clear and cloudless during these 4 months.
- Remaining 2/3 have a wide spread of variability – long, flat tails in distribution.
- These observations may not be generalizable - obviously, results will vary for different seasons and locations.
- Reporting the maximum change between intervals can be misleading, because this is an by definition a statistical outlier – especially an issue as intervals become shorter.
- It is also misleading to report variability over one interval in the same units as another interval.

For instance, while it may be tempting to report a measured change of 10% in 10 seconds as 60% / minute, this is incorrect, because the former value is a nearly instantaneous maximum and not sustained.

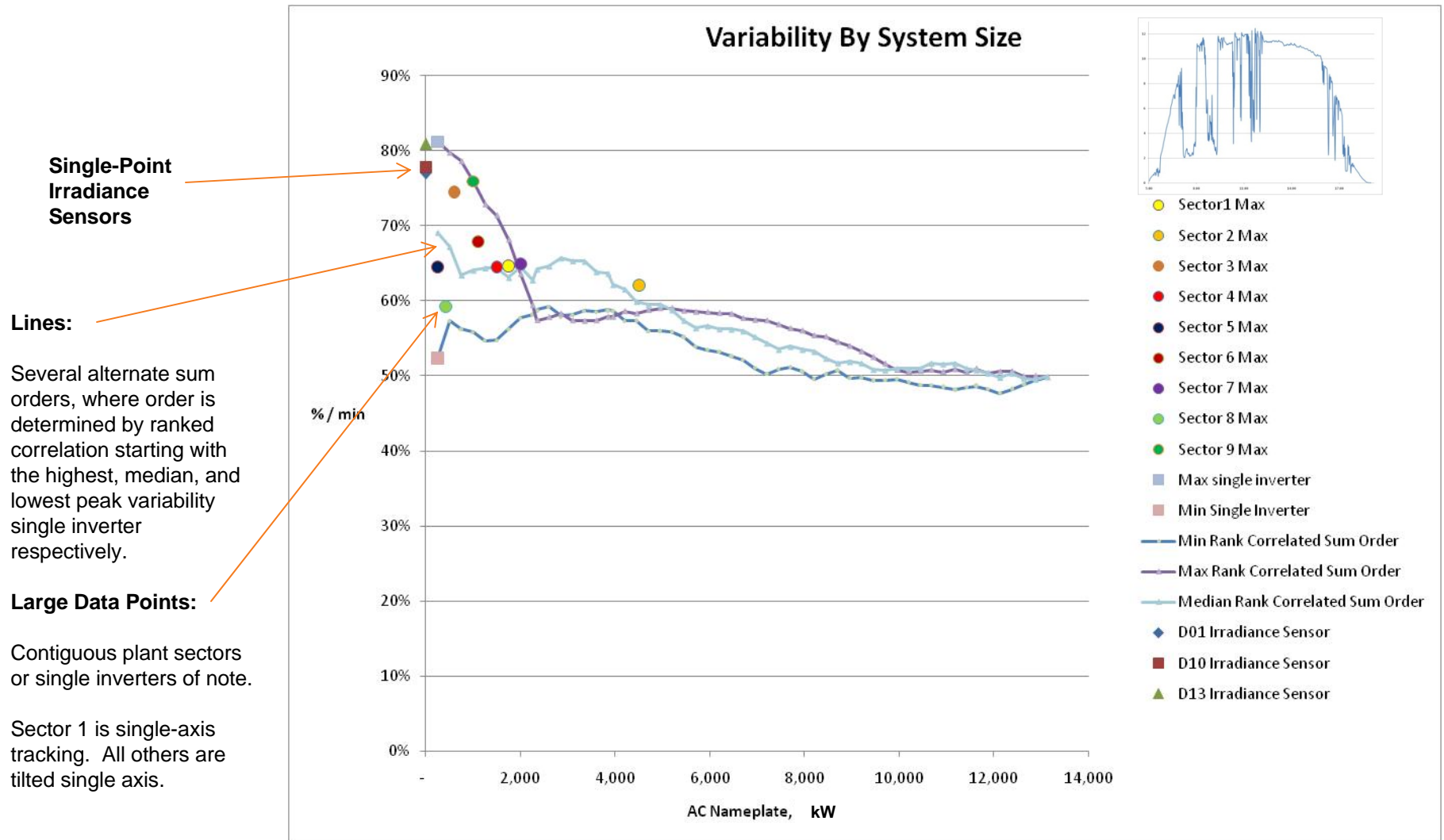
How Does Variability Scale?



Ordered Correlation of **changes** in 1-minute output across inverters
Reference is median peak variability inverter for this day

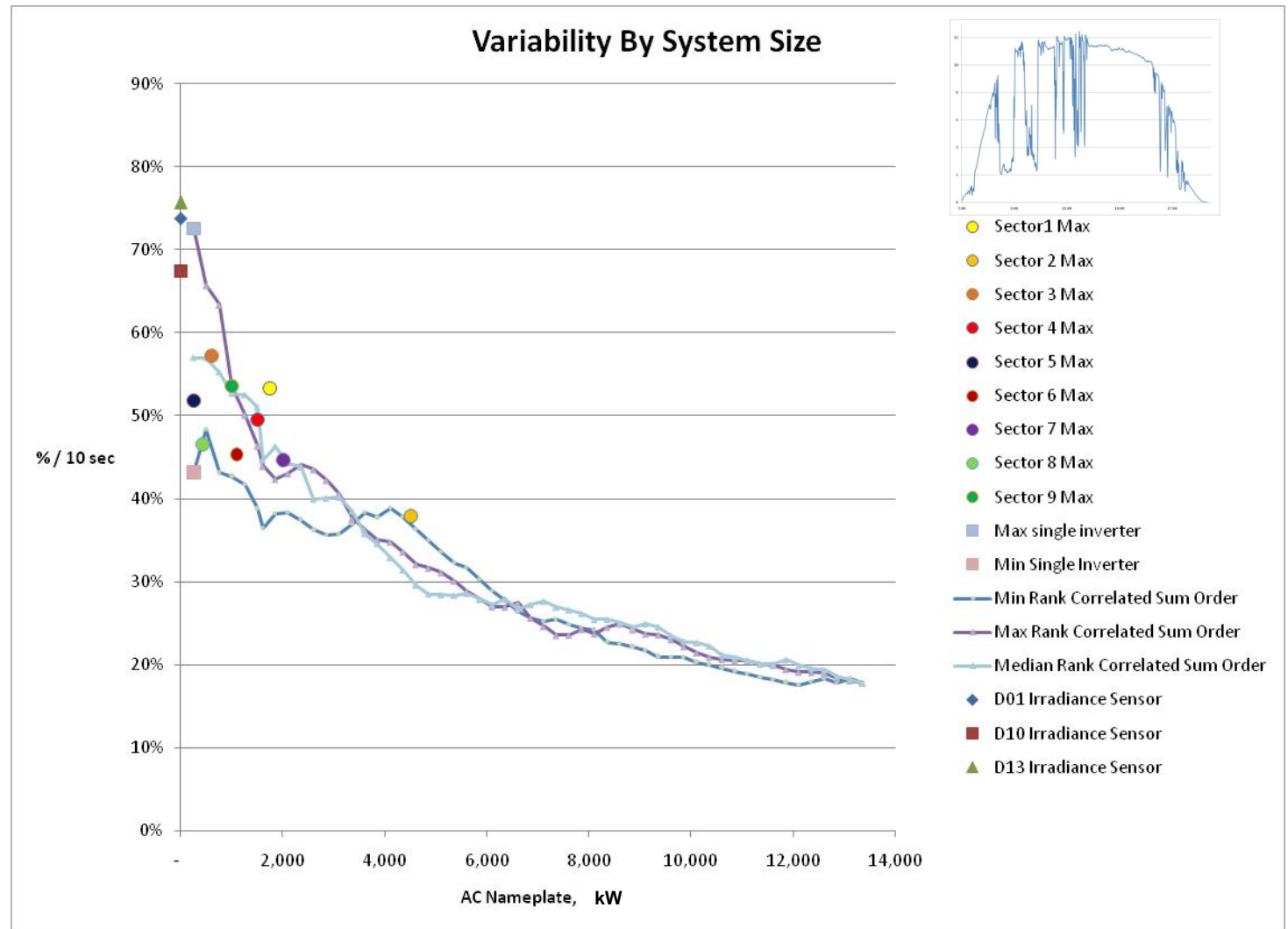
How Does Variability Scale?

Maximum 1-minute change, on the highest 1-minute variability day



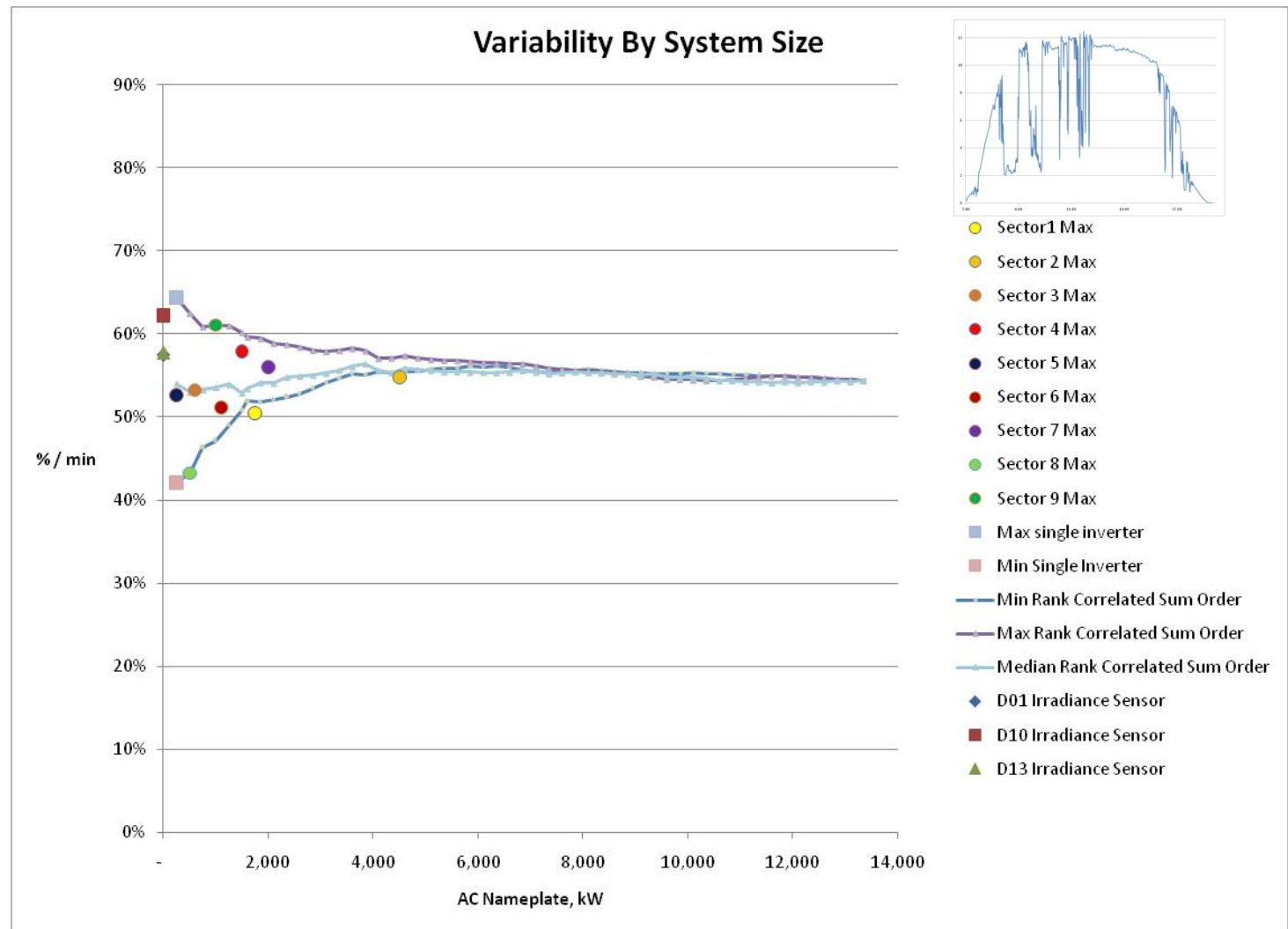
How Does Variability Scale?

Maximum 10 second change, on the highest 1-minute variability day

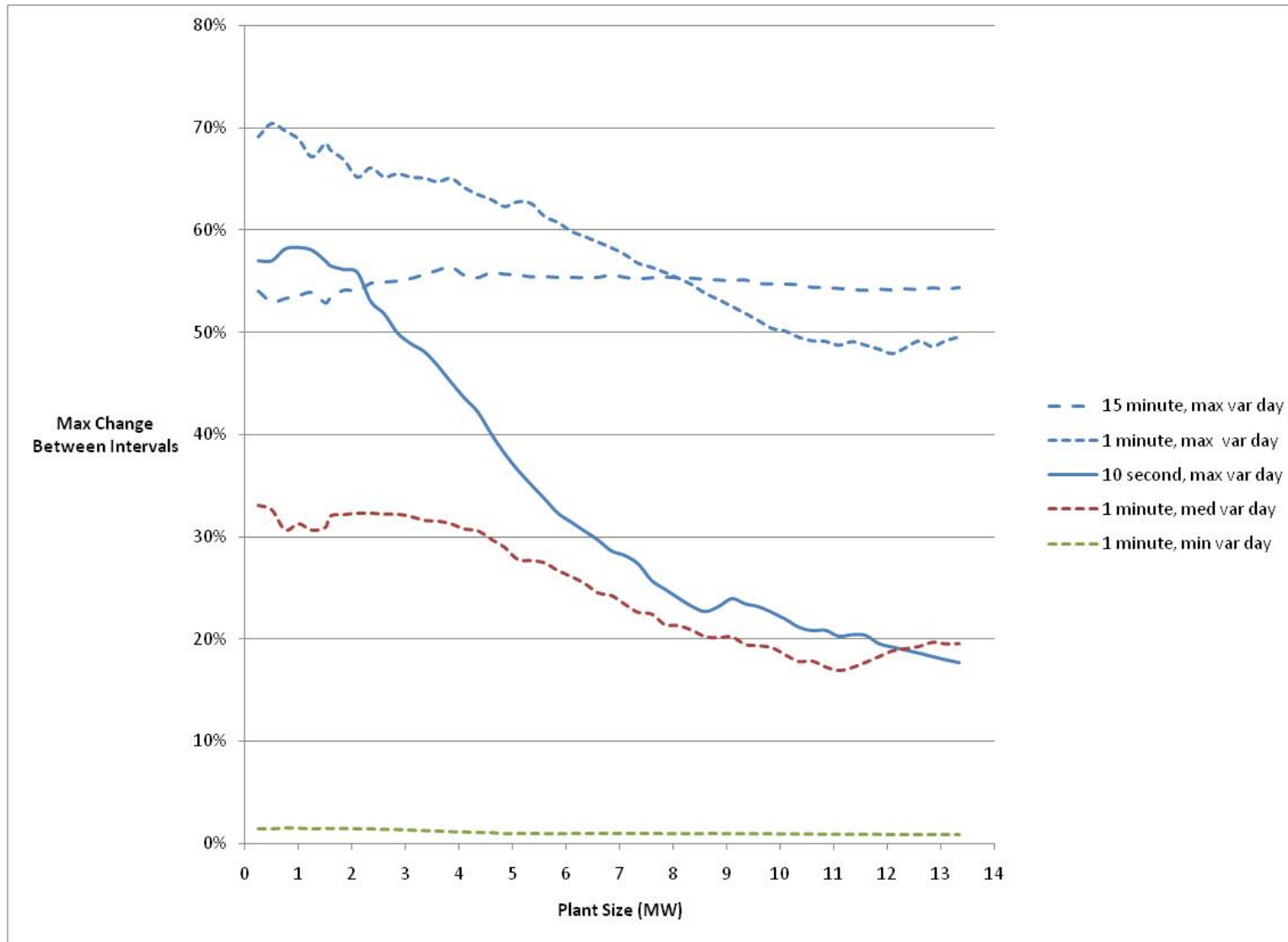


How Does Variability Scale?

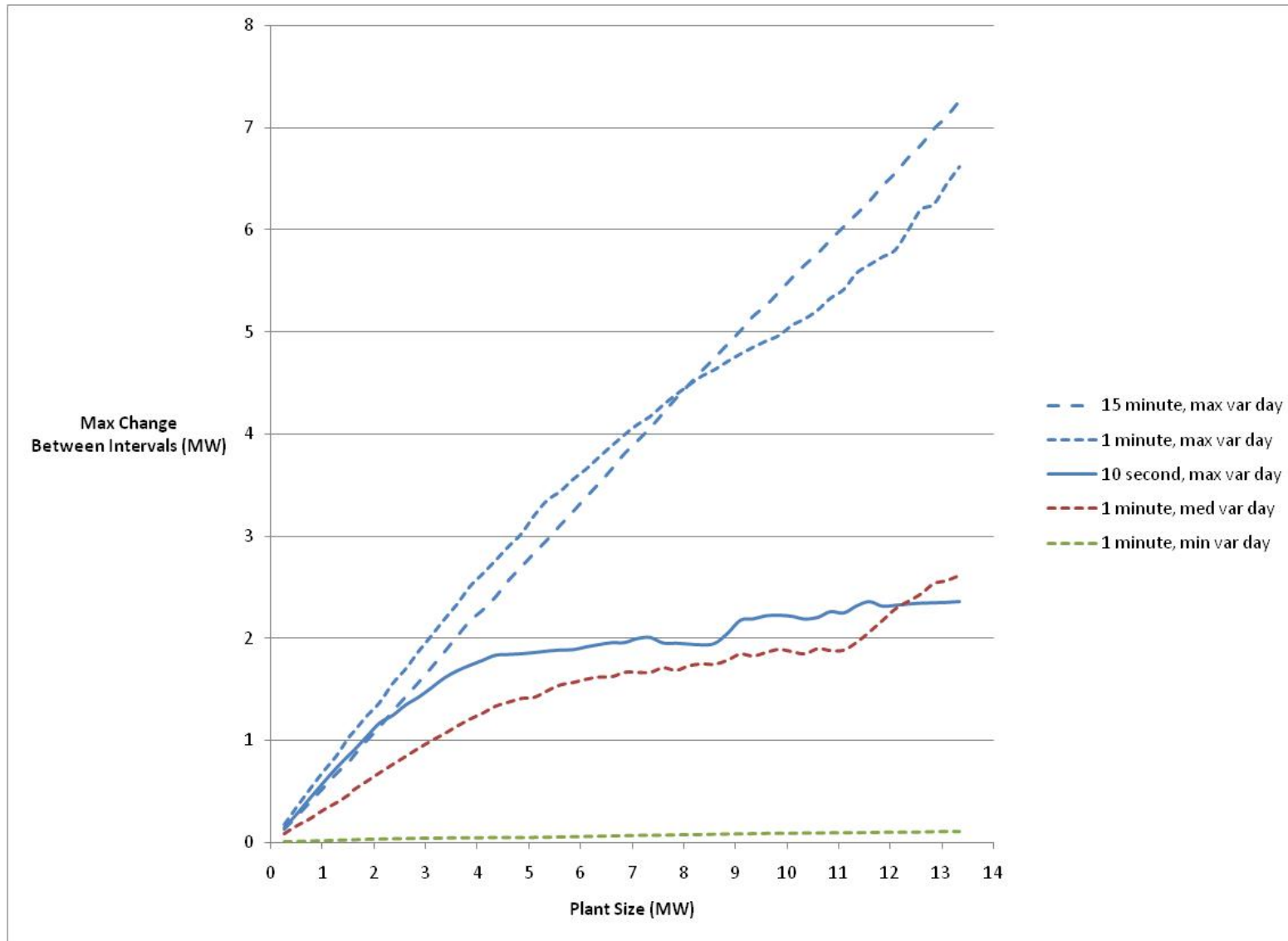
Maximum 15 minute change, on the highest 1-minute variability day



How Does Variability Scale?



How Does Variability Scale?



Variability Comparisons – Scale Matters!

Is CSP really smoother?

A few factors:

- **Thermal mass** - commonly cited
- **Scale** - CSP plant shown is 6X size of PV plant
- **Plant Operations** - CSP operators often actively control plant output to avoid transients which can damage the equipment

What is the relative contribution of these factors?

Similar questions pertain to comparisons with wind generation.

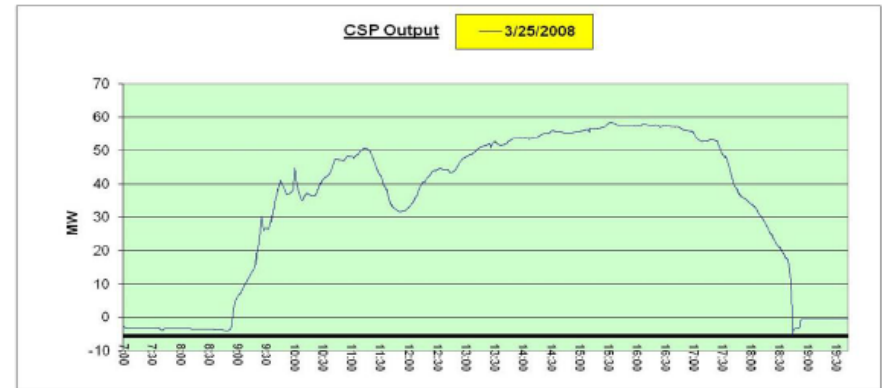


Figure 2.10: Parabolic trough CSP plant on a partly-cloudy day (Sampling time of 10 sec.)

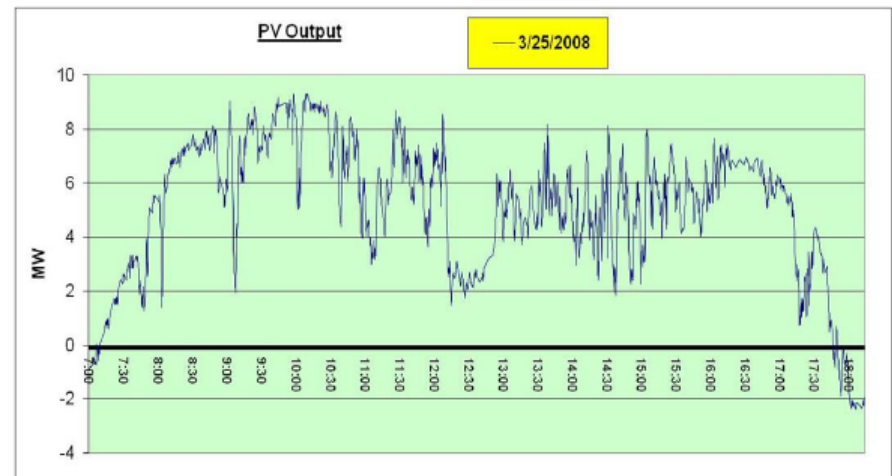


Figure 2.12: PV Plant output on a partly-cloudy day (Sampling time 10 seconds)

Figures from NERC Special Report: Accommodating High Levels of Variable Generation

Variability Scale – Conclusions*

- **Mitigation of variability with geographical diversity depends strongly on the time interval considered and is significant. At this scale (teens of MW), maximum daily variability (%):**

- Is constant with size on a 15 min basis
- Modestly decreases with size on a 1 min basis – ~35% reduction versus point measurement.
- Strongly decreases with size on a 10 sec basis – ~70% reduction versus point measurement.

- **For a given day and location, the maximum variability of a “system” of a given nameplate rating can vary widely on a percentage basis, especially for small systems. Contributing factors include:**

- Sum order – Whether it is physically contiguous; aspect ratio; orientation relative to cloud movement.
- Specific variations in cloud patterns relative to location – non-uniform, 2D effects of small clouds.
- Varying DC ratings of inverter blocks, all of which have the same nominal AC nameplate.
- **Relatively minor sources of variance may appear as large differences on a % per interval basis** which will make it difficult to draw meaningful conclusions about larger systems. The differences are small on a kW / interval basis for small systems.

* For the analyzed data set

Variability Scale - Conclusions

- **Variability of even a relatively small PV block (250 kW) is, in general, significantly lower than single-point irradiance measurements at 1 minute intervals and below.**

Use of a single point irradiance measurement to estimate the short-interval variability of commercial and utility scale PV systems will likely significantly over predict actual variability.

What's Next?

- Continue to develop understanding of how variability scales with system size, and geographical dispersion, for different locations and system types.
- Determine what data intervals are most critical and work to standardize.
- Develop modeling tools to study the impact of PV system dynamics on the utility system – both distribution and transmission.
- Develop appropriate, consistent interconnection requirements to ensure that PV systems do not needlessly contribute instability in the event of a fault.
- Develop forecasting methods

SunPower is committed to participating in collaborative activities to get this done!

- NERC IVGTF participant
- WECC PV Integration Task Force member
- DOE Solar Vision 2030 Study participant
- **And of course, honored to be with you here today!**

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