Proposed Methodology Using the Energy Storage System Prioritization Index

Guillermo Lopez-Cardalda, Eduardo I. Ortiz-Rivera

[1]Department of Electrical and Computer Engineering,
University of Puerto Rico, Mayaguez, Puerto Rico

***Abstract*— The past years Puerto Rico has experienced an increase on blackouts and power outages. The blackouts and power outages aggravated even more after hurricane Maria. This paper proposes a methodology based on Puerto Rico's experience using the energy of the load to rank them and identify which load should be prioritized for a backup power system. The proposed methodology classifies loads into 5 groups: critical, essential, discretionary, non-essential and expendable. Then is presented a model of equations to determine which loads should be considered in the inclusion of a backup energy storage system for a short-term or mid-term investment. A cased of study was used to demonstrate how to use the proposed methodology. These proposed/criteria methodology can be changed or adapted for different regions around the world and for different loads that need energy storage systems.**

Keywords—Resiliency, Energy Storage Selection Prioritization Index

I. INTRODUCTION

Power outages and long-term blackouts cause many problems in the areas of economics, transportation, communication, security, and health. Figure 1 shows the economic effects during the last 20 years [1]. From this graph it can be obtained that historically severe storms cause the most costly damage and continues to increase during the years. Some storm examples are hurricane Sandy, hurricane Harvey, and most recently Texas's winter storm. These outages are lethal for citizens/customers that rely on medical devices that require constant power. This paper addresses the potential impact of storage systems using Puerto Rico as an example. The island of Puerto Rico during the last 4 years has been experiencing the negative effects of a very unreliable electric grid. The Puerto Rico Electric Power Authority (PREPA) (now managed by LUMA) could benefit from energy storage as a potential area of investment given the availability of renewable energy sources on the island (e.g., solar, wind, hydro) [2][3]. Microgrids with energy storage capabilities have been proven to enhance the power system reliability and resiliency. Energy storage systems (ESS) have been shown to be useful in mitigating and compensating for fluctuations in the electric grid caused by insufficient and unreliable generation. ESS design is affected by the number of critical loads, typical duration of power outages, impact to loads, etc. The Energy Storage System Prioritization Index (ESSPI) is a tool for the identification and prioritization of loads and is also useful in the coordination of Rapid Response Mobile Energy Storage System (RRMESS). RRMESS are defined as mobile systems that carry a Battery Energy Storage System (BESS) from one place to another.

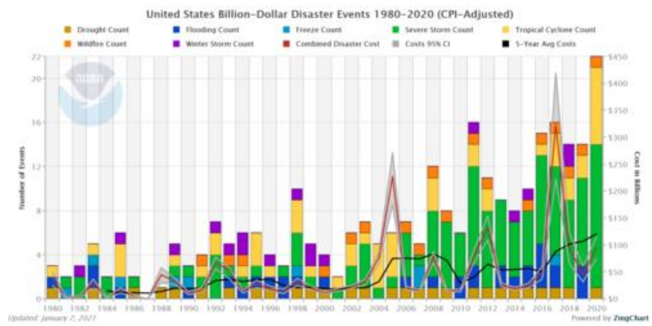

Fig. 1: U.S. Billion-dollar Weather and Climate Disasters, 1980 - 2020 (NCEI Accession 0209268) [1].

Section II in this paper provides background and context for Puerto Rico's energy crisis. Sections III to IV explain the importance of ESS with a brief introduction to the different commercially available storage system technologies that can be used in Puerto Rico and other similar locations. Section V provides guidance on load identification and ranking criteria. Section VI presents a quantitative criterion called Energy Storage System Prioritization Index (ESSPI) which builds on the ranking criteria outlined in Section V and provides guidance on the critical load selection process.

II. BACKGROUND OF ENERGY CRISIS IN PUERTO RICO

The local utility in Puerto Rico has been plagued by numerous blackouts and major power outages during the last decade. Historical data, for the period of 2015-2016, reports more than 54,000 power outages in Puerto Rico. There was an increase in power outages of 24% compared to 2014. Another example is the incident that occurred in Aguirre power plant, located at the southern part of Puerto Rico, was affected by a fire that started within the facilities, causing a three-day blackout (September 21, 2016) [4]. A year after the Aguirre power plant failure, on September 20, 2017, hurricane Maria made landfall on Puerto Rico causing extensive damage to the electrical network. The electrical grid took 325 days to recover, becoming the longest blackout in USA history [2]. According to the Energy Information Administration (EIA), PREPA has experienced outage rates 12 times higher than the U.S. average [5], [6]. For more information about hurricane Maria's effects on PR or PR grid see [2][7][8]. PREPA had previously looked into BESS in 1994 [9].

III. WHY IS ENERGY STORAGE IMPORTANT?

Governments around the world have been spending extensively on ESS projects. The U.S. utility-scale battery storage power capacity has more than quadrupled from the end of 2014 (214 MW) through March 2019 (899 MW) [10]. China has projected cumulative battery capacity of 489 megawatts (MW) or 843 megawatt-hours (MWh) in 2017 to 12.5 gigawatts (GW) or 32.1GWh by 2024 [11]. Some relevant functions of energy storage in microgrids include [12]:

- Stability support— requiring storage capacity durations ranging from fractions of a second to seconds.
- Match different dynamic characteristics of sources/loads— requiring storage capacity durations ranging from seconds to minutes.
- Provide ride through for failures or backup functions— requiring capacity durations ranging from seconds to hours.
- Complement renewable sources—requiring storage capacity durations ranging from a few minutes to hours.

ESS can increase the utilization of power-generation by absorbing power that exceeds the current demand. ESS can smooth the operating costs of a system by charging when energy is significantly cheap and discharging at times when energy rates are much higher. This behavior is called demand charge management [13]. The work being presented focuses on systems that operate as backup or Rapid Response Mobile Energy Storage System.

IV. Example of Commercially Available Energy Storage Systems and Technologies

The technologies described here are available in the market that can be used as ESS [14]. The scope of our research is focused on BESS. There are other types of energy storage systems worth mentioning such as [15]: Pumped Hydroelectric Storage, Mechanical Energy Storage, Hydrogen Energy Storage, Thermal Energy Storage, Compressed Air Energy Storage and Supercapacitors.

A. *General flow battery characteristics:*

- Applicable to storage levels that require a duration of a few minutes to a few hours
- No degradation in “energy storage capacity”
- No potential for fire
- Relatively high cycle/lifespan (For Vanadium)

Vanadium based system specific characteristics:

- Excellent for energy applications that require durations longer than 4 hours
- Lower roundtrip efficiency but longer life and no degradation
- No risk of thermal runaway
- More nascent technology [16]

B. *General solid state battery characteristics:*

- A range of electrochemical storage solutions, including advanced chemistry batteries and capacitors.

Lithium based system specific characteristics:

- Multiple chemistries available
- Rapidly expanding manufacturing base leading to cost reductions
- Efficient power and energy density
- Cost reduction continues [17]
- Rapid Response Mobile Energy Storage System

V. Load Ranking Criteria for Energy Storage Systems

The ranking system outlined in this section separates loads into five categories ranging from least important to most important (*note: examples presented here are based on the reality of Puerto Rico, it is suggested that the loads to be ranked according to the experience for each region/country)*:

- Expendable (0) – Loads with minimal impact. Majority of users do not benefit from them and do not provide life sustaining services. For example: parking lots, flood lighting in sports complexes, advertising lighting and billboards etc. EXL
- Non-Essential (1) – Do not provide life sustaining services, but may impact a non-trivial number of people. For example: cinemas, satellite government offices, coffee shops, bars/pubs, etc. NEL
- Discretionary (2) – Do not provide life sustaining service, but may impact a non-trivial number of people and provide useful services or goods. For example: department stores, private offices, etc. DL
- Essential (3) – Have high impact on services for the majority of people. Provide non-critical life sustaining services or manufacturing capability that supports critical services. For example, restaurants, the pharmaceutical industry, bakeries, agriculture, food processing industry, fire department, etc. EL
- Critical (4) – indispensable and absolute necessary loads for life sustaining, health and security services. For example, food stores, shelters, hospitals, police departments, communications, government, etc. CL

The proposed load ranking system is related to the projected time recovery horizon of each load. The Reliability, Resiliency & Recovery Energy Systems (RE3) concept presented in this paper is treated as three kinds/types of investment:

1. Short-Term Investment – guarantees a reliable system that includes Critical Loads (CL) and Essential Loads (EL).
2. Mid-Term Investment – guarantees a resilient system that includes Discretionary Loads (EL) and Non-Essential Loads (DL).
3. Long-Term Investment – guarantees a fully recovered system that includes Expendable Loads (EXL).

The RE3 Segmentation Curve presented in Fig. 2 is the expected energy restoration time curve for all loads after a blackout. The idea of the RE3 concept is to minimize the impact of a blackout to society wellbeing and economy as mentioned before.

For more information on black start and BESS integration guidelines see "*System Restoration from Blackstart Resources*" and "*Modeling, and Simulations of BPS Connected Battery Energy Storage Systems and Hybrid Power Plants"* from the North American Electric Reliability Corporation (NERC), and Order No. 841-845 of the Federal Energy Regulatory Commission (FERC) [18],[19],[20], [21].

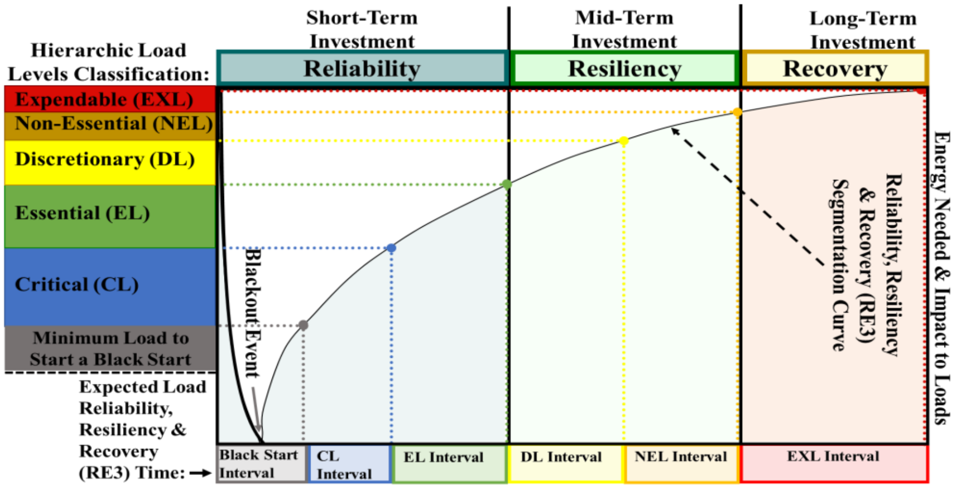

Fig. 2: Proposed Load Reliability, Resiliency & Recovery Load (RE3) Curve. This figure illustrates how should be the RE3 after a blackout.

VI. Proposed Energy Storage Selection Prioritization Index

This section describes the methodology for the proposed Energy Storage Selection Prioritization Index (ESSPI). The different ESSPI variables are:

1. $t_{(n)}$ – Maximum Critical Recovery Time: The maximum down time a load can experience before services are affected. Maximum critical recovery time is measured in *days*. **Example:** A hospital does not have energy because an outage occurred. How many days can it stand to be without power before affecting patients?
2. $T_{(n)}$ – Complete Recovery Time: Number of *days* a load requires to recover from a blackout. After an event, analysis of the affected areas is required to gauge the complete energy restoration time. **Example:** The transmission lines that energize the hospital are damaged and their repair requires seven days to be completed. The complete recovery time for the hospital is seven days.
3. $CLE_{(n)}$– Critical Load Energy: Total energy needed from loads classified as critical in section 5. Units are in *kilowatt-hours (kWh).*
4. $ELE_{(n)}$– Essential Load Energy: Total energy needed from loads classified as essential in section 5. Units are in *kilowatt-hours (kWh).*
5. $DLE_{(n)}$– Discretionary Load Energy: Total energy needed from loads classified as discretionary in section 5. Units are in *kilowatt-hours (kWh).*
6. $NELE_{(n)}$– Non-Essential Load Energy: Total energy needed from loads classified as non-essential in section 5. Units are in *kilowatt-hours (kWh).*
7. $EXLE_{(n)}$– Expendable Load Energy: Total energy needed from loads classified as expendable in section 5. Units are in *kilowatt-hours (kWh).*
8. VLE– Vital Load Energy: The sum of the number of *i* $CLE_{(n)}$ loads and the number of *j* $ELE_{(n)}$ loads of the system. Units are in *kilowatt-hours (kWh).*

$$VLE = \sum_{n=1}^{i} CLE_{(n)} + \sum_{n=1}^{j} ELE_{(n)} \tag{1}$$

9. SLE– Supplementary Load Energy: The sum of all the number of *m* $DLE_{(n)}$ loads and the number of *k* $NELE_{(n)}$ loads of the system. Units are in *kilowatt-hours (kWh).*

$$SLG = \sum_{n=1}^{m} DLE_{(n)} + \sum_{n=1}^{k} NELE_{(n)} \tag{2}$$

10. TLE– Total Load Energy: The sum of the VLE, SLE and all the *q* $EXLE_{(n)}$ loads. Units are in *kilowatt-hours (kWh).*

$$TLE = VLE + SLE + \sum_{n=1}^{q} EXLE_{(n)} \tag{3}$$

11. $PoCLI_{(n)}$ – Precent of Classified Load Impact: Each *type of load* (ToL) divided by *TLE*.

$$PoCL_{(n)} = \frac{ToL}{TLE} \times 100$$

12. $STESSPI_{(n)}$– Short-Term Energy Storage Selection Prioritization Index: Eq. 4 and Eq. 5 are used to calculate the index that helps prioritize loads earmarked for short-term ESS investment. Each load classified as critical or essential will have an assigned value as defined in Eq. 4 and Eq. 5 respectively. Loads with higher index values will be prioritized overloads with lower index values.

$$STESSPI_{(n)} = \frac{CLE_{(n)}}{VLE}\left(\frac{T_{(n)}}{t_{(n)}}\right) \tag{5}$$

$$STESSPI_{(n)} = \frac{ELE_{(n)}}{VLE}\left(\frac{T_{(n)}}{t_{(n)}}\right) \tag{6}$$

13. $MTESSPI_{(n)}$– Mid-Term Energy Storage Selection Prioritization Index: Eq. 7 and Eq. 8 are used to calculate the index that helps prioritize loads earmarked for mid-term ESS investment. Each load classified as discretionary or non-essential will have an assigned value as defined in Eq. 7 and Eq. 8, respectively. Loads with higher index values will be prioritized overloads with lower index values.

$$MTESSPI_{(n)} = \frac{DLE_{(n)}}{VLE + SLE}\left(\frac{T_{(n)}}{t_{(n)}}\right) \quad (7)$$

$$MTESSPI_{(n)} = \frac{NELE_{(n)}}{VLE + SLE}\left(\frac{T_{(n)}}{t_{(n)}}\right) \quad (8)$$

VII. ESSPI Test Case Scenario: Culebra, PR

The following ESSPI test case scenario will use the data provided by NREL report (Contract No. DE-AC36-08GO28308) [20]. Culebra is a small island part of the Puerto Rico archipelago with a population of nearly 1,700 [21]. After hurricane Maria, Culebra's electrical energy services took more than a year to recover to the current electrical system state. The NREL report provides information related to critical and essential loads in this municipality. From the NREL report the following buildings were considered as critical (Table 1) and essential (Table 2). These buildings are the Health Clinic, Wastewater Treatment Plant (WWTP), Municipal Building, Police Station and Fire Station. For the demonstration of the case study the municipal building it will be considered as discretionary (Table 2). The blue color indicates the buildings considered as critical loads (CL), the green color indicates the buildings considered as essential loads (EL) and the yellow color indicates the buildings considered as discretionary. The Maximum Critical Recovery Time (t) for the hospital is based on research on how time a hospital can withstand without energy [22]. The other scenarios are estimations based on community feedback and other scenarios are modified for proof of concept of ESSPI [23]. In case of Under Normal Recovery Time Event (T) this time is presented as a hypothetical case where the service is down for any reason just to prove with different cases for the ESSPI analysis. Table 3 and Table 4 present the inputs and results for the ESSPI analysis.

As it can be seen the Maximum Critical Recovery Time (t) from the health clinic means they are capable of withstanding 3 days without energy (considering it has a backup generator) and Under Normal Recovery Time Event (T) means they have to wait 2 days until the energy is recovered. After evaluating Comparing the health clinic case with the WWTP which cannot stay more than 6 hours without energy, the WWTP's STESSPI is much bigger which means it cannot stay without energy after an event that affects the energy services. For the case of MTESSPI it can be seen that the value of the index is bigger (Table 4) when compared with the hospital (Table 3), because the classification beforehand of this load as CL still keeps its prioritization of being integrated on a BSS. By performing an analysis with ESSPI one can identify between each rank, in cases of CLG, which one is has a higher priority and would receive the services from an ESS after an event. ESSPI can discriminate between loads that have already an electrical backup system by adding the time to $t_{(n)}$ like the hospital example. In case of RRMESS existence based on the ESSPI results WWTP and Hospital Clinic would receive priority.

Fig. 3: Sky view of a part of Culebra

Table 1: Buildings that are considered as critical loads (CL)

Infrastructure Type (Culebra, PR)	Health Clinic	WWTP
Annual Energy Use (KWh)	251,712	248,200

Table 2: Buildings considered essential loads (EL) and discretionary (DL)

Infrastructure Type (Culebra, PR)	Police Station	Fire Station	Municipal Building
Annual Energy Use (KWh)	41,086	27,316	203,085

Table 3: ESSPI Analysis for Short-Term

Infrastructure Type (Culebra, PR)	Health Clinic	WWTP	Police Station	Fire Station
t (days)	3	0.25	1	1
T (days)	2	2	1	3
STESSPI	0.2953	3.4938	0.0723	0.1442

Table 4: ESSPI Analysis for Mid-Term

Infrastructure Type (Culebra, PR)	Municipal Building
t (days)	1
T (days)	2
MTESSPI	0.5265

VIII. Conclusion

ESS should be considered not only for Puerto Rico but also for locations in the Caribbean like the US Virgin Islands. Energy storage should be analyzed based on the impact to the electric utility but its potential benefits to guarantee energy to critical loads. Also, ESS could provide an added value and improve the reliability of the current electric grid. Investment on energy storage systems could provide reasonable solutions to remote loads, industrial loads, and sensitive loads to mitigate energy fluctuations. At the present, PREPA should consider the investment of energy storage systems using locate state properties to increase the reliability of the current electric system.

The ESSPI presented in this paper can be used to rank loads in any macro or micro scale electrical system. Also, ESSPI can identify which load has to be prioritize based on the energy, maximum time a load that can withstand without energy and how many days (time) it takes to recover the blackout/outage.

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