Comparing Ramp Rates from Large and Small PV systems, and Selection of Batteries for Ramp Rate Control

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***Abstract* — We compare the AC power fluctuations from a 1.6 MW and a 2 kW photovoltaic (PV) system. Both of these PV generating stations exhibit fluctuations exceeding 50% of their rated capacity in under 10 seconds. The smaller system can fluctuate more rapidly, exhibiting 50% dropouts in 3 seconds. Although the MW-scale system covers 4000 times as much ground area, the bandwidth of the fluctuations is remarkably similar. We explore explanations for this observation, and we discuss the impact of this on battery sizing.**

***Index Terms* — grid interconnection, monitoring, output fluctuations, intermittency, battery integration**

I. Introduction

Fluctuation in AC power output from PV systems is a challenge for utility operators. Especially on partly cloudy days, the AC power output from a 2 kW system can exhibit 50% dropouts in just 3 seconds. Increases in power output can occur equally rapidly as clouds pass by. In scenarios with large PV systems on the grid, such rapid fluctuations may cause power ramp rates in excess of what utility companies can handle without additional spinning reserves.

Utility companies with high renewable energy penetration, such as Puerto Rico Electric Power Authority (PREPA), have established maximum allowable ramp rates, e.g. 10% per minute, based on the PV system's rated capacity [1]. Prior to installing a PV system on the PREPA grid, the designer must ensure ramp rates will be controlled by some means. Energy Storage Systems (ESS), curtailment, cloud forecasting and micro-grids have all been proposed as solutions to this problem[2]. Another hedge against fluctuations is a geographic diversity of PV system locations. However, the aerial size of a PV system is likely not, in itself, sufficient to limit the ramp rate of its AC power output to 10% per minute.

In this paper we compare fluctuations in power from large and small PV systems. A 1.6 MW system (spread over 100 m by 350 m in map view) and a 2 kW system (9 m by 1 m) are both monitored simultaneously with data sampling every 1 second. The two systems are located in Tucson, AZ, ten km apart from each other. As expected, the ramp rate from the smaller system is faster when normalized by system power rating (i.e., when fluctuations are reported in fraction of capacity per second). However, the 1.6 MW system still fluctuates rapidly with an observed worse case dropout of 50% in 9 seconds. First we describe the systems (Sec. II) and present data on their ramp rates (Sec. III). Then we explore explanations and implications of these observed ramp rates (Sec. IV). Section V describes battery power ratings that would enable compliance with various ramp rate regulations.

II. System Descriptions

The 1.6 MW system is shown in Fig. 1, and the 2 kW system (precisely1935 watts) is shown in Fig. 2.

Fig. 1. The 1.6 MW system used in this study. (Top) Arial view. (Bottom) One of the authors (A.B.) in front of the PV rows.

Fig. 2. The 2 kW system used in this study is the front 9 modules.

The large (1.6 MW) system shown in Fig. 1 is a single-axis tracker composed of 4224 units of SOLON Blue (poly-Si) modules. Its location, at the University of Arizona Science and Technology Park (UASTP), is approximately 10 km SW of the smaller PV system studied in this paper. Also at the UASTP is a 0.35 MW battery now operated in conjunction with the PV system by SOLON America. Experimental demonstration is underway for algorithms that make our hybrid PV+battery system comply with ramp rate rules. Results of a battery operated in conjunction with the 1.6 MW PV power plant will be presented elsewhere.

The 2 kW system shown in Fig. 2 is composed of 9 units of SunPower 215W monocrystalline Si modules held at a fixed angle. It is located at the Tucson Electric Power Solar Test Yard (TEP STY). At the same site, there are 20 more PV systems of a similar 1-2 kW size and one 30 kW system. The aggregate output from the STY is about 60 kW.

As we shall show in Section III, the fluctuations from the two systems are roughly similar in bandwidth. This is a surprise given that the transit time for a particular shadow edge to pass over an entire PV system should depend on the PV system's linear dimension. We return to this simple expectation in Section IV (Discussion).

The observed fluctuations have implications for battery sizing and system deployment strategies that we will discuss in Section V. The simple conclusion here is that to ensure a 10% per minute ramp rate, battery capacity and power will scale roughly linearly with PV system capacity, without a significant economy of scale as was naively expected.

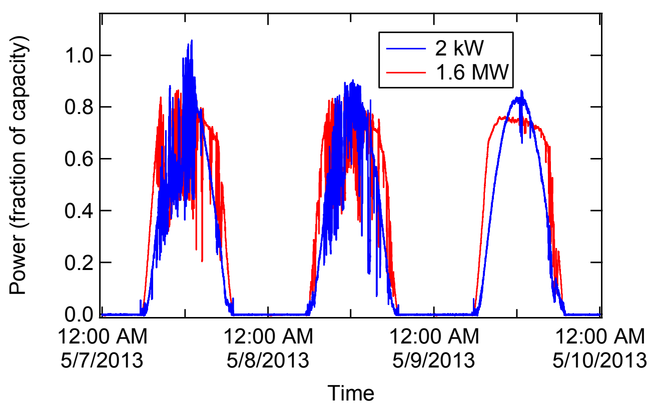

Fig. 3. Time series of power output, normalized by system rating on cloudy days. As clouds move over each system, power output rapidly drops and rebounds.

III. Data and Fluctuations

Data shown in Figs. 3 - 6 demonstrate simultaneous fluctuations in AC power output from the 2 kW and the 1.6 MW PV systems. Figure 3 shows three days in May. Figure 4 shows 10 minutes of fluctuating output. Figure 5 shows the ramp rate calculated by taking the derivative (d/dt) of the power time-series. Figure 6 shows a histogram of ramp rate occurrence.

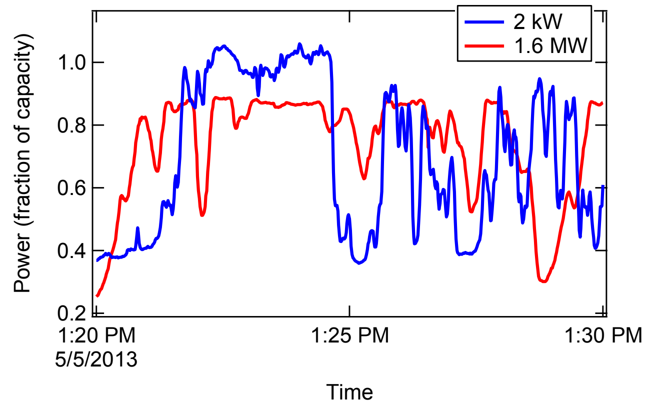

Fig. 4. Ten minutes of power data, sampled every 1 second, from the 2 kW and the 1.6 MW PV systems on a partly cloudy day. Since the PV systems are separated by 10 km they do not have strongly correlated shadow events, but they are exposed to similar weather, with similar wind velocities and cloud types.

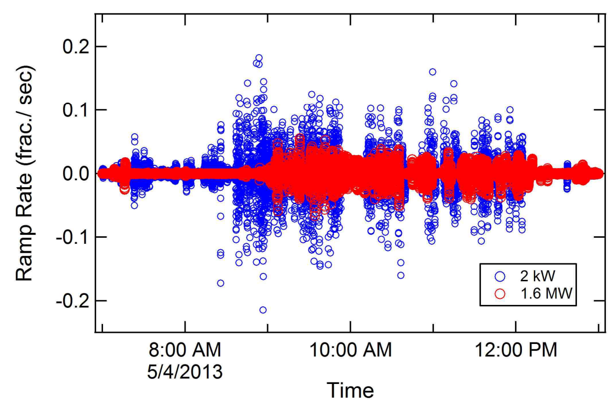

Fig. 5. Ramp rates for the 2 kW and 1.6 MW PV systems. The Ramp rate is shown in fraction of capacity per second. This is the derivative of the power time-series for a partly cloudy day, May 4th.

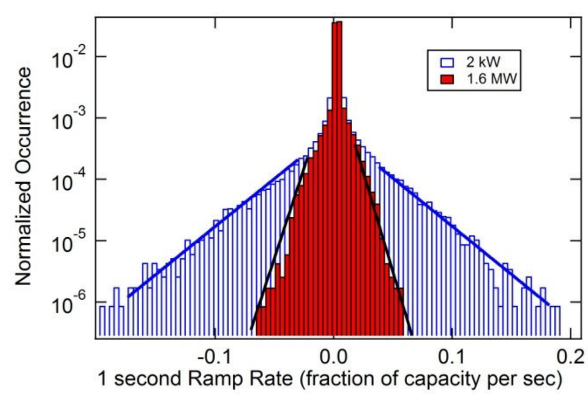

Fig. 6. Histogram of normalized ramp rates for the 2kW and 1.6 MW PV systems for month of May 2013. The wings of the histograms are fit to equation (1).

The wings of the histograms in Fig. 6 (i.e. the data excluding the lowest 10% of ramp rates) are well described by exponentially decreasing probability distributions for ramp rates:

$$P(\text{ramp rate}) = N\,10^{-|\text{ramp}|/G} \qquad (1)$$

where N is the number of occurrences of zero ramp rate, and G is the rate for which the probability P falls to 10%. The best fit function (1) appears as a line on the log-linear plot in Fig. 6. The fit values for ramp up and ramp down are nearly symmetrical.

Similar histograms can be computed for time periods other than one month. Table I summarizes the best fit parameter G for both PV systems during various weather patterns.

TABLE I. RESULTS OF COMPARING RAMP RATE HISTOGRAMS TO EQUATION (1). THE BEST FIT PARAMETER G IS REPORTED.

Weather (Day)	G 2kW	G 1.6MW	G 2kW / G 1.6MW
All days in May 2013	3.2	2.4	1.33
PM Clouds (May 5)	2.2	1.8	1.22
Light Clouds (May 10)	2.0	1.7	1.18
Sunny (May 17)	1.3	2.3	0.56

Data shown in Fig. 7 and Fig. 8 demonstrate how slowly-sampled (or time-averaged) data would result in smaller reported ramp rates. For these figures, each point of power output is replaced with a boxcar average of the surrounding points. Fig. 8 shows the 99.99th percentile ramp rate histogram versus the width, in seconds, of a boxcar average.

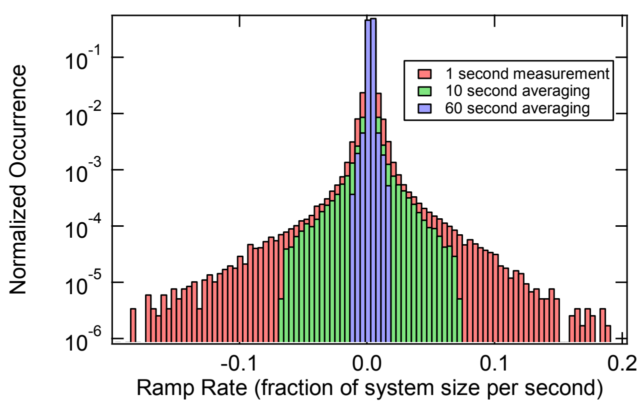

Fig. 7. Normalized histogram of ramp rates observed May 2013 for the 2kW system and histograms after output has been boxcar averaged for 10 seconds and 60 seconds.

We chose to report certain values at the 99.99th percentile as this corresponds to events observed approximately 10 times per month. Such a frequency we consider to represent the commonly observable extreme.

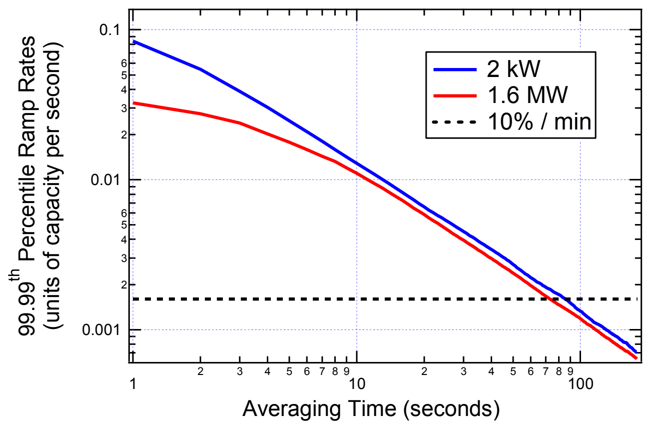

Fig 8. 99.99th percentile of maximum observed ramp rate during May 2013 after the power has been boxcar averaged.

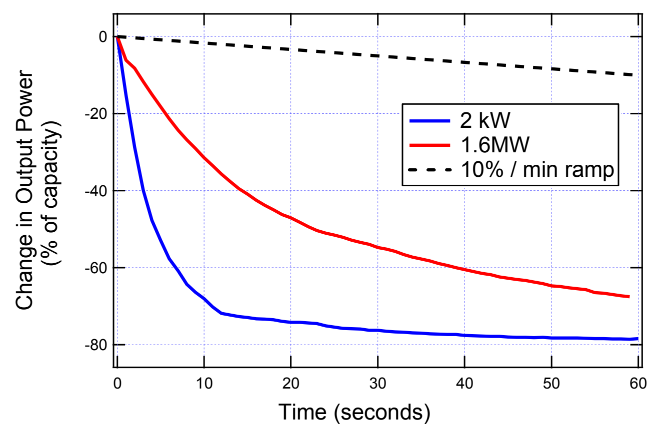

Fig. 9. 99.99th percentile of maximum observed change in output power (Delta P) after various times (Delta t) for each system during the month of May 2013. The dashed line corresponds to a change of 10% of system size per minute.

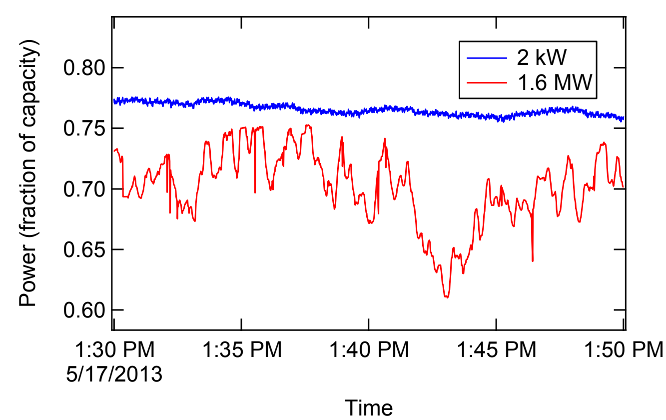

Fig. 10. 50-100 kW fluctuations in the 1.6 MW system on a sunny afternoon.

IV. Discussion

The histograms and the best fit, *P*(ramp rate), reveal that under cloudy skies the 2 kW system exhibits ramp rates as high as 5%/sec fifteen to twenty times more often than the 1.6 MW system. Extreme ramp rates such as 10%/sec are routinely observed in the 2 kW but are quite rare in the 1.6 MW system. So the probability of fast fluctuations is indeed greater for the small system.

Given measurements every 1 second, the larger PV system had a maximum (or 99.99th percentile) ramp rate that was only one third as much as the small system. But the suppression of fluctuations is less significant if one examines data with larger averaging times. This effect is visible in Fig. 8 and is summarized in Table II.

TABLE II. RELATIONSHIP BETWEEN THE RATIO OF HIGHEST (99.99TH PERCENTILE) OBSERVED RAMP RATES AND THE AVERAGING TIME

Avg time (τ)	RR (1.6MW) / RR(2kW)
1 sec	0.3
3 sec	0.4
10 sec	0.5
30 sec	0.75
60 sec	0.87
120 sec	0.90

A different statistic is how many seconds are required before a PV system changes its output by 50% of nameplate value. Figure 9 demonstrates the 99.99th percentile observed decrease in output scaled to system size from both systems during the month of May. On this score, we find that the 2 kW system occasionally exhibits fluctuations of 50% (1 kW) in 4 seconds. In comparison, the 1.6 MW system exhibits fluctuations of 50% (800 kW) in 23 seconds.

The large PV system covers 4000 times more area than the small system (35,000 m^2 as opposed to 9 m^2). This ratio is the result of several factors. First, it is rated to produce 800 times more power. Second, between each 4 m wide row there is a 4 m space, whereas the small system is composed of just one row. Additionally, the smaller system is made of SunPower modules which can be more compact for a given power capacity because of their higher efficiency.

Given the ratio of areas covered by the PV systems, one might naïvely expect the fluctuations to be 63 times slower for the larger system. 63 is approximately the square root of the ratio of area, which is a good estimate for the relative lengths and widths (i.e. linear dimensions) for the systems. This factor of 63 times slower might result if the power output were simply reduced in proportion to the transit time for shadows to propagate over a system's length.

The finding that the 99.99th percentile ramp rates are at most 3 times different (i.e. much less than the factor of 63) may be explained by three different hypotheses:

1. Although the large system covers more area, the electrical configuration is significantly different. A single shaded module in a string reduces the power of that string by more than the sticker wattage of the module. Therefore even large systems can be hobbled by dappled shade in short time scales. This is similar to a mismatch loss, where the mismatch in irradiance changes suddenly when the first module in a string gets shaded by a cloud.

2. The ramp rate may be determined by the spatial gradient in opacity for a cloud edge, compounded with the cloud velocity. This is different than the transit time a shadow edge across the length of a PV system.

3. There is more proportional energy stored in the inverter for the small system.

The observation that on sunny days the small system has generally smaller ramp rates suggests that hypothesis 1 has merit. As demonstrated in fig 10, an analysis of sunny days revels that during clear sky days in May the 1.6 MW system exhibited 50-100 kW fluctuations. The individual inverters in the large system report these changes as well. This may be the result of a poor MPPT algorithm or the result of irregular irradiance across the field.

Investigation with inverter manufacturer of the large system and inside similar inverters in the small system indicates the capacitive energy on the DC bus is about 3000J for the large system and 50J for the small system. While the small system does have proportionally more stored energy, these capacities will sustain output for much less than one second.

The impact of time averaging reveals that the while the small system does exhibit more frequent extreme ramp rates, these are generally of very short duration. If power output from the two systems is boxcar averaged for just 10 seconds, they exhibit remarkably similar behavior. This is important when attempting to correlate the width of a ramp rate histogram with the size of an ESS needed to control ramp rates. While the two systems have very different extreme ramp rates as measured at the one second interval, the extreme ramp rates, as measured by the 99.99th percentile ramp rate, do converge on time scales greater than one minute as presented in Figure. 8.

Figure 9 indicates that the commonly observed large changes in power inside a one minute period for both systems are far greater than the 10% maximum allowed by PREPA. This suggests that while the larger system may require a proportionally smaller ESS to control ramp rates, the battery size will not be dramatically smaller.

V. Controlling Ramp Rates with a Battery

The utility electrical grid responds to changes in either generation or load with a change in grid frequency. Line frequency is used to signal at all points in the grid how well current generation and load are matched. On a short time scale the rotational inertia of generators as well as automatic governors respond to match generation to load. On a longer time scale the 'throttle' of generation is adjusted to compensate for mismatch. The sensitivity of a small electrical grid, such as an island, to changes in a Photovoltaic Facility (PVF) output will vary with the time scale (Δt) over which these changes occur. For example the frequency excursion due to a relatively large power change in 1 second, such as step function, may be negligible so long as the 6 second change is not greater than 0.1% of the total load on the grid. To minimize significant frequency excursions, all generation including PV should control ramp rates in power output.

An efficient system for ramp rate regulation will require only the minimum intervention by an ESS to respect ramp rate limits at a variety of time scales. This may be done through dynamically computing high and low limits for current power production. If the native output of the PVF falls within this deadband no intervention by an ESS will be required, otherwise only the minimum intervention is required to bring the net output within the deadband.

High and low limits for power output at any time $P(t_0)$ are based upon an allowed ramp rate ($\Delta P/\Delta$t) and an averaging time (τ). Clarification is needed to precisely explain how the allowed ramp rate is used to establish limits. For example, a given ramp rate such as "10% per minute" may be expressed several ways:

$$\frac{\Delta P}{\Delta \mathrm{t}} = \frac{10\%}{60\ \mathrm{s}} = \frac{1\%}{6\ \mathrm{s}} = \frac{0.16\%}{1\ \mathrm{s}} = \frac{100\%}{10\ \mathrm{min}}$$

So we must define the duration (Δt) over which changes in power (ΔP) will be evaluated. Furthermore, the averaging time (τ) for power measurements is important. Instantaneous measurements are less meaningful because they are less accurate. That is why we recommend a clearly defined averaging time (τ), even if it is shorter than Δt.

We may define high and low limits based on a rolling box-car average of power

$$\text{Low Limit} = L_1(t_0) = \left[\frac{1}{\tau}\int_{t_0-\mathrm{t}_1-\tau}^{t_0-\mathrm{t}_1} P(\xi)\,d\xi\right] - \Delta P$$

$$\text{High Limit} = L_2(t_0) = \left[\frac{1}{\tau}\int_{t_0-\mathrm{t}_1-\tau}^{t_0-\mathrm{t}_1} P(\xi)\,d\xi\right] + \Delta P$$

where t_0 is the present time, τ is the averaging time, t_1 is the time "ago", i.e. the end of the averaging time-window, and $P(t)$ is the power time-series, expressed as $P(\xi)$ for the purpose of integrating over time. The term in brackets computes the average power some time ago. The ramp rate regulation then requires the power at any present time $P(t_0)$ deviate from this term in brackets by no more than +/- ΔP. As is common practice and as we have in previous sections, we note ΔP as a fraction of the nameplate DC power rating for the photovoltaic system, or "% of Pmax".

For consistency, we recommend the present power be computed with a similar average

$$P(t_0) = \frac{1}{\tau'}\int_{t_0-\tau'}^{t_0} P(\xi)\,d\xi$$

where the averaging time (τ') may in general be different from τ for historical power. We will use $\tau' = 1$ second for the remainder of the discussion. Now, with these definitions, we may more clearly state that complying with the ramp rate regulation means that

$$\text{Low Limit} < P(t_0) < \text{High Limit}$$

To expand this method into an algorithm capable of simultaneously controlling multiple time scales we identify the specified τ, t_1 and ΔP as a rule. A set of rules considering different time scales and ramp rate may be simultaneously applied and the most restrictive low and high limits selected. This could permit, for example, controlling ramp rates to a 10% of nameplate change in 60 seconds and 3% in 6 seconds. Such a rule set may be attractive since it permits a wider deadband on the short time scale, but still controls large changes in output.

We consider a simplifying choice where $\Delta P/\Delta$t = 10%/min, = 2 $\times$ Δt, and $t_1 = 1$ s. In this case "10% per minute" would mean, if Δt were set to 60s, that the limits are set by +/- 10% of Pmax plus the recent power averaged over a two minute wide rolling time-window centered one minute ago. Furthermore, choosing $\tau' = 1s$ would then mean that $P(t_0)$ is averaged over the time-window from one second ago through the present.

There is still the possibility that "10% per minute" means stricter limits set by +/- 1% of Pmax plus the power averaged over a 12 second window. An alternative, absurdly relaxed meaning would be that "10% per minute" means the limits are set by +/- 100% of Pmax plus the average power over 20 minutes. The assignment of τ is critical to measuring a ramp rate.

Next, we explore what battery power is needed, as a fraction of PV system size in each case, still assuming $\tau = 2 \times \Delta$t, $t_1 = 1$ second, and $\Delta P/\Delta$t = 10%, but now explicitly considering different values of τ.

This is performed by simulation where a battery response is applied to the recorded power from each system in order to create a summed output which is in compliance with the rule set. In cases where the battery was too small to fully control upward ramp rates, we assumed these ramps could be controlled by selective curtailment of the inverter. So upward ramp rates are always compliant in this simulation. Tables II and III show results for the two systems.

It is also interesting to explore battery size requirement if less than perfect compliance is permitted. By reducing the battery system and tallying seconds where the output of the aggregate system violates the rule set, we mapped out the battery size requirement for each of the rule sets where compliance is required 99.5% of operating seconds and for 98% of operating seconds. An operating second is any second during the day when the system is delivering power to the grid. The month of data studied in simulation contained a mixture of mostly sunny, cloudy and partly cloudy days. To prevent the sunny days from skewing the results, each day is individually scored for compliance.

The results recorded for 99.5% and 98% compliance represent the minimum battery size rounded up to the nearest whole percentage which will be at least 99.5% or 98% compliant on the most difficult day of the month. This day was typically May 6th for both systems.

The smaller system experiences fast dropouts on the 1 to 10 second scale as demonstrated in Fig. 9. The battery power rating must be sufficient to handle the maximum dropout. Compared to the required ramp rate, the generation dropouts occur nearly instantly.

VI. Conclusion

Fluctuations in output power of a 2 kW and 1.6 MW PV system do not scale with system area as might be expected. On time scales shorter than 10 seconds the small system has demonstrably more dynamic output. At longer times, the behaviors converge. We proposed and discussed three hypotheses that may explain this finding.

We also studied the power output ramp rates of the two systems to determine an optimal battery size. The time-window used to measure ramp rates has a strong impact on the required battery size. We proposed a method for measuring and defining ramp rates at multiple time scales. We recommended that PREPA issue a revised ramp rate rule that clarifies (a) the detailed definition of ramp rates with specific averaging times, and (b) different allowable ramp rates (that are slightly more relaxed rules) for the shortest averaging times.

The size of the battery grows nearly linearly with the size of the system. While the ramp rates of the small system are initially greater than the large one, power output from both still changes much faster than the maximum PREPA permitted rate. Just 60 seconds after a leading edge cloud event, the output is reduced by nearly the same percentage from both systems in the extreme cases.

We note that if the intention of the ramp rate requirement is to control even the most extreme cases then the battery must be sized accordingly. However it is significant that a small relaxation in the compliance requirement from 100% to 98% results in a significantly smaller battery system requirement, particularly for the large system. This corresponds to sizing the battery for all but the most difficult days.

TABLE III. BATTERY POWER NEEDED TO COMPLY WITH RAMP RATES, BASED ON ONE MONTH OF DATA FROM THE 1.6 MW PV SYSTEM. THE SINGLE RAMP RATE "10% PER MINUTE" IS EXPRESSED SEVERAL WAYS IN THE FIRST COLUMN. BATTERY POWER IS EXPRESSED IN AC POWER, AS A FRACTION OF PV NAMEPLATE DC POWER.

Maximum allowed ramp rate ($\Delta P/\Delta t$)	**Battery power for 100% compliance**	**Battery power for 99.5% compliance**	**Battery power for 98% compliance**
100% / 10 min	0	0	0
20% / 2 min	47 %	37 %	14 %
10% / 1 min	55 %	45 %	23 %
5 % / 30 sec	59 %	48 %	26 %
1% / 6 sec	60 %	50 %	27 %
0.16% / 1 sec	64 %	52 %	27 %

TABLE IV. BATTERY POWER NEEDED TO COMPLY WITH RAMP RATES, BASED ON ONE MONTH OF DATA FROM THE 2 KW PV SYSTEM.

Maximum allowed ramp rate ($\Delta P/\Delta t$)	**Battery power for 100% compliance**	**Battery power for 99.5% compliance**	**Battery power for 98% compliance**
100% / 10 min	0	0	0
20% / 2 min	52 %	44%	29 %
10% / 1 min	62 %	56 %	37 %
5 % / 30 sec	68 %	59 %	40 %
1% / 6 sec	72 %	58 %	40 %
0.16% / 1 sec	73 %	59 %	40 %

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