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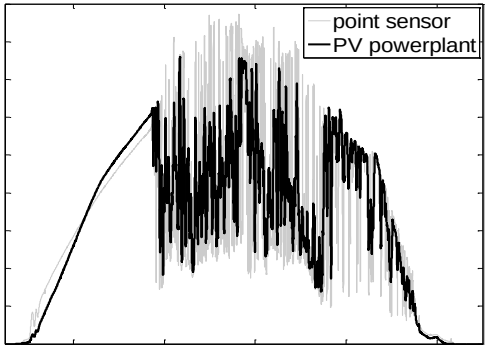

Simulated PV Power Plant Variability:

Impact of Utility-imposed Ramp Limitations in Puerto Rico

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PREPA 10% Limitation

- The Puerto Rico Electric Power Authority's (PREPA) Minimum Technical Requirements for Photovoltaic Generation Projects lists:
  - RAMP RATE CONTROL: Ramp Rate Control is required to smoothly transition from one output level to another. The PV facility shall be able to control the rate of change of power output during some circumstances, including but not limited to: (1) rate of increase of power, (2) rate of decrease of power, (3) rate of increase of power when a curtailment of power output is released; (4) rate of decrease in power when curtailment limit is engaged. **A 10 % per minute rate (based on nameplate capacity) limitation shall be enforced.** This limit applies both to the increase and decrease of power output.[1] [emphasis added]
- To quote a solar developer, "What this entails from a system design perspective is unknown until we can get some predictive basis of the level of solar variability at the site."

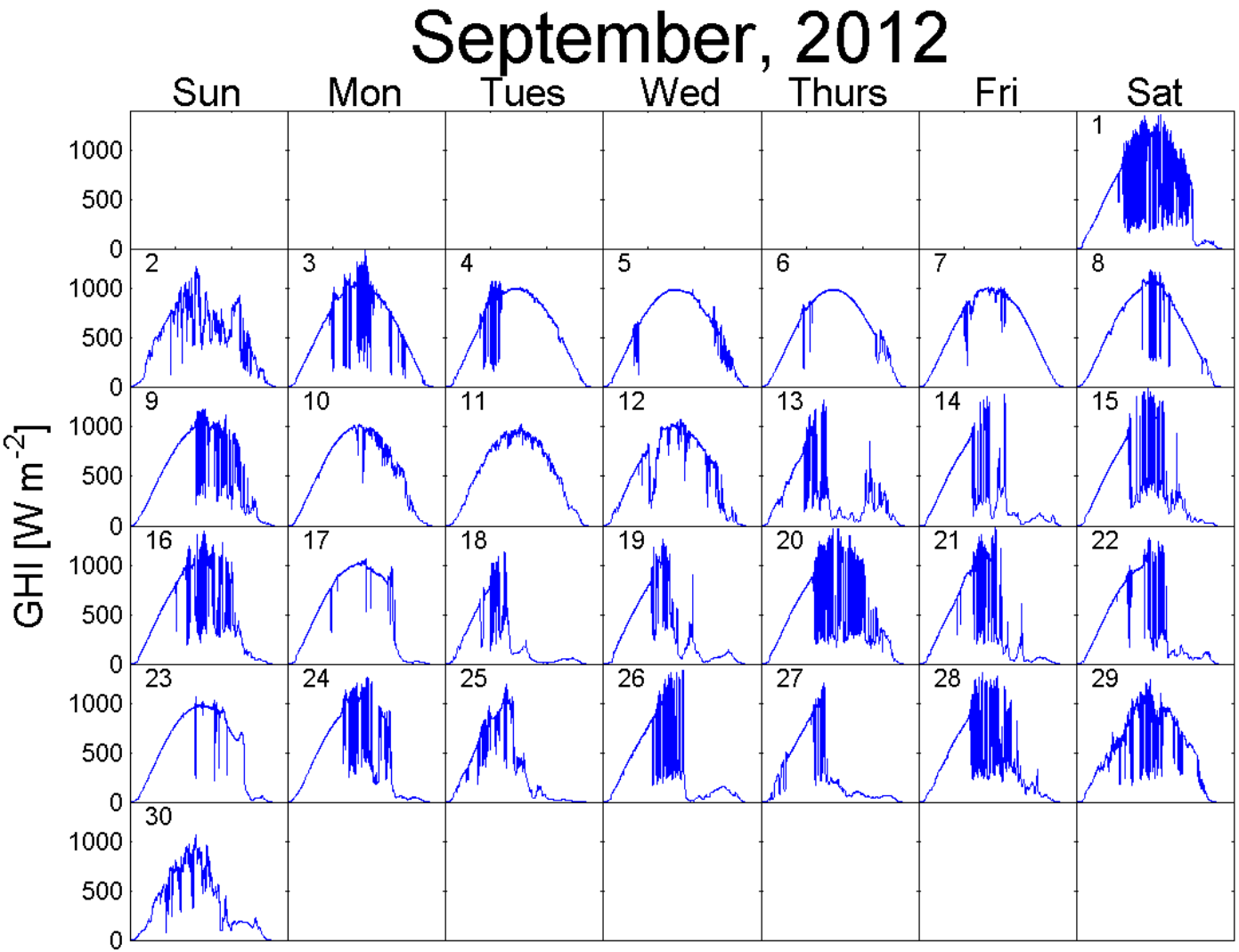
[1]*Puerto Rico Electric Power Authority Minimum Technical Requirements for Photovoltaic Generation (PV) Projects* (2012) http://www.fpsadvisorygroup.com/rso_request_for_quals/PREPA_Appendix_E_PV_Minimum_Technical_Requirements.pdf

Solar Data Scarce in PR

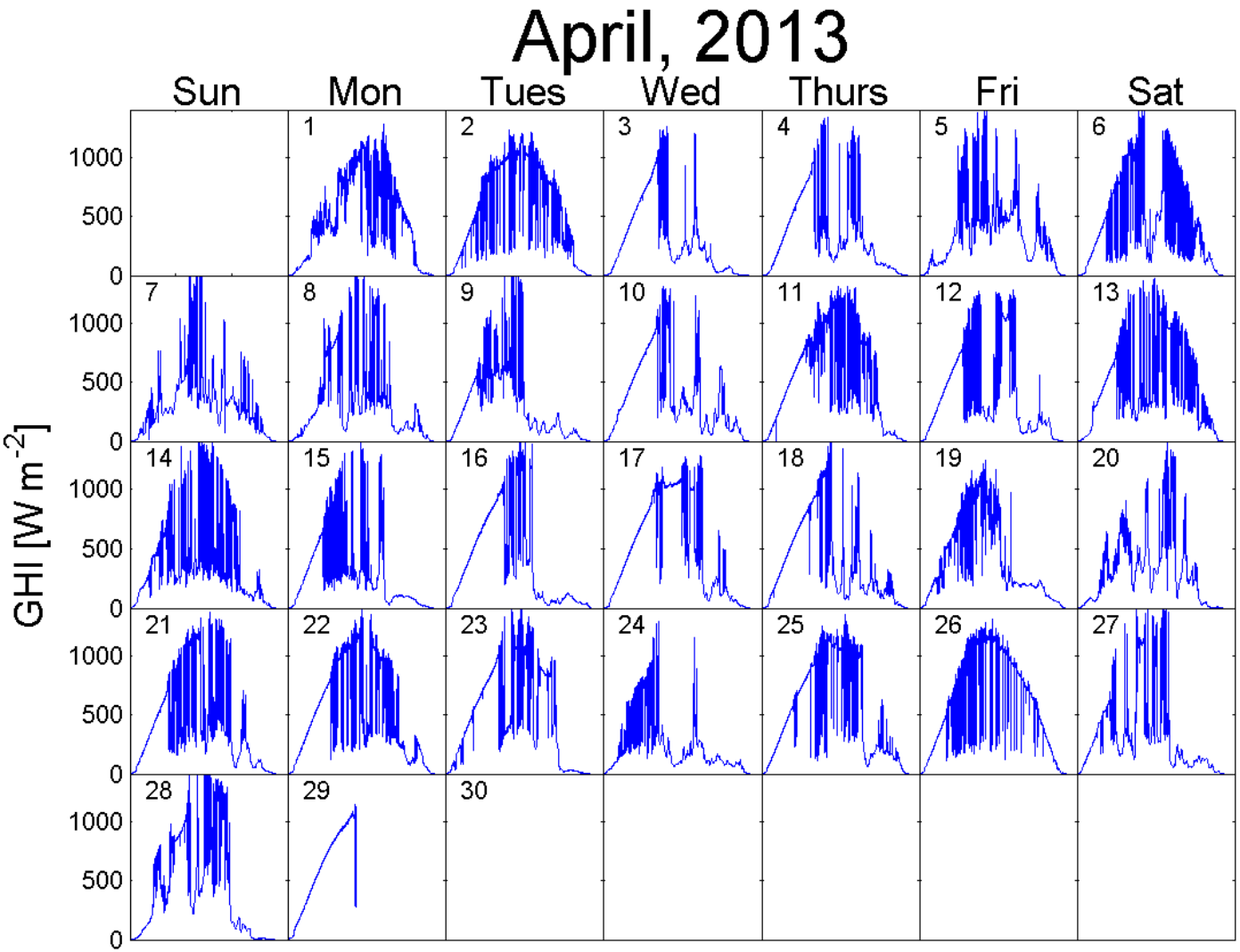
- As of summer 2012, no solar radiation data at 1-minute resolution was publicly available.[1]
  - 7 ground sensors on western half of island at 1-hour[2]
  - 1-km, 1-hour satellite-based irradiance[3]
- In September 2012, the Kleissl Lab Group at the UC San Diego started collecting 1-second irradiance measurements at the University of Puerto Rico, Mayaguez.

[1]Personal communication with Professor Eric Harmsen, Agricultural and Biosystems Engineering Dept., University of Puerto Rico - Mayaguez
[2] National Resources Conservation Service Soil Climate Analysis Network: http://www.wcc.nrcs.usda.gov/scan/Puerto_Rico/puerto_rico.html
[3] PRAGWATER Solar Radiation Data: http://pragwater.com/solar-radiation-data-for-pr-dr-and-haiti/

Mayaguez Solar Resource



Mayaguez Solar Resource

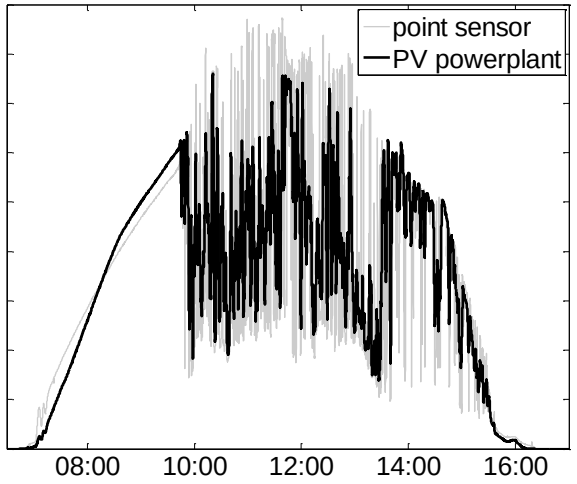


In-Plant Smoothing

- 1-minute ramps mostly caused by clouds passing over PV modules.
  - difficult to predict
  - can cause significant ramps in the output of a single PV module

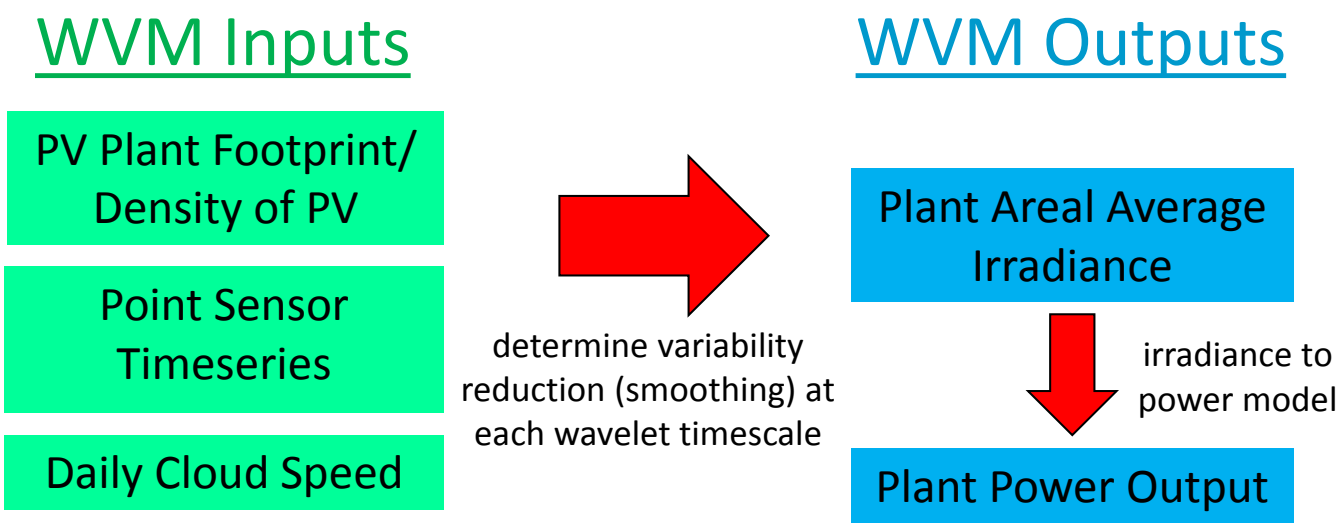
- But….
- For PV plants, there is smoothing due to spatial diversity within the plant.
  - Cloud edge incident timings are not synchronized over all PV modules.
- This variability reduction (VR) depends on plant layout, timescale, and meteorological conditions.

↑ Plant Size [# of modules]
↑ Absolute Variability [MWs]
↓ Relative Variability [% of capacity]



WVM to Upscale Variability

- The wavelet variability model (WVM) is a method for simulating PV power plant output variability given:
  - measurements from a single irradiance point sensor
  - knowledge of the power plant footprint and PV density (e.g., GCR)
  - the daily cloud speed.

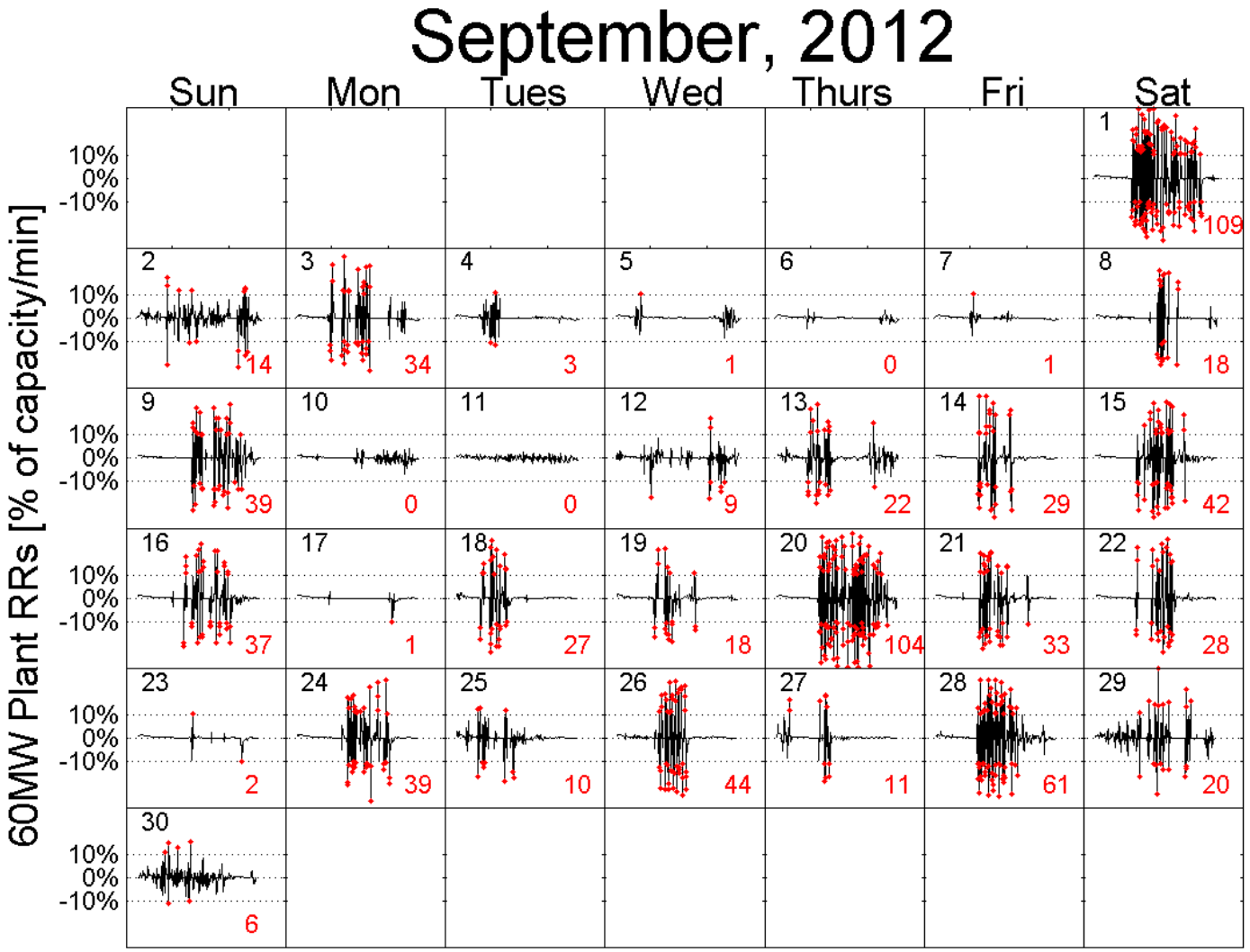


Running the WVM

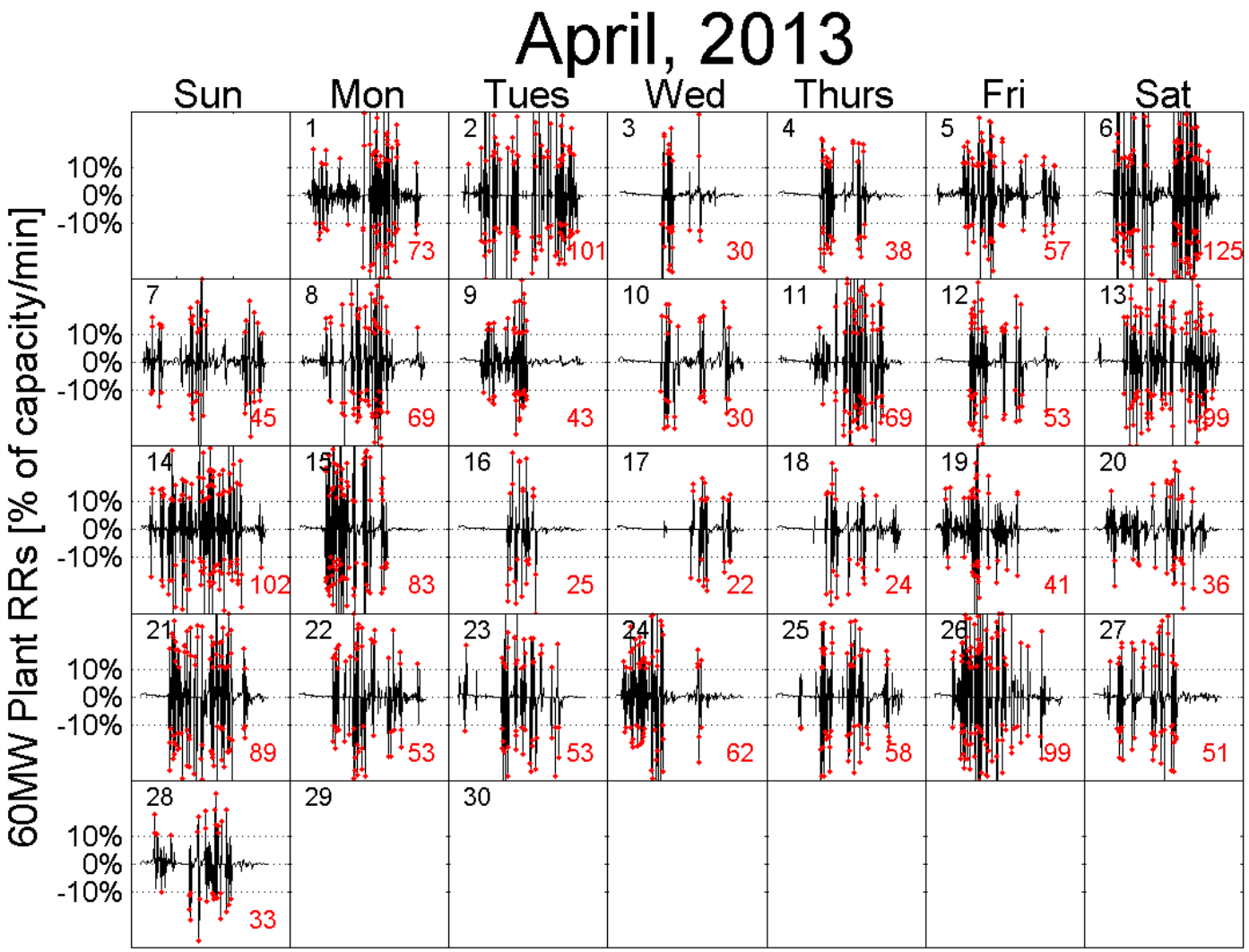
- 5MW, 10MW, 20MW, 40MW, 60MW [AC ratings] square PV plants
- Cloud speed found from UCSD/Mayaguez triangular sensor network
- Single axis tracking
- Linear irradiance => power model
  - Ignores effects of temperature, shading, inverter MPPT, etc. which may both scale the power output and contribute to the variability.
- Plant output capped at AC rated capacity
- $$RR_{1-min}(t) = \frac{\sum_{i=1s}^{60s} P(t+i)}{60s} - \frac{\sum_{i=1s}^{60s} P(t-60s+i)}{60s}$$

  For t of whole minutes (e.g., 8:00, 8:01, 8:02…)
  - Other RR definitions can be used, depending on PREPA definition

Violations of 10% rule

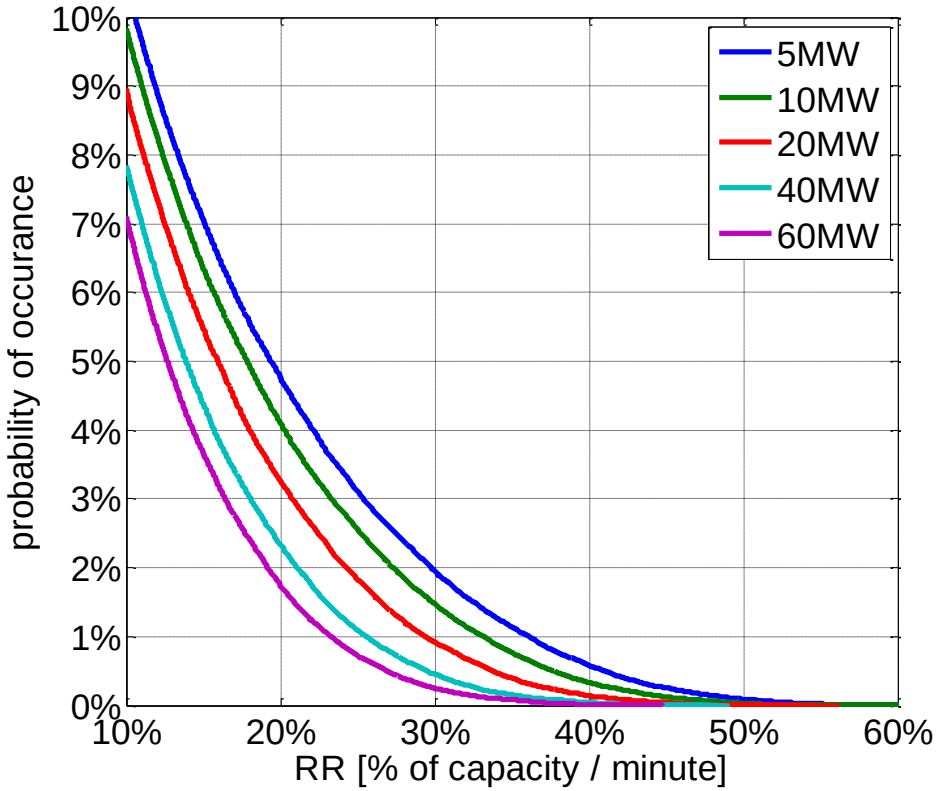


Violations of 10% rule



Ramp Magnitudes/Probabilities

- For 190 days in September-April



	5MW	10MW	20MW	40MW	60MW
Probability of >10%/min ramp [% of daylight minutes]	10.6%	9.9%	9.0%	7.9%	7.1%

Implications for 10% limitation

- Significant storage and advanced control algorithms will be required to comply, as RRs often exceed 10% even for large plants.
  - May significantly increase the costs of installing PV plants in PR.

Raises some questions:

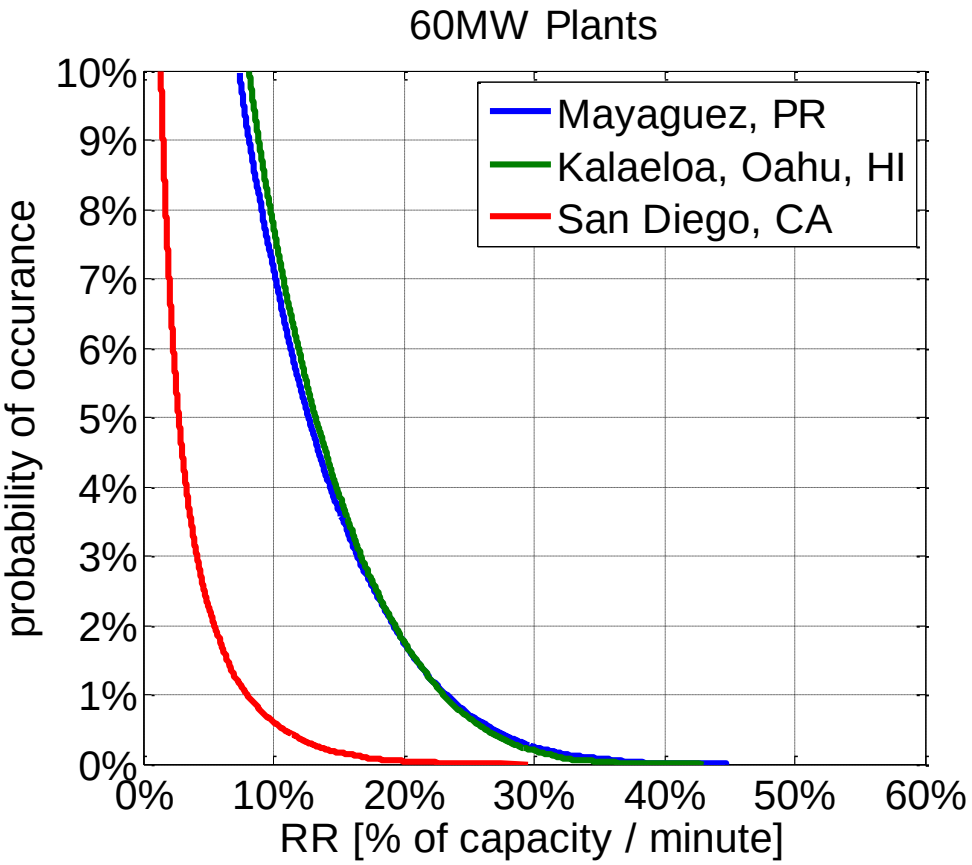
- Is 10% of capacity the best metric? Use MWs instead?

	99th percentile RR	
	% of capacity	MWs
5MW	36%	1.8MW
60MW	23%	14.0MW

- Should limitation be applied to a single system or a fleet of systems (w/reduced variability due to geographic smoothing)?
- What is the magnitude of load variability relative to PV variability?

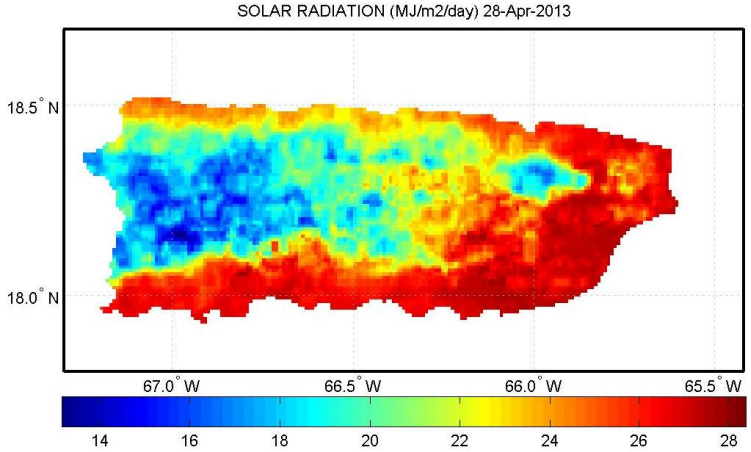
Compare to Hawaii and San Diego

- Some studies have used proxy data, e.g., from Hawaii.
  - Is this reasonable? How does PR variability compare to other locations?



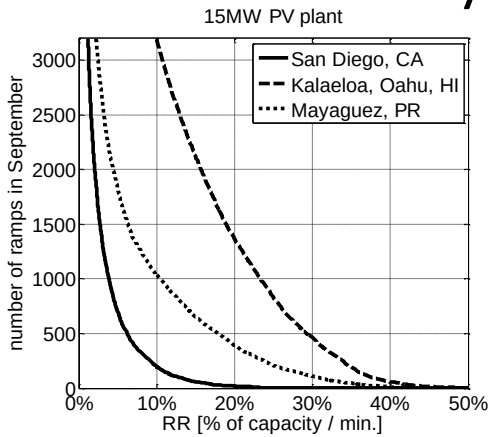
Cautions!

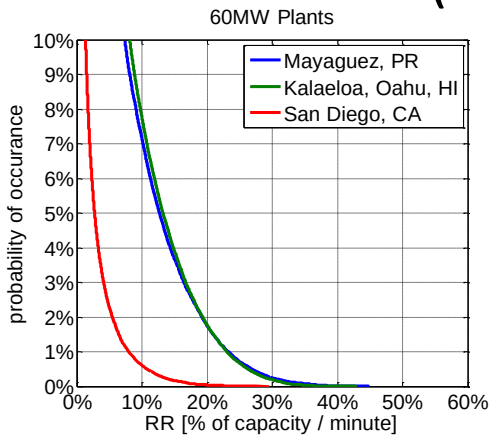
- The analysis presented here is meant to be illustrative, not exact.
- Irradiance statistic may vary significantly away from Mayaguez.



- Certain seasonal effects may not be accounted for (e.g, hurricanes).

<u>Sept. Only</u>:
PR ~1/2 as variable as HI





<u>Sept-April</u>:
PR ~ equally variable as HI

Summary

- 1-sec irradiance shows that PR highly variable.
- 10% RR limitation will be violated often, even for large plants.
- Variability over ~1/2 year is similar to variability in Hawaii.

Further studies should be run to determine the impact of PV in PR and see if there is a more appropriate RR limitation:

- RR limitation in MWs
- RR definition based on application
- Down ramps only
- Load variability
- Aggregate systems into a fleet

Thank You!

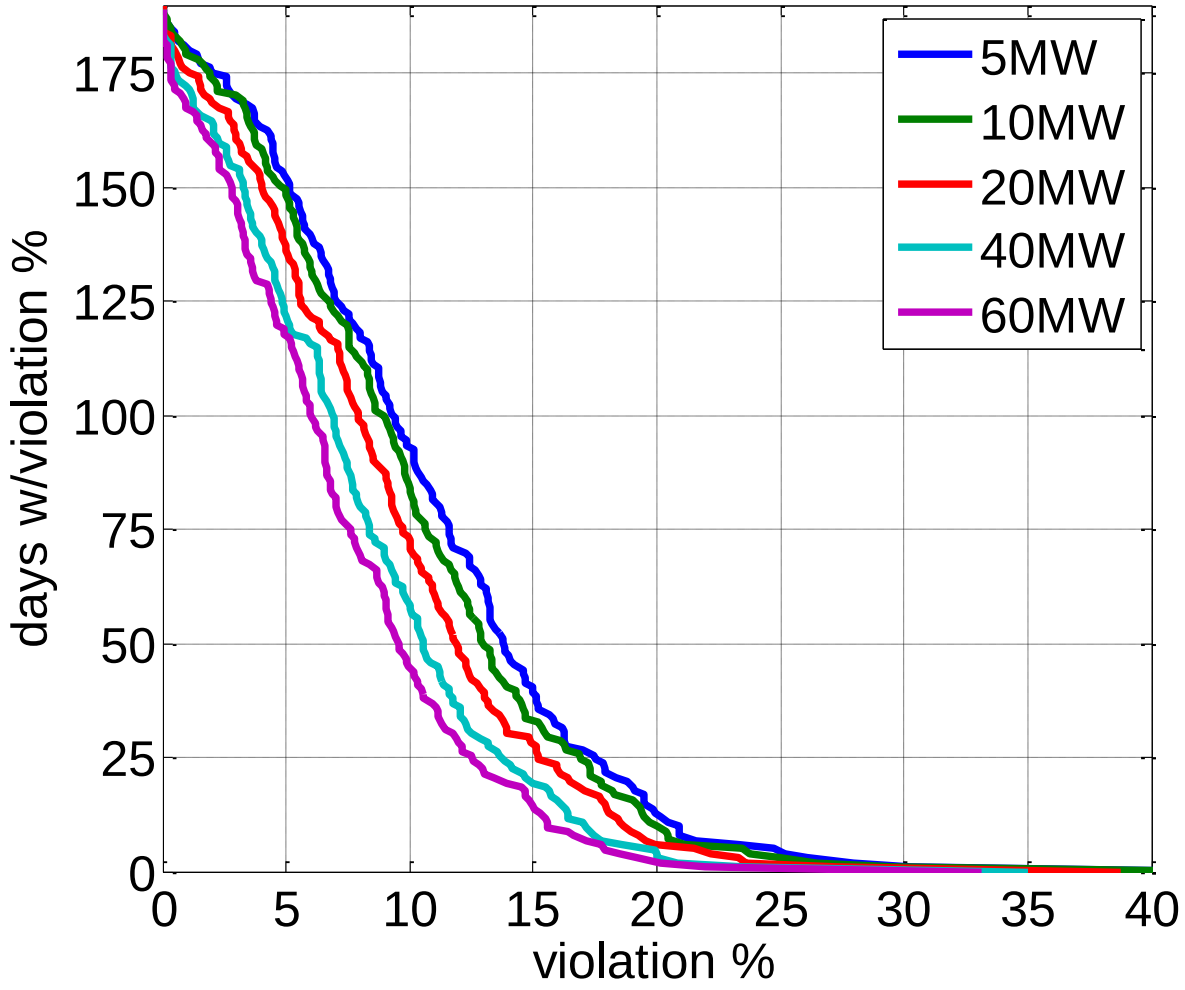
Sandia National Laboratories

Questions/Comments?

mlave@sandia.gov

Violations per Day

- Out of 190 total days:

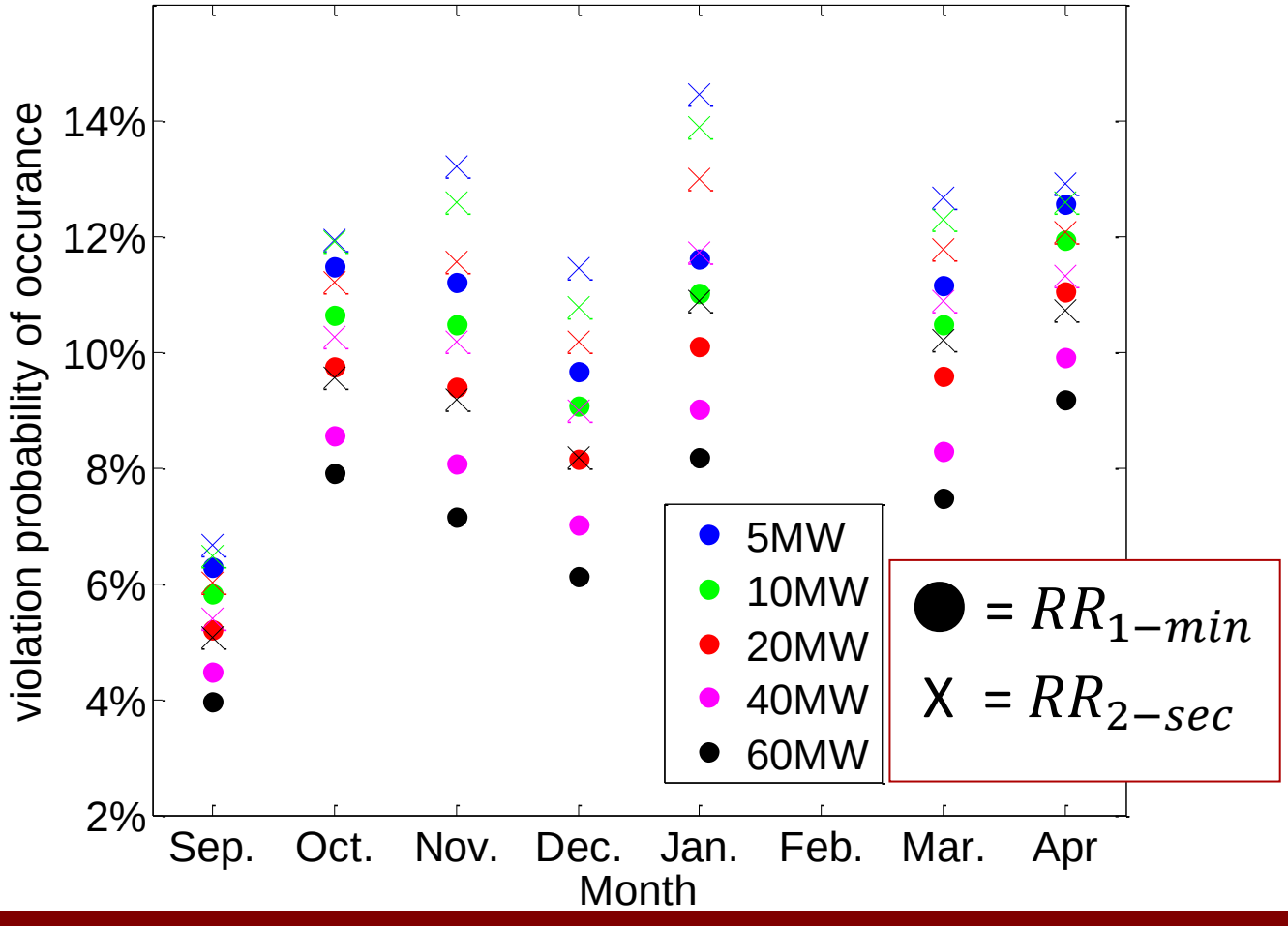


Comparing the 2 Definitions

$$RR_{2-sec}(t) = \frac{P(t) - P(t-2)}{2s}$$

violation = 10%/min = 0.33%/2-sec

For any t (e.g., 8:00:01, 8:01:02, 8:01:03…)



Comparing the 2 Definitions