Simulated PV Power Plant Variability: Impact of Utility-imposed Ramp Limitations in Puerto Rico

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***Abstract* — The variability of solar PV power plants has led to some utilities imposing ramp limitations. For example, the Puerto Rico Electric Power Authority (PREPA) includes a 10% of capacity per minute limit on ramp rates produced by PV power plants in its minimum technical requirements for photovoltaic generation projects. However, it is difficult to determine storage requirements to comply with ramp limitations for plants in the planning or construction phase since the variability of the plant output is not known. In this paper, we use the wavelet variability model (WVM) to upscale irradiance measured in Mayaguez, PR to simulate various sizes of PV power plants. The results show that ramps will often exceed 10%, even for the largest plants (60MW) that benefit the most from in-plant spatial smoothing, meaning significant amounts of storage will be needed to meet the PREPA requirement. The results from Puerto Rico are compared to sites in San Diego and Oahu, Hawaii. Significant differences are seen in the ramp rate distributions of the three locations, demonstrating the importance of performing location-specific simulations.**

***Index Terms* — solar power, solar energy generation, power generation planning, energy storage, distributed power generation.**

I. PV Power Plant Variability

Solar PV power plants produce output that can change significantly at short timescales due to changing cloud cover. This variability may be a concern to grid operators as unanticipated changes in PV plant power output can strain the electric grid. Based on this concern, the Puerto Rico Electric Power Authority (PREPA) lists in its minimum technical requirements for photovoltaic generation projects that ramp rates must not exceed 10% of nameplate capacity per minute [1]. In order to comply with this requirement, PV power plant variability must be counteracted in some way (e.g., by battery storage). However, the 1-minute variability in Puerto Rico is not well understood and so it is difficult to estimate the magnitude and frequency of PV power plant ramp rates. In this paper, we simulate the variability of potential PV systems in Puerto Rico to understand the impact of the PREPA 10% limitation.

Changes in power output (ramps) that occur at short timescales such as 1-minute are due to clouds passing over PV modules. Cloud-caused variability is difficult to predict and can cause significant ramps in the output of a single PV module. When considering a PV power plant, though, spatial diversity within the plant leads to a reduction in the magnitude of ramps as cloud timings are not synchronized over all PV modules within the plant. This is seen visually in Fig. 1, where the envelope of fluctuations is smaller for the PV power plant than for the single point sensor, showing that the relative variability is reduced for the PV power plant. The variability reduction (VR) changes from plant to plant and day by day since the smoothing depends on plant layout, the timescale of interest, and the daily meteorological conditions.

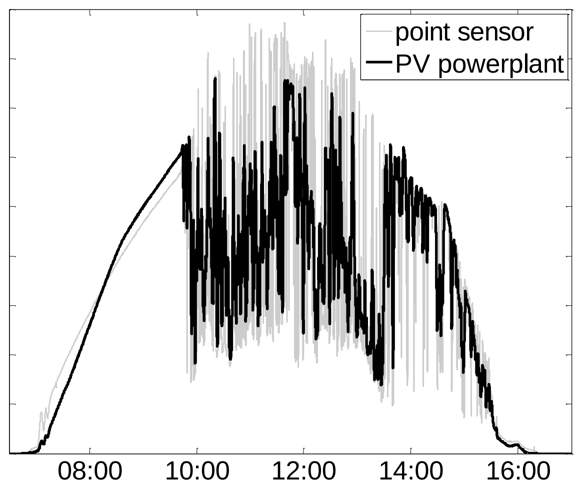

Fig. 1: Comparison of the relative variability of a point sensor (light grey) to the total power output of a 48MW PV power plant (dark black). The y-axis units have been scaled to allow for easy comparison.

II. WVM for Simulating PV Plant Variability

The wavelet variability model (WVM) [2] is a method for simulating PV power plant output variability given (1) measurements from a single irradiance point sensor, (2) knowledge of the power plant footprint and PV density (Watts of installed capacity per m^2), and (3) the daily cloud speed. The WVM uses these inputs to estimate the VR over the area of the plant (Fig. 2). The WVM produces simulated plant power output at the same temporal resolution as the input irradiance point sensor.

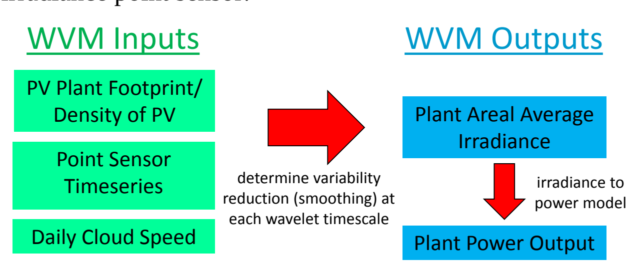

Fig. 2. Diagram showing the inputs and outputs for the WVM.

III. WVM Applied to Simulate Puerto Rico Ramps

Because of the proposed PREPA 10% ramp rate limitation, many solar developers have become interested in estimating RRs for PV plants being installed or considered in Puerto Rico. Ramp rate simulations are needed to make storage sizing decisions, test control algorithms, and estimate the additional costs of complying with the limitation. The WVM is a perfect tool for simulating PV power plant ramp rates in Puerto Rico.

The Kleissl Lab Group at the University of California, San Diego has been collecting 1-second irradiance measurements at the University of Puerto Rico, Mayaguez since September, 2012 [3]. These sensors are used for both a high-frequency irradiance input to the WVM, and for determining the cloud speed.

The GHI for each day in April 2013 is shown in Fig. 4. Some days were clear in the morning but nearly every day is highly variable by midday (with changes in irradiance exceeding 50% in 1-minute). We caution that the Mayaguez data may not accurately represent other locations in Puerto Rico. Mayaguez is on the western coast of Puerto Rico, so locations further inland or on different coasts may have different irradiance statistics due to different weather patterns.

Irradiance data from Mayaguez is currently available for the date range of September 2012 through April 2013. Due to data outages, though, only 190 of these 242 days have a full daily profile (at least 8 hours of data collected). Most of the data outage occurred in February and early March, though occasional days in other months are also missing.

For each of these days with full data, the WVM was used to simulate 5MW, 10MW, 20MW, 40MW, and 60MW square-shaped PV power plants in Mayaguez. The plants were set to have a typical utility-scale PV density of 30 W m^{-2}, and a linear irradiance to power model was used to convert the WVM simulated plant-average irradiance to plant power output. The linear model was used for simplicity, though it neglects effects such as temperature, shading, and inverter characteristics, which may contribute to variability. The analysis presented here is meant to be illustrative and to give a broad understanding of the variability of PV plants in Puerto Rico.

In analyzing the simulated PV power plant output, particular attention was given to the number of violations of the PREPA 10% rule. Fig. 4 shows the daily ramp rates of the 60MW plant in April 2013, with violations highlighted as red dots and summed for each day. There were a significant number of violations on all days in April. The least variable day (April 17th) had 22 violations, while the most variable day (April 6th) had 125 violations, or nearly one violation every five minutes during daylight. The majority of the large ramp rates occur in the middle of the day, which is consistent with the GHI timeseries being most variable midday.

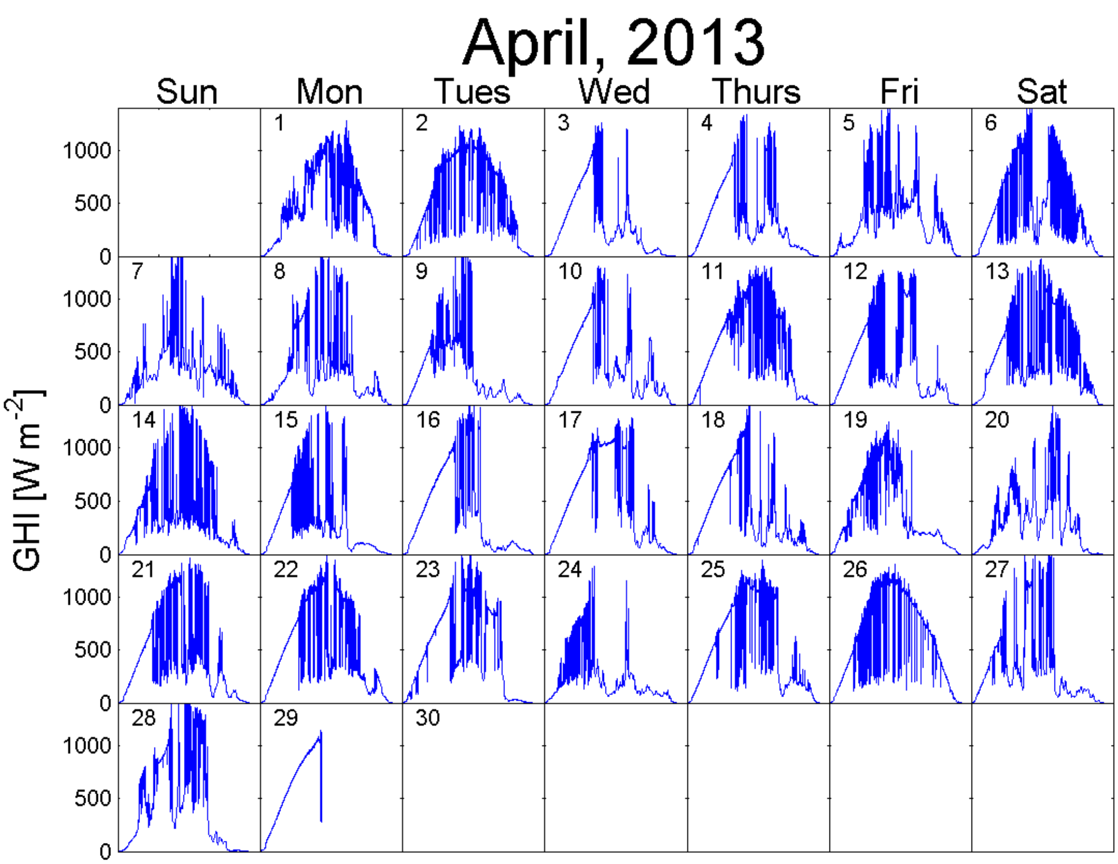

Fig. 3. Calendar plot for April, 2013 showing the daily GHI profiles at Mayaguez, PR.

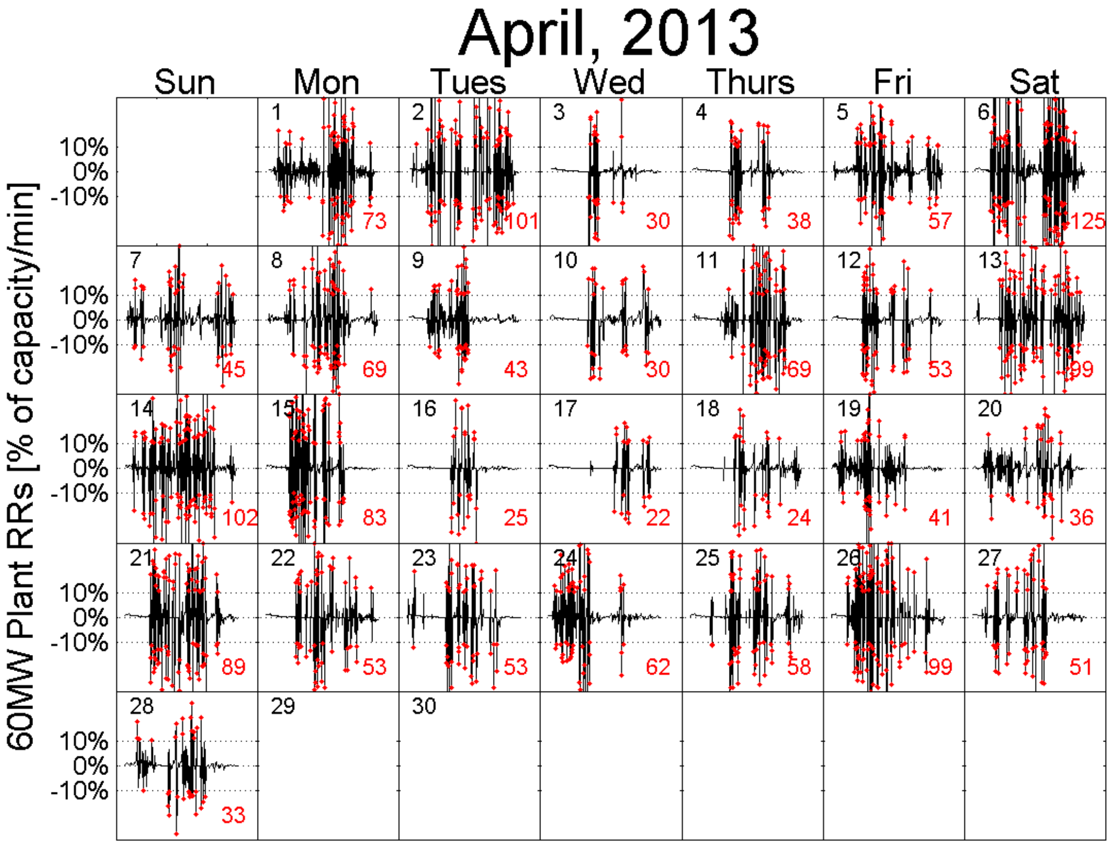

Fig. 4. Calendar plot for April, 2013 showing the ramp rates for a simulated 60MW PV plant in Mayaguez. Violations of the PREPA 10% limitation are shown as red dots and the number of violations on each day is listed in the bottom right of each daily box.

Table I shows the percentage of daylight minutes with violations for each month and for the whole data range. No data was recorded in the month of February, but all other months had at least 16 days of data and so should provide meaningful percentages. September 2012 was the least variable month and April 2013 was the most variable for all plant sizes. For all months, the violations decrease as the plant size increases due to the increased spatial diversity in larger plants. However, the rate of this decrease changes month-to-month as meteorological conditions change.

TABLE I
PERCENTAGE OF DAYLIGHT MINUTES WITH RRS LARGER THAN 10% OF CAPACITY PER MINUTE (“VIOLATIONS”).

	5MW	**10MW**	**20MW**	**40MW**	**60MW**
September	6.3%	5.8%	5.2%	4.5%	4.0%
October	11.5%	10.6%	9.7%	8.6%	7.9%
November	11.2%	10.5%	9.4%	8.1%	7.1%
December	9.7%	9.1%	8.1%	7%	6.1%
January	11.6%	11.0%	10.1%	9.0%	8.2%
February	-	-	-	-	-
March	11.2%	10.5%	9.6%	8.3%	7.5%
April	12.6%	11.9%	11.0%	9.9%	9.2%
All 190 days (Sept. -Apr)	**10.6%**	**9.9%**	**9.0%**	**7.9%**	**7.1%**

It is also important to consider not only the number of violations but also the magnitude of 1-minute RRs. Assuming that compliance with the technical requirements is always mandatory (rather than, e.g., 95% or 99% compliance), then:

(i) The size of storage needed is a function of the energy required to reduce the largest violation to a 10% per minute ramp.

(ii) The lifetime of the storage system (determined by the number of charge / discharge cycles) is a function of the overall number of violations

Fig. 5 shows the distribution of large (>10% of capacity) 1-minute RRs. We can see the effect of spatial smoothing within the plants, as the larger plants always have smaller relative ramp rates since they have more spatial diversity. The 99th percentile RR at the 5MW plant was 36% of capacity, while the 99th percentile RR for the 60MW plant was only 23% of capacity. However, in MWs the RRs at the 60MW plant will still be much larger than the maximum RRs at the 5MW plant: in this case, the 99th percentile ramps are 1.8MW and 14.0MW, respectively. As such, even though the 60MW plant will have fewer violations, and violations will tend to be less severe in terms of percent of capacity, it will still require a larger storage system (in terms of MWh of energy capacity) than the 5MW plant.

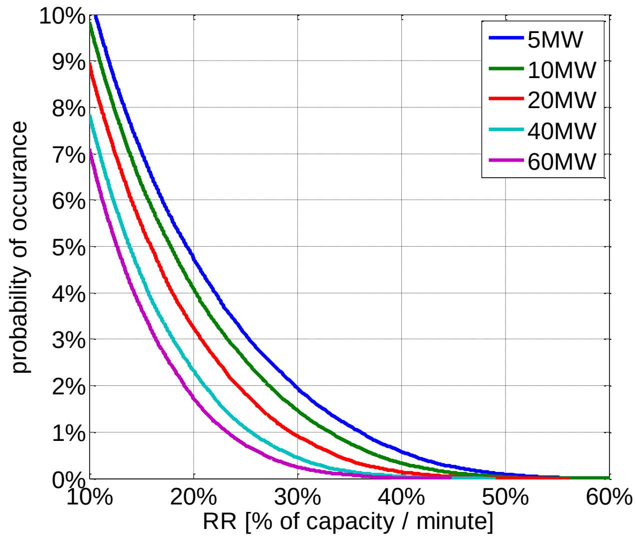

Fig. 5: Probability of occurrence during daylight of large 1-minute RRs in September 2012.

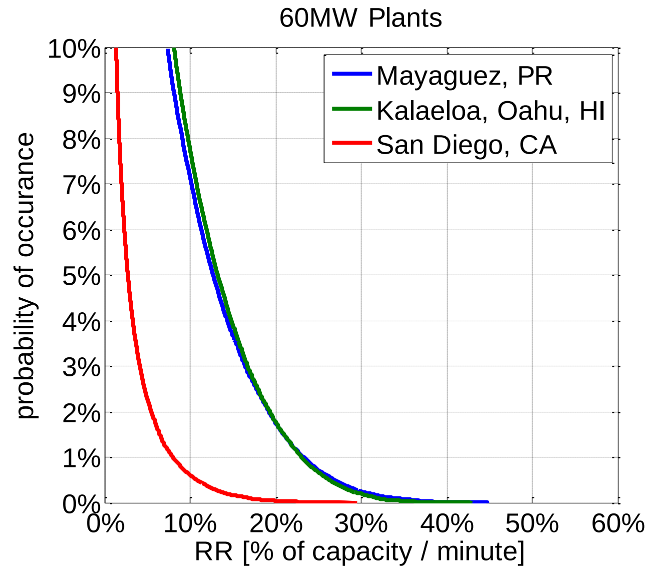

Fig. 6: Probability of occurrence during daylight of 1-minute RRs for simulated 60MW PV power plants in Mayaguez, PR, Kalaeloa, Oahu, Hawaii; and San Diego, California.

IV. Comparison of PR to Other Locations

The WVM results presented for Puerto Rico show significant variability. We wonder, though, how the variability in Puerto Rico compares to other locations. This has been an especially important question due to the limited data availability, as some researchers have used Hawaii or other location data as a proxy for Puerto Rico.

To answer this question, we used the WVM to simulate 60MW PV power plants in Kalaeloa, Oahu, Hawaii [4] and San Diego, California [5] in addition to Mayaguez. For consistency, we choose the same 190 day range for Kalaeloa and San Diego as used for Mayaguez, except that 4 days did not have data available in San Diego, so only 186 days were compared. Kalaeloa data is only available from 2010 and 2011, so the corresponding days in those years were used.

Based on the irradiance timeseries, nearly every day at Kalaeloa is highly variable, while San Diego has a mix of clear, partly cloudy, and foggy days. San Diego and Kalaeloa were chosen partly due to data convenience, but also because they represent coastal locations that may have similar meteorological conditions as locations in Puerto Rico (especially Kalaeloa, since Hawaii is an island at similar latitude to Puerto Rico).

Fig. 6 shows the comparison of ramp rates for the 60MW plants at each location. Perhaps most striking is how well the distributions of ramp rates at Kalaeloa match those in Mayaguez. This indicates that Hawaii may indeed be a good proxy for Puerto Rico. The ramp distributions in San Diego are very different. If a 60MW PV plant in San Diego were held to the PREPA 10% limitation, it would violate only 0.6% of the time. A 60MW plant in Kalaeloa, on the other hand, would violate 7.8% of the time (similar to the 7.1% noted for Mayaguez earlier). Additionally, the 99th percentile RR in San Diego was only 8.0% of capacity, while the 99th percentile RRs at Mayaguez and Kalaeloa were much larger: 23.3% and 23.1%, respectively. This means that not only would San Diego have fewer violations, but it would also require less storage energy to counter its violations.

We caution, though, that these results are presented for only 186 days in the September-April timeframe, and so may not be fully representative of annual trends. June through November is hurricane season in Puerto Rico, but is largely excluded from this analysis. Including that time period may differentiate the Mayaguez and Kalaeloa ramp rate statistics, as Hawaii is not prone to hurricanes. The San Diego statistics may also be affected by the time range chose, and the “May-gray” and “June-gloom” fog-dominated months are not included in this analysis.

V. Conclusion

The PREPA 10% per minute ramp rate control limitation has strong implications for PV power plants in Puerto Rico. Based on the results presented here, PV plants in Mayaguez, PR may exceed the limitation as often as once every five minutes, even for very large power plants (60MWs). In order to comply, large amounts of batteries or other ramp mitigation strategies will be required, which will considerably increase the cost of installing PV systems in Puerto Rico.

The PREPA 10% limitation is meant to protect the utility from significant changes in power output from PV plants. Due to the added costs of compliance imposed on plant operators, it is worth considering the rule critically. Is the limitation overly conservative, causing added cost to developers for no reason? To answer this, a detailed understanding of the PREPA electric grid operation and the possible locations of PV power plants would be required. This may be possible in a future study, but here we make a few general notes.

The limitation is set up as a percent of capacity, and is applied to even relatively small-scale systems (a few MWs). A 10% ramp of a 5MW system is drastically different than a 10% ramp of a 50MW system (0.5 vs. 5MW ramps). In many cases, the small system ramp may be on the order of load variability, meaning the utility will already be used to dealing with variability of this magnitude, so it may not be necessary to impose a ramp limitation on small plants. Instead, the ramp limitation may be better applied in units of power (e.g., MWs) rather than percentage of plant capacity.

Additionally, when aggregating many PV systems, the ramp rates as a percent of capacity for fleet of systems will be reduced. For example, if 10 different systems in Puerto Rico were aggregated, their variability could be reduced by a factor of the square root of the number of systems, or over 3 times reduced. This means that even if 30% of capacity ramps occurred at one system, the fleet output may not experience 10% ramps in violation of the PREPA limitation. Essentially, as more PV connected to the electric grid, the benefit from geographic smoothing becomes greater, and ramp rates may be less of a problem. Thus, deepening on the interconnection locations, the 10% limitation may more appropriately be applied to a local fleet of systems rather than a single PV power plant.

To build on this work, future variability analysis in Puerto Rico should work to both quantify the costs to plant operators (of storage, etc.) of complying with the 10% limitation, and to determine what magnitude of PV variability introduces negative effects to the electric grid to test if the 10% limitation is an appropriate metric for limiting ramp rates in Puerto Rico.

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References

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

[2] M. Lave, J. Kleissl, and J. S. Stein, "A Wavelet-Based Variability Model (WVM) for Solar PV Power Plants," *Sustainable Energy, IEEE Transactions on,* vol. PP, pp. 1-9, 2012.

[3] DOE (2012). *DOE-Funded Solar Variability Model in High Demand in Puerto Rico*. https://solarhighpen.energy.gov/article/doe_funded_solar_variability_model_in_high_demand_in_puerto_rico?print

[4] *NREL: Measurement and Instrumentation Data Center*. www.nrel.gov/midc

[5] *UC San Diego DEMROES Irradiance Sensor Network*. http://solar.ucsd.edu/demroes/