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Using Energy Storage to Support Puerto's Rico's Transmission System

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ABSTRACT

As part of the DOE's multi-laboratory effort to provide analysis and tools to support reconstruction and modernization of the Puerto Rico electric grid, Sandia National Laboratory was tasked with making recommendations for how to use energy storage to support the transmission system. Puerto Rico's electric grid is outdated and still recovering from the 2017 hurricane season, and targeted improvements are needed to restore reliability and to provide resilience for future extreme events. This report examined the most critical near-term issues with the transmission system: frequency regulation and response, and analyzed the impacts of incorporating energy storage systems of varying sizes with the goal of immediately minimizing load shedding while laying the foundation for future renewable energy integration. The analysis concluded that 240 MW/60 MWh of energy storage would stabilize system frequency sufficiently to avoid loss of load for rapid load changes or generation outages up to and including loss of the largest generation unit on the island.

ACKNOWLEDGEMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
Hz	Hertz
kV	Kilovolt
MW	Megawatt
MWh	Megawatt hour
PREPA	Puerto Rico Electric Power Authority
STACOM	Static Synchronous Compensator

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INTRODUCTION

As part of the multi-lab effort to provide analysis and tools in support of the Puerto Rico electricity grid, Sandia National Laboratories (Sandia) was tasked with identifying opportunities for deployment of stationary energy storage to support the transmission system.

To enable this effort, Puerto Rico Electric Power Authority (PREPA) provided steady state and dynamic cases developed by Siemens for previous studies of renewable penetration into the PREPA-operated grid as well as cases used to evaluate voltage and dynamic stability. To briefly summarize the findings of those reports:

The renewable integration study[1] looked at future penetration levels up to twelve percent. While PREPA and others have set goals that exceed this penetration level over the next couple of decades, even the twelve percent level would represent a significant change from the current state of things, and so it is convenient and, for the purposes of this present study, reasonable to note that one essential conclusion of that study was that integration of renewable generation would require installation of energy storage equal to at least ten percent of installed renewable capacity, or about one hundred megawatts. Indulging briefly in a mental estimation exercise, projecting the ten percent of renewable capacity ratio into a future potentially containing 30-40% renewable penetration might be expected to require several hundred megawatts. We concede that this is a gross generalization, and make the statement only to demonstrate that an evolution of the grid toward reliance on renewables will certainly require increasing levels of energy storage.

The reliability study[2] provided by PREPA for this study effort concluded that the most pressing stability issue was that of voltage instability. The report also concludes that dynamic instability is not expected to be a concern (under traditional reliability-based evaluation criteria), although the report cites varying levels of spinning reserve margin, depending on the load level scenario studied. The integration study cited above discusses necessary reserve margin, stating that a spinning reserve of 300 MW and regulating reserve of 150 MW must be maintained in addition to 150 MW of fast start reserve.[1] In the integration study, in most cases renewable generation allowed base load units to be operated with sufficient regulating and total spinning reserves. However, during night peak conditions when PV generation was not producing, up to 300 MW of gas turbines was necessary to meet minimum reserve margins. Further, the reliability study (where required reserves are not mentioned), the existing generation fleet only provided 186-210 MW of spinning reserve, and did not discuss how regulating or fast-start reserve margins would be maintained. Without belaboring this point too much, the point is that PREPA is facing reserve shortfalls that could range in to the hundreds of megawatts. And while the reliability study concludes that existing generation is sufficient to *recover* after a large loss of generation, PREPA operators have indicated to the multi-lab team that day-to-day frequency deviations can be severe and can (and sometimes do) lead to unintentional under-frequency line and load shedding. Because it is an island, Puerto Rico's electricity system is particularly sensitive to large frequency excursions due to its inherently low inertia. So even if the system does not shed load, frequency can vary wildly to levels that would be considered unacceptable in any situation in the mainland United States grid. Operators occasionally

[1] It is unclear from the two reports cited whether the reserve margin minimums mentioned in the integration study are fixed minimums or load dependent. The cases studied included loads ranging between 2368 MW and 3181 MW.

must intervene manually in frequency and voltage deviations to bring the system back to equilibrium (which is to say, to bring system frequency back to 60 Hz).

The San Juan load center in the north comprises the majority of PREPA load, and it is in the north that operators typically see problems when trying to move large amount of power from south to north. According to the stability study, when low voltages occur, they are "centered" around the Bayamon and Montecillo substations. It is for this reason that PREPA has plans to install STATCOM's at these two buses.

Based on the various inputs referenced above, we begin the present analysis by making two assumptions:

1. That the most immediate way energy storage can benefit the Puerto Rico grid is by providing fast response services including frequency regulation and response, and perhaps voltage support.
2. Energy storage is modeled as being located at the Bayamon 115kV bus.

To summarize, the present study focuses on identifying the minimum level of energy storage that will be necessary to keep system frequency above a level that triggers under-frequency line and load shedding relays to operate until spinning or supplemental reserves can be brought online to compensate for generator/load mismatch. Essentially, we propose using energy storage to allow the grid get from one stable operating point to the next without significant frequency deviation and without unintentional loss of load. The essence of the strategy we propose is to help grid operators with the problems they face today while designing in a way that allows investments in expansion *as it is needed* to support future renewable integration. In this way, the initial investment costs can be minimized. Said even more simply: invest in energy storage **power** first, then add **energy** capacity later.

1. BASE CASE

The steady state case we used for this analysis was the PREPA 2021 STATCOM case.[2] The load modeled in the case was 2551 MW. According to conversations with Siemens and PREPA, this load level was a reasonable approximation of near term peak levels. The corresponding 2021 dynamic case[3] was used to perform all dynamic simulations.

The energy storage model used was the STORAGE1 model which was developed by Siemens. We chose to work with this model because it is the model Siemens has, and is, using for current energy storage-based dynamic studies. Model parameters were modified to reflect modern energy storage system response times. Specifically, activation and deactivation settings were modified to increase the energy storage system's sensitivity to frequency changes. Storage model gain was increased to reflect the ramp rate capabilities of modern energy storage systems.

[2] 2021-with_STATCOMs-1SCC800-2833MW_G-1.sav. STATCOM's disabled.

[3] PREPA_dyn_FY2021.snp

2. ANALYSIS

As previously mentioned, energy storage was modeled at the Bayamon 115 kV bus. The analysis included starting from the base case with no energy storage modeled, and incremented energy storage in 20 MW steps. We bound the energy storage size by simulating each storage increment against loss of the largest generator in the system: Aguirre 1 dispatched at 380 MW.[4] The justification for this is the assumption that no single event on the system – generator loss or load step – will exceed the impact of the loss of the largest generator. Said another way, by sizing for the loss of the largest generator, the analysis inherently arrives at an energy storage level that will allow for smaller step functions the system sees due to any other generator or load change.
While minimizing load loss was the objective of the analysis, we found that trip settings of under-frequency line and load shedding relays provided a convenient context for understanding results. Conversely, under-frequency trip settings might also be tailored to provide a more controlled load shed profile with respect to available system resources. We do not pursue this idea further in the present study.

In examining the under-frequency line and load trip relay settings in the dynamic case, 58.6 Hz stands out as reasonable minimum threshold frequency. It can be seen in tables 1 and 2 that the trip delay settings for line and load models display an obvious cutoff at 58.6 Hz. In both cases, trip settings below 58.6 Hz are set to shed load quite quickly, while frequencies above 58.6 are tolerated for progressively longer periods of time. AT 58.6 Hz there is a sort of "no man's land" between millisecond order of magnitude settings on the low end and five seconds on the high end.

Based on this, we selected a frequency "threshold" between "fast" acting trips (less than 5 seconds) and the "slow" trips (5 seconds or more) at 58.6 Hz. Therefore, for this analysis we assume that the minimum energy storage power rating will keep system frequency from falling below 58.6 Hz for more than five seconds.

[4] Nameplate capacity of Aguirre Unit 1 is 450 MW, but the large southern generators are dispatched at less than nameplate to provide reserve capacity.

Table 3-1, Under-frequency line trip average settings[5]

Fmin (Hz)	No. of Models	Average trip Setting (sec)
59.2	2	22.5
59	3	20
58.7	1	10
58.6	**5**	**5**
58.6	**6**	**0.03**
58.5	19	0.06
58.4	2	0.06
58.2	29	0.04
58.1	19	0.05
58	11	0.05
57.9	11	0.06
57.8	11	0.05
57.7	7	0.04

Table 3-2, Under-frequency load trip average settings

Fmin (Hz)	No. of Models	Average trip Setting (sec)
59.2	1	60
59.2	7	25
59	4	20
58.8	15	15
58.7	9	10
58.6	**11**	**5**
58.6	**16**	**0.02**
58.5	2	0.03
58.4	8	0.04
58.2	3	0.06
58.1	2	0.03
57.9	3	0.05
57.8	1	0.05
57.7	14	0.05

[5] All trip setting information is taken from the under-frequency line and load trip settings in the dynamic model.

3. RESULTS

Figure 1 shows the results for 20 MW energy storage increments up to 300 MW. The horizontal lines indicate the trip setting thresholds shown in tables 1 and 2 above. It can be seen in the figure that all increments above 220 MW maintain frequency above the minimum 58.6 Hz cutoff. On closer review, however, it was found that while the 220 MW energy storage injection did prevent the nadir from falling below 58.6 Hz, it affected total system recovery in a way that prolonged frequency recovery just long enough to cause tripping for all relays set to 10 seconds at 58.7 Hz, one relay set at 20 seconds at 59.2, and all of relays set at 25 seconds at 59.2 Hz. The relays set to 15 seconds at 58.8 Hz missed tripping by a fraction of a second. Therefore, the first storage increment that avoids frequency drops that might trigger load shedding is 240 MW.

Figures 2 and three are close-up views of figure one to better display frequency behavior near the minimum threshold.

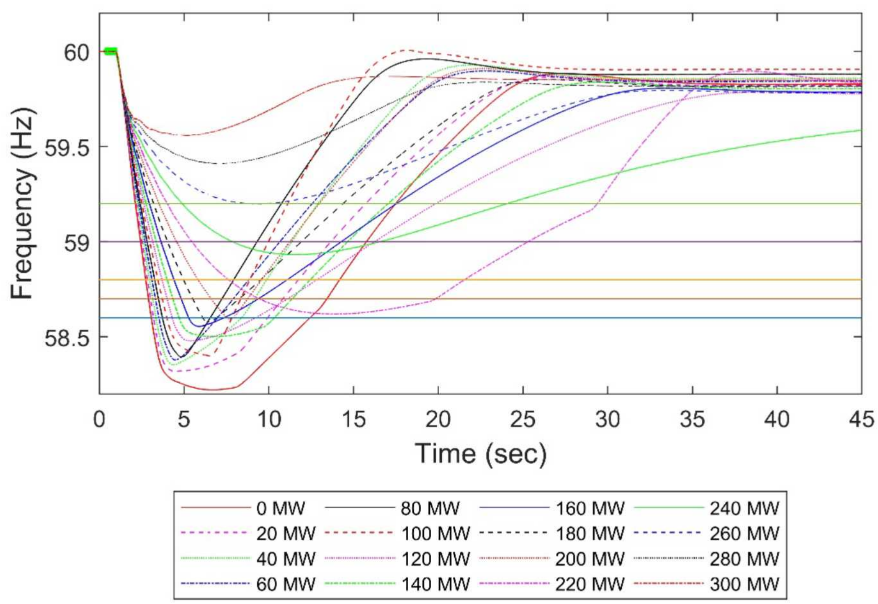

Figure 4-1. Frequency response of 20 MW energy storage power increments for loss of Aguirre Unit 1 showing settling times

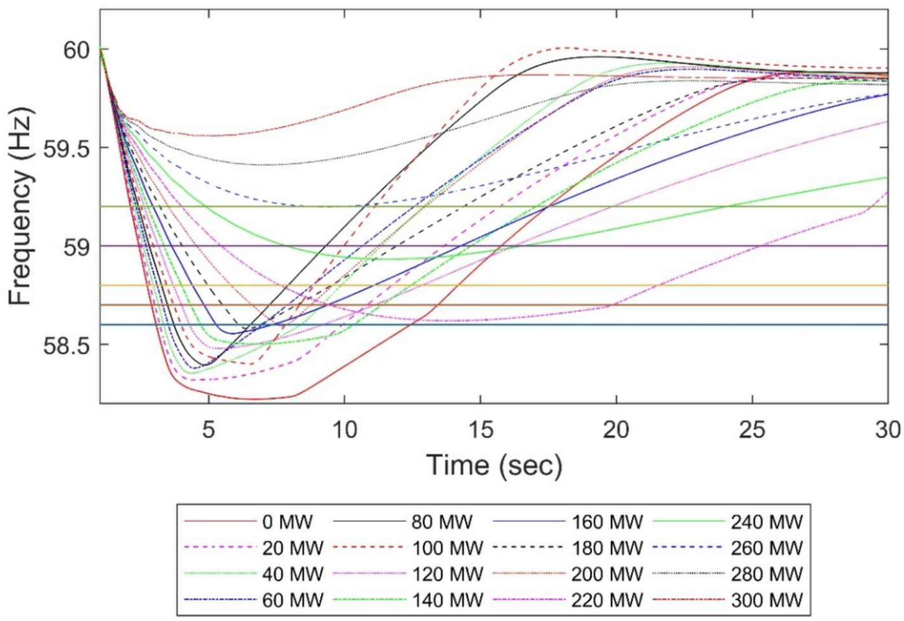

Figure 4-2. Frequency response of 20 MW energy storage power increments for loss of Aguirre Unit 1 showing behavior near trip setting thresholds

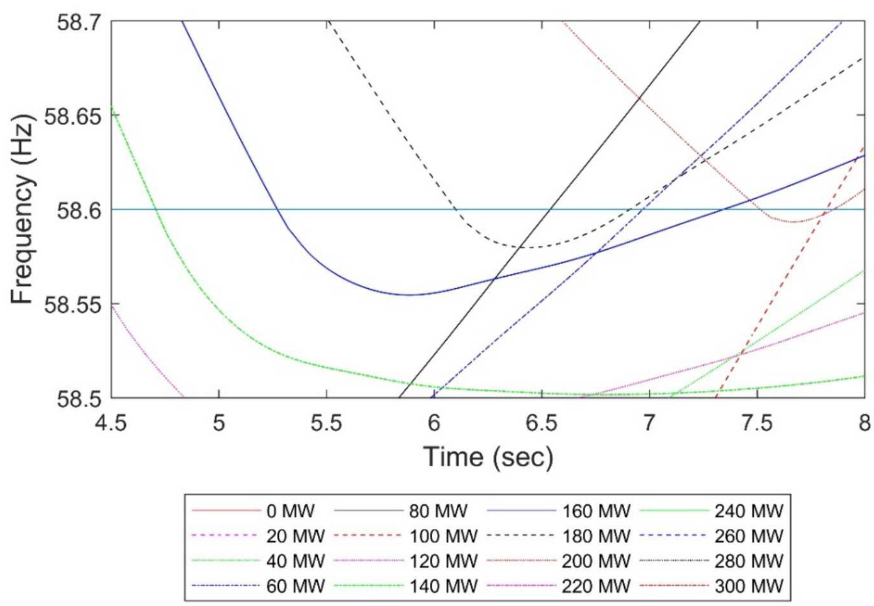

Figure 4-3. Frequency response of 20 MW energy storage power increments for loss of Aguirre Unit 1 near the 58.6 Hz minimum trip threshold

Figures 4 and 5 show load shedding with respect to energy storage increment following the loss of Aguirre Unit 1. Figure 4 is from the perspective of load remaining on line as under-frequency devices shed load to stabilize the system. Figure 5 shows the total accumulation of load being shed. Note that the flat "load shed" across the bottom of figures 5-13 is not a true load shed; rather, it indicates the frequency dependent portion of the original load since, as frequency drops, apparent system load drops. The analog of this phenomenon in figure 4 is apparent in the straight lines representing higher storage increments: while there are no obvious drops in load, the post-disturbance load still settles below the original load due to frequency dependence of loads. As with the frequency graphs, the load shed graphs show that load is being shed until the storage system size reaches 240 MW.

Figures 6-9 break the load shedding action down by area (as defined in the power flow cases) across Puerto Rico. As would be expected, the majority of load shedding is in the north. This behavior supports initial placement of energy storage in the San Juan region.

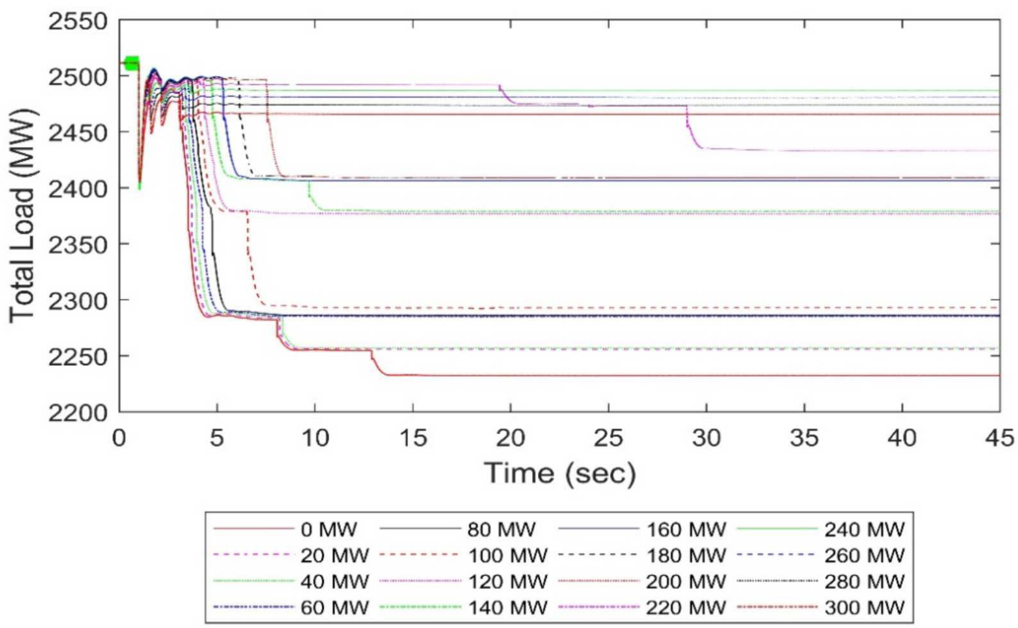

Figure 4-4. Post-disturbance system load as a function of energy storage increment

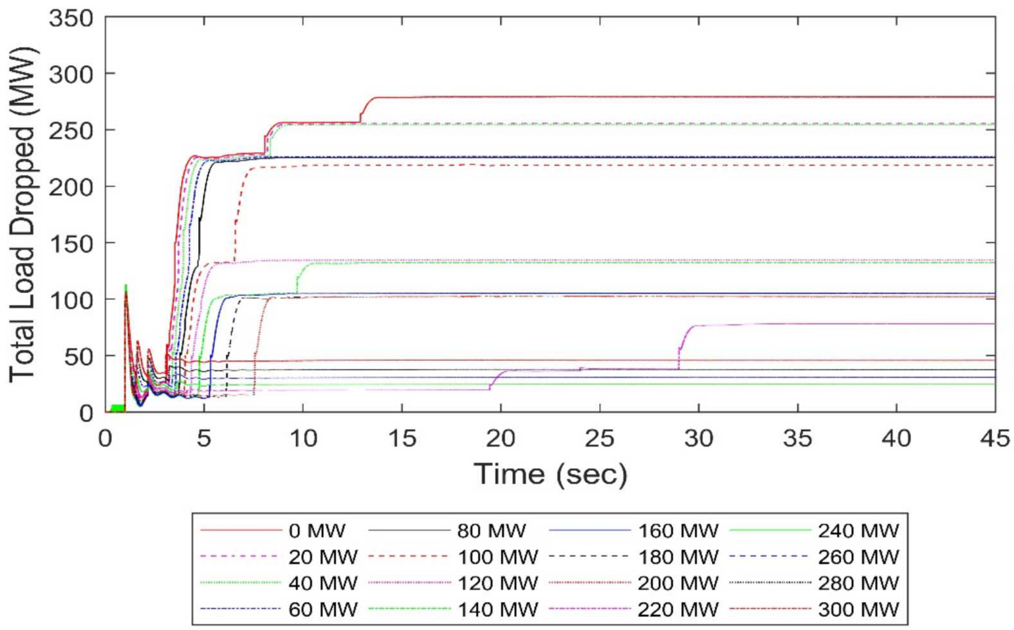

Figure 4-5. Post disturbance load shed as a function of energy storage increment

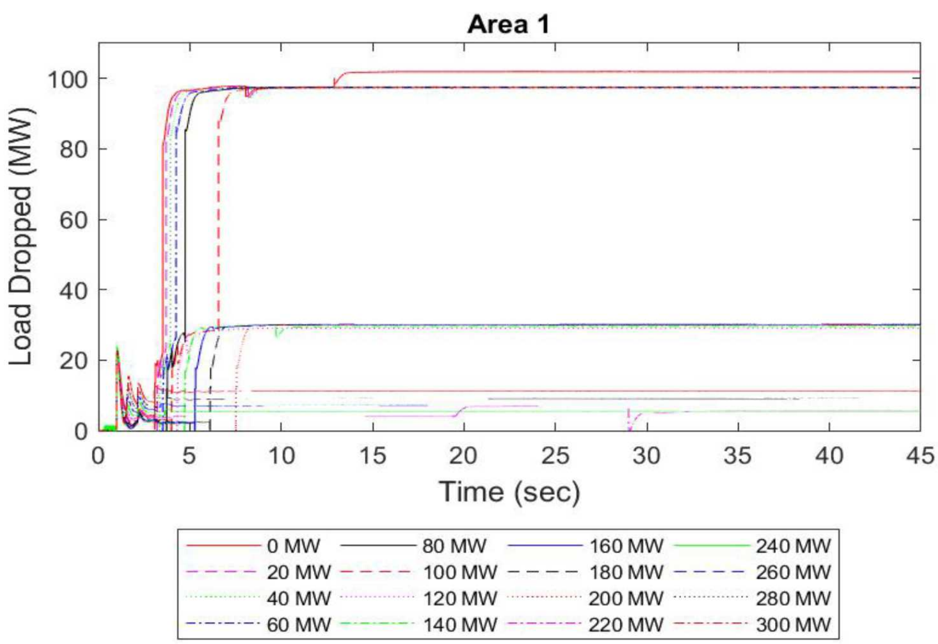

Figure 4-6. Area 1 – San Juan load shedding with respect to storage size

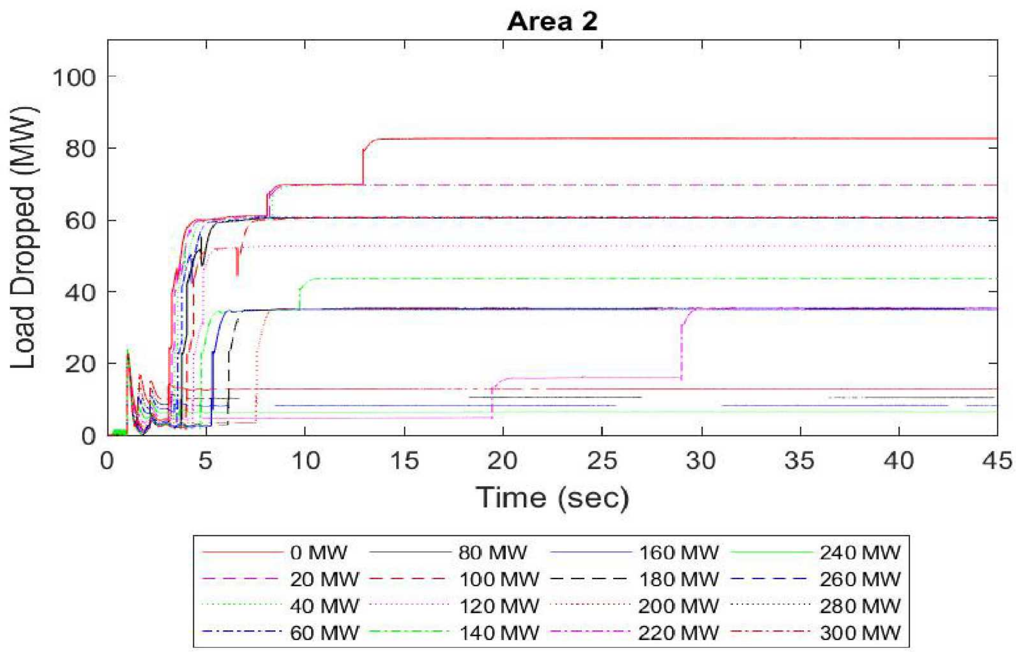

Figure 4-7. Area 2 –Bayamon load shedding with respect to storage size

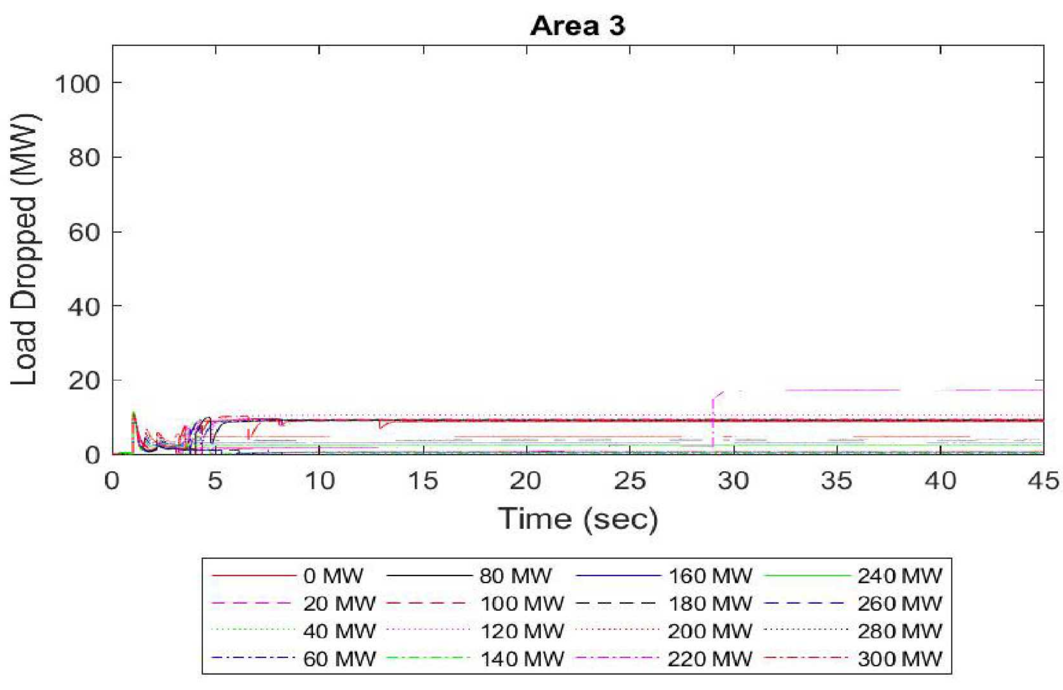

Figure 4-8. Area 3 – Carolina load shedding with respect to storage size

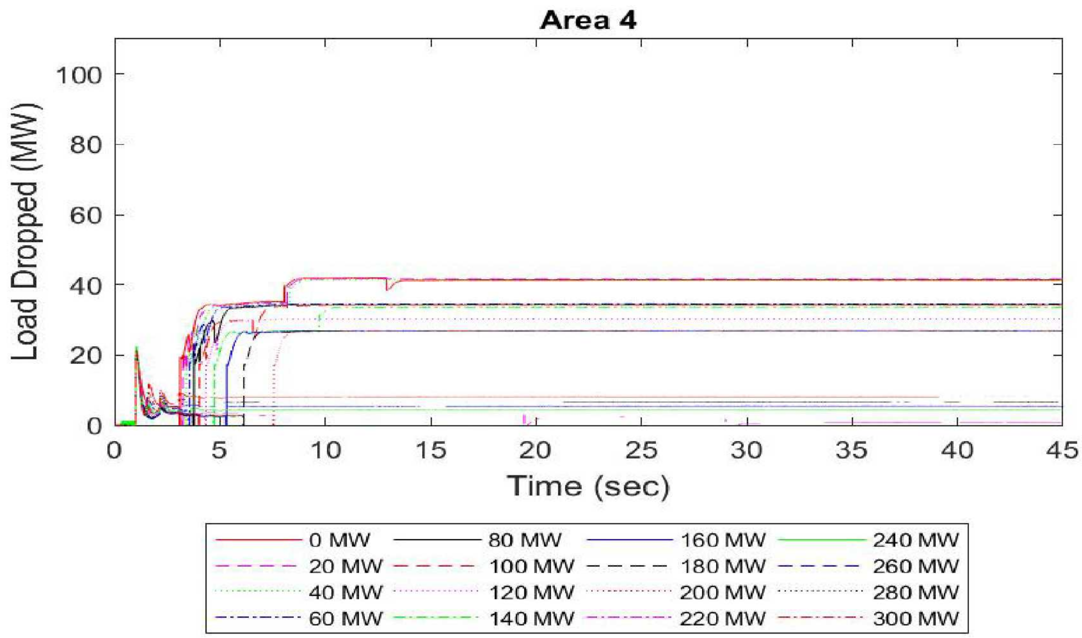

Figure 4-9. Area 4 – Caguas load shedding with respect to storage size

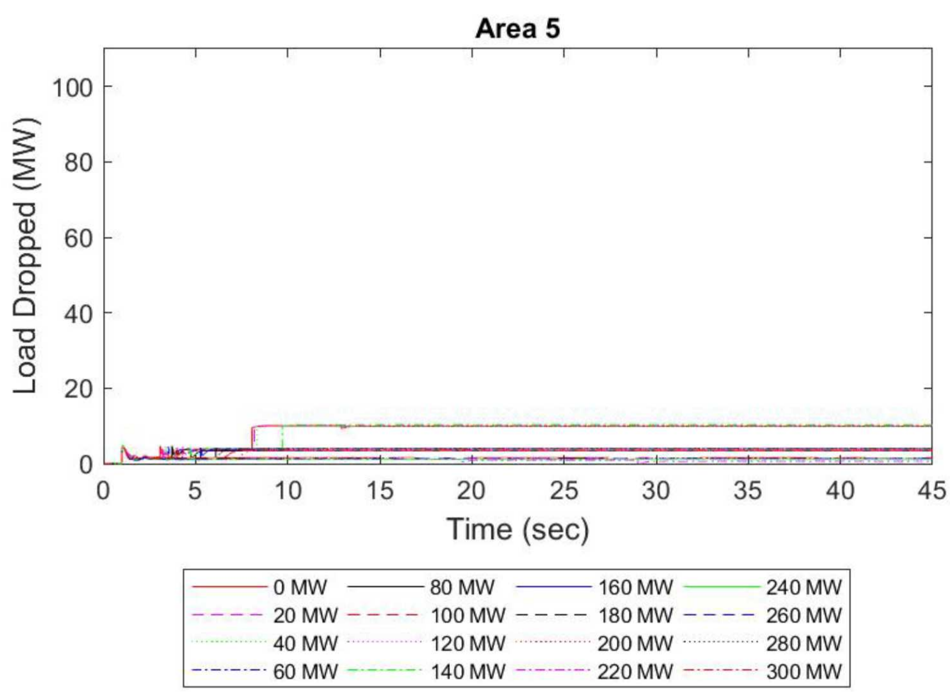

Figure 4-10. Area 5 – Ponce East load shedding with respect to storage size

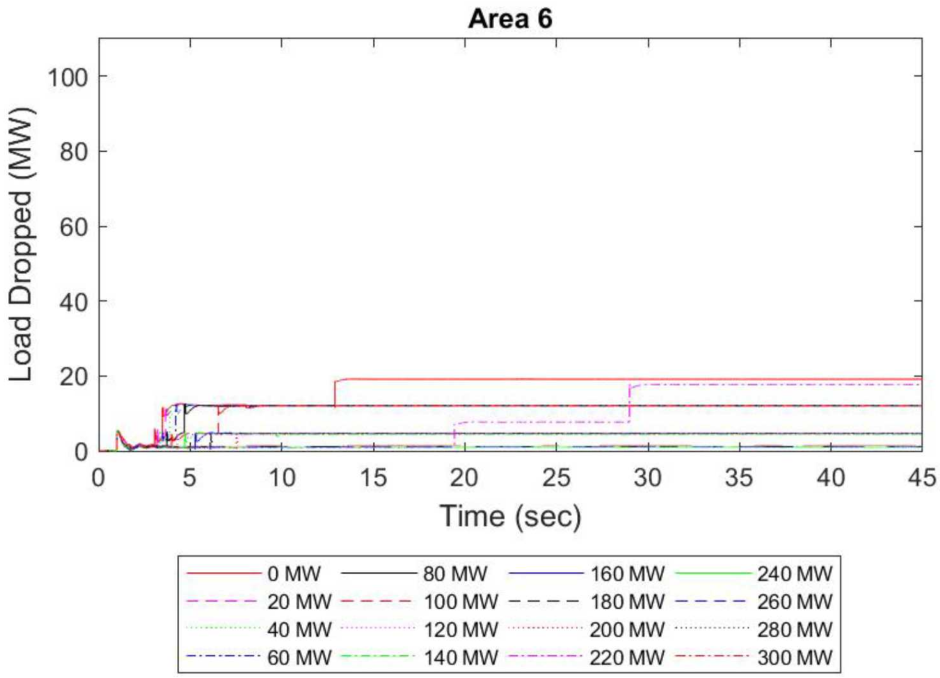

Figure 4-11. Area 6 – Ponce West load shedding with respect to storage size

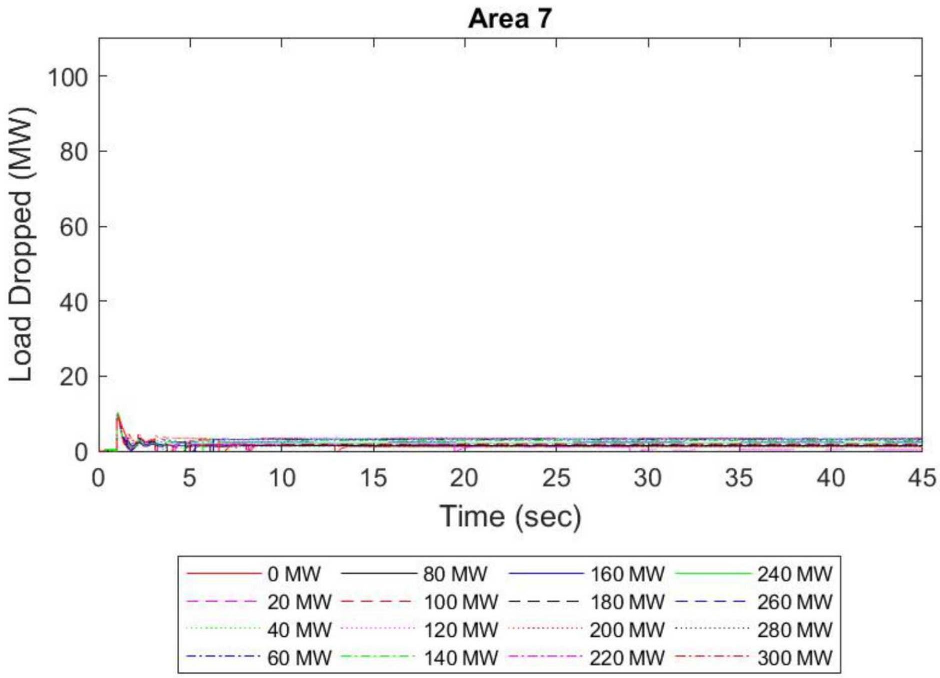

Figure 4-12. Area 7 – Arecibo load shedding with respect to storage size

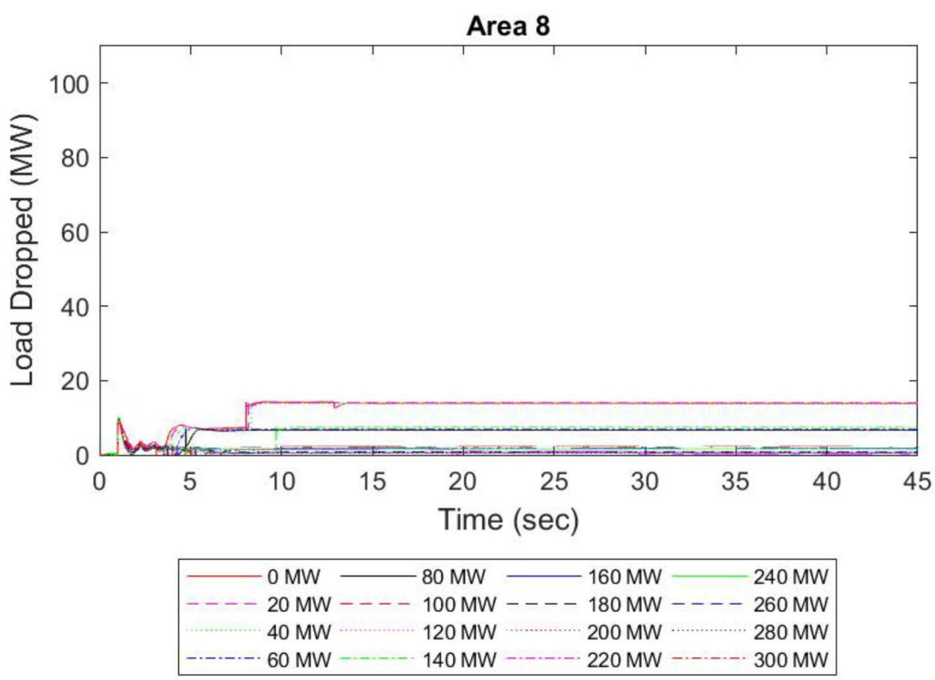

Figure 4-13. Area 8 – Mayaguez load shedding with respect to storage size

4. CONCLUSIONS

The results of this analysis indicate that a 240 MW energy storage system would be sufficient to support system frequency and to avoid load shedding for the worst single generator outage. As was discussed earlier, a "fifteen minute" storage system would be sufficient to realize the benefits of frequency regulation as well as the more severe duty of frequency response. Therefore, the minimum size recommendation is an energy storage system rated for 240 MW/60 MWh. It is worth pointing out that this storage size corresponds very well with the conclusions of previous PREPA studies (cited in this report). For example, the renewable integration study estimates renewable generation will require an amount of energy storage power capacity roughly equal to 10% of new generation capacity – anywhere from 100 MW to 250 MW, depending on how much renewable generation is realized; and both studies indicate potential regulating and spinning reserve deficits or having to use hundreds of megawatts of gas turbines to meet reserve margins.

Based on current industry average storage costs we would estimate a budgetary cost to implement the initial power-focused energy storage capacity would be $100-125 million[6]. We offer this estimate only as an order of magnitude figure; actual costs would depend on a variety of factors including such as choice of technology, manufacturer, integrator costs, etc. When deciding on an investment strategy, the cost of an energy storage system should be balanced by the benefit storage can provide when compared to slower acting traditional generation, as well as taking into consideration that, if designed properly, energy capacity can be added relatively easily to the installations to expand time shifting capabilities and support future renewable penetration goals.

[6] Energy storage system costs based on industry average prices for Li-ion, including power electronics, engineering, procurement and construction, balance of system, and soft costs. Taken from McKinsey & Company, 2017.

REFERENCES

[1] Siemens PTI Report Number: R017-14 PREPA Renewable Generation Integration Study

[2] Siemens PTI Report Number: R056-15, PREPA's System Reliability Study Supplementary Evaluation

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