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Analysis of Microgrid Locations Benefitting Community Resilience for Puerto Rico

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Abstract

An analysis of microgrids to increase resilience was conducted for the island of Puerto Rico. Critical infrastructure throughout the island was mapped to the key services provided by those sectors to help inform primary and secondary service sources during a major disruption to the electrical grid. Additionally, a resilience metric of burden was developed to quantify community resilience, and a related baseline resilience figure was calculated for the area. To improve resilience, Sandia performed an analysis of where clusters of critical infrastructure are located and used these suggested resilience node locations to create a portfolio of 159 microgrid options throughout Puerto Rico. The team then calculated the impact of these microgrids on the region's ability to provide critical services during an outage, and compared this impact to high-level estimates of cost for each microgrid to generate a set of efficient microgrid portfolios costing in the range of $218-$917M. This analysis is a refinement of the analysis delivered on June 01, 2018.

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1. INTRODUCTION

The US Department of Energy's (DOE's) Office of Electricity Delivery and Energy Reliability, in collaboration with DOE's Office of Policy, has funded the national laboratories to perform modeling, analysis, and high-level design of resilience-enhancement options for the Commonwealth of Puerto Rico. Among other responsibilities, DOE will be making recommendations to the Department of Housing and Urban Development (HUD) and the Federal Emergency Management Agency (FEMA), while supporting efforts to better prepare Puerto Rico for future storm seasons. Sandia has been tasked with concentrating on improvements in the categories of energy storage and microgrids. In addition, the software tools employed in this analysis will be delivered to Puerto Rico and associated stakeholders in Phase 2 of this effort.

This report describes recommendations for microgrid deployment and/or pre-positioning and hardening of existing electrical distribution system assets in Puerto Rico. Sandia National Laboratories (Sandia) has performed an analysis of microgrid locations conducive to improving community response to major disruptions across the island. These recommendations are supported by the Urban Resilience Planning Process, which focuses on designing and evaluating infrastructure improvements in order to improve community-focused, performance-based resilience metrics. This analysis concentrates on making recommendations for microgrids that will improve the resilience of communities throughout Puerto Rico. This study has been performed for the entire island of Puerto Rico, including the islands of Culebra and Vieques. Figure 1 shows the planning regions for Puerto Rico Electric Power Authority (PREPA) which are used throughout this study. Figure 2 shows the population density across Puerto Rico.

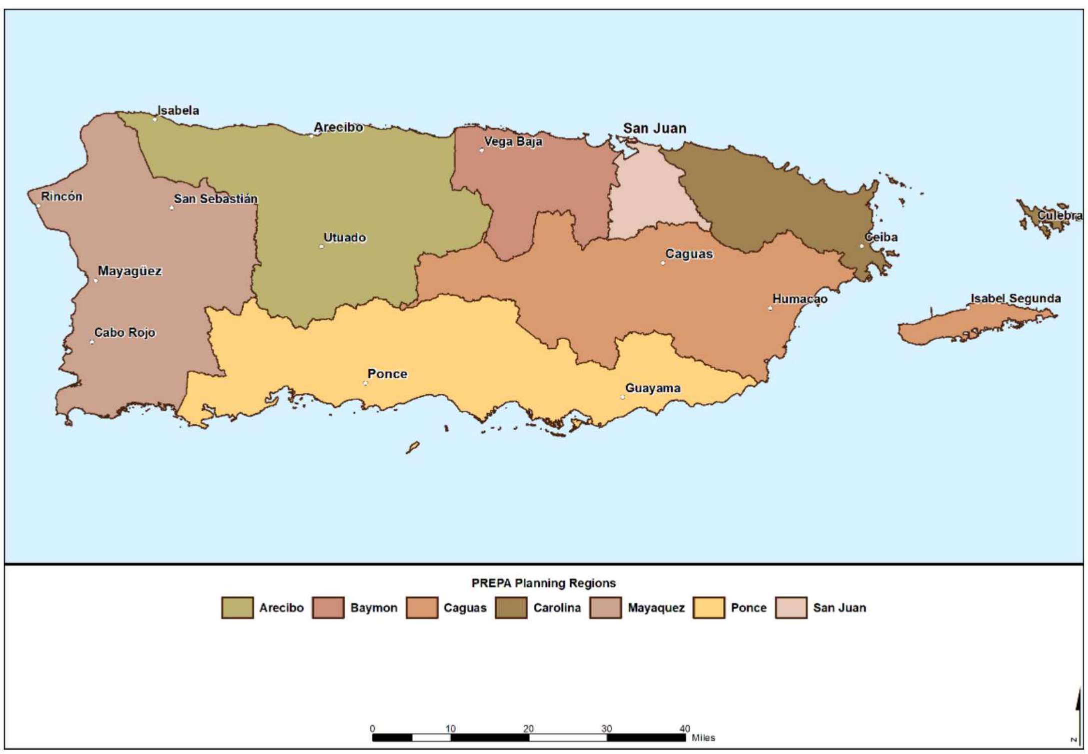

Figure 1. PREPA Planning Regions Used in this Analysis

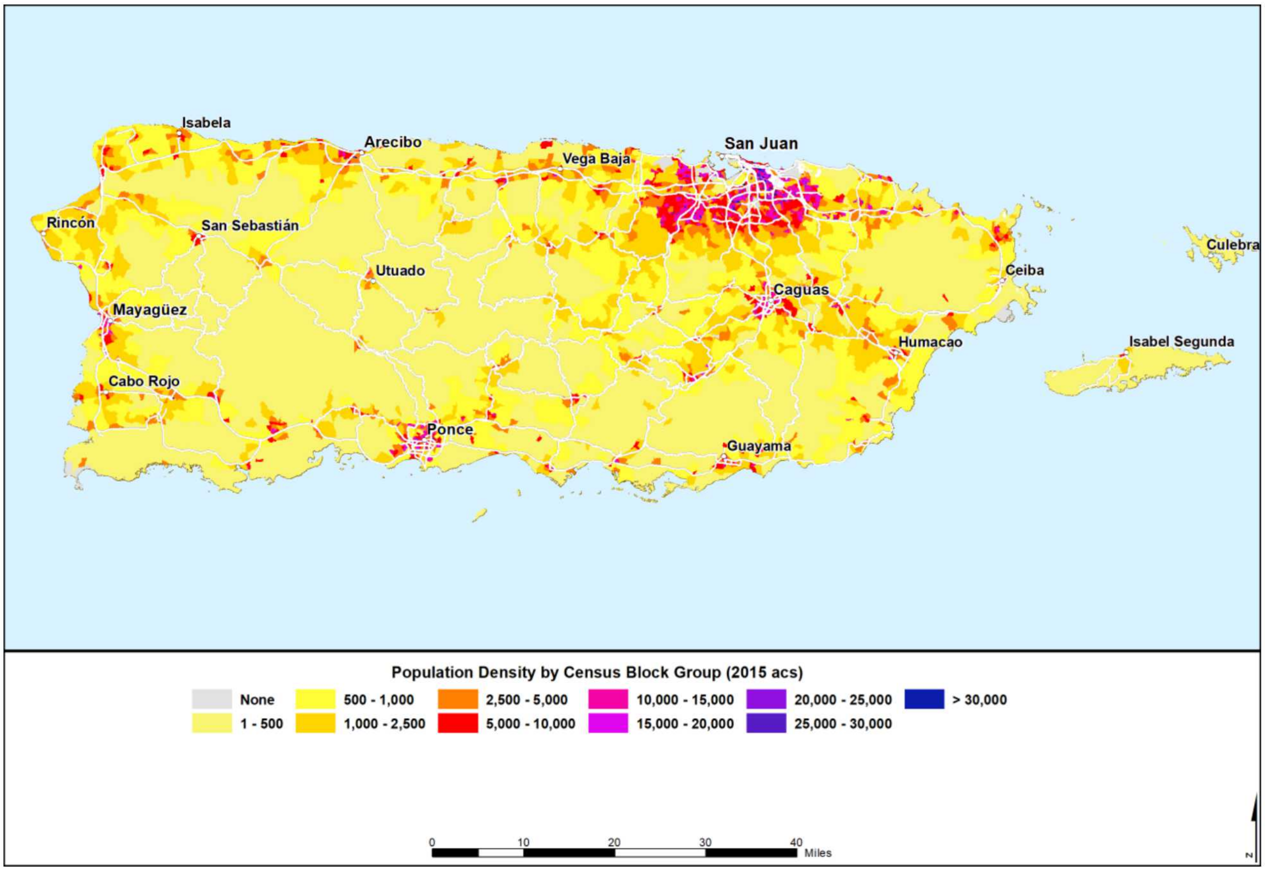

Figure 2. Map of Puerto Rico Population Density by Census Block Group (US Census Bureau 2015)

2. SHOCKS, STRESSES, AND KEY INFRASTRUCTURES

For this analysis, Sandia considered flooding, high winds, earthquakes, and landslide as the major drivers of consequence to Puerto Rico. Other hazards Sandia discussed but did not incorporate directly into this analysis include tsunami, cyber-attack, electromagnetic pulse, and dam failure. For flooding, the 100-year and 500-year floods as designated by FEMA within the National Flood Hazard Layer represent probabilistic flood risk associated with multiple threat types – hurricanes, rain storms, coastal flooding, etc. (FEMA, 2017). The 100-year flood has a 1% probability of occurrence within any given year, while the 500-year flood similarly has a 0.2% probability of occurrence within a given year. The 100-year and 500-year flood contours for Puerto Rico are illustrated in Figure 3.

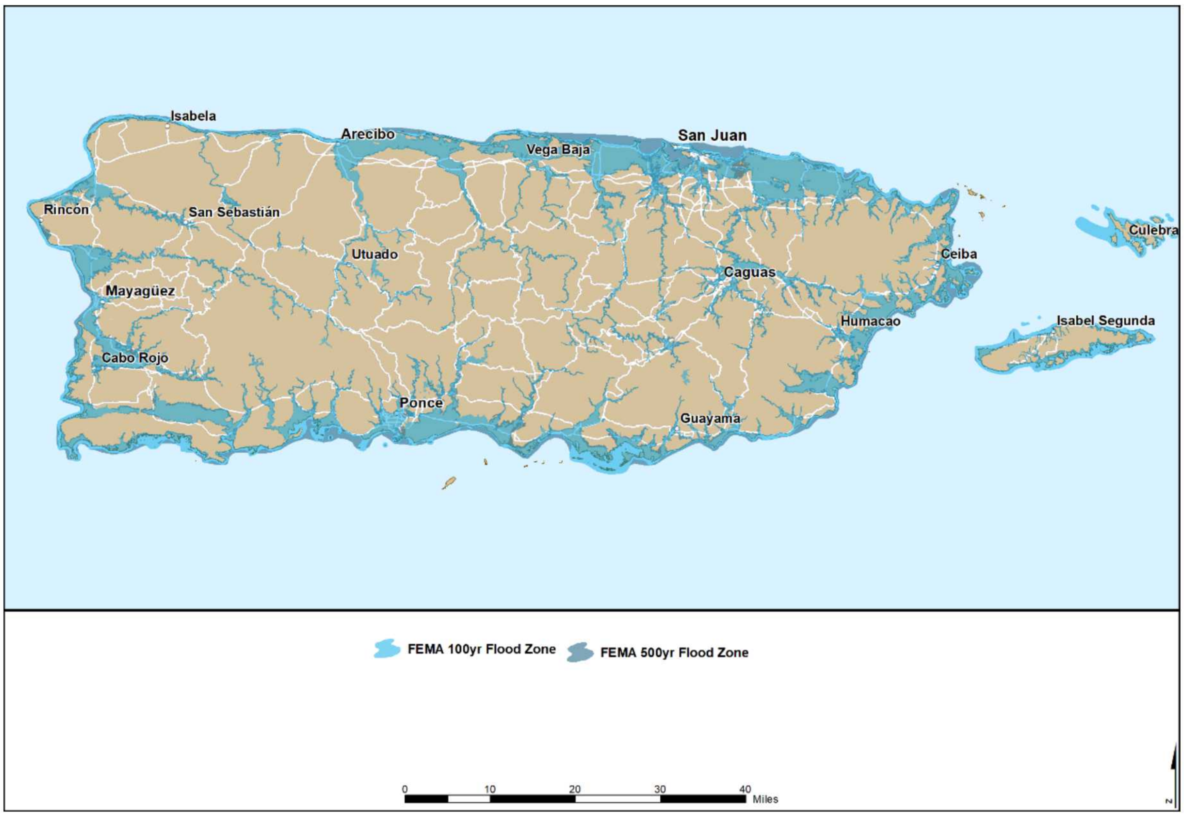

Figure 3. The 100-year and 500-year FEMA Flood Zones for Puerto Rico

For the wind hazard, Sandia consulted research supporting ASCE 7-10 which calculates the peak gust wind speeds for 50-year, 100-year, and 700-year return periods across multiple threat types including hurricanes. Wind contours for the 50, 100, and 700-year return periods are illustrated in Vickery et al. (2007). For landslide, Sandia incorporated the landslide susceptibility layers that were shared by the Puerto Rico government and US FEMA following Hurricane Maria, illustrated in Figure 4. No occurrence probabilities were associated with this dataset. For earthquake, Sandia consulted the US Geological Survey (USGS) Seismic Hazard Maps, which were last populated for Puerto Rico in 2003 (USGS 2003). These maps describe likelihood of various extents of damage (light, moderate, etc.) at a 2% chance in 50 years and a 10% chance in 50 years, illustrated in Figure 5.

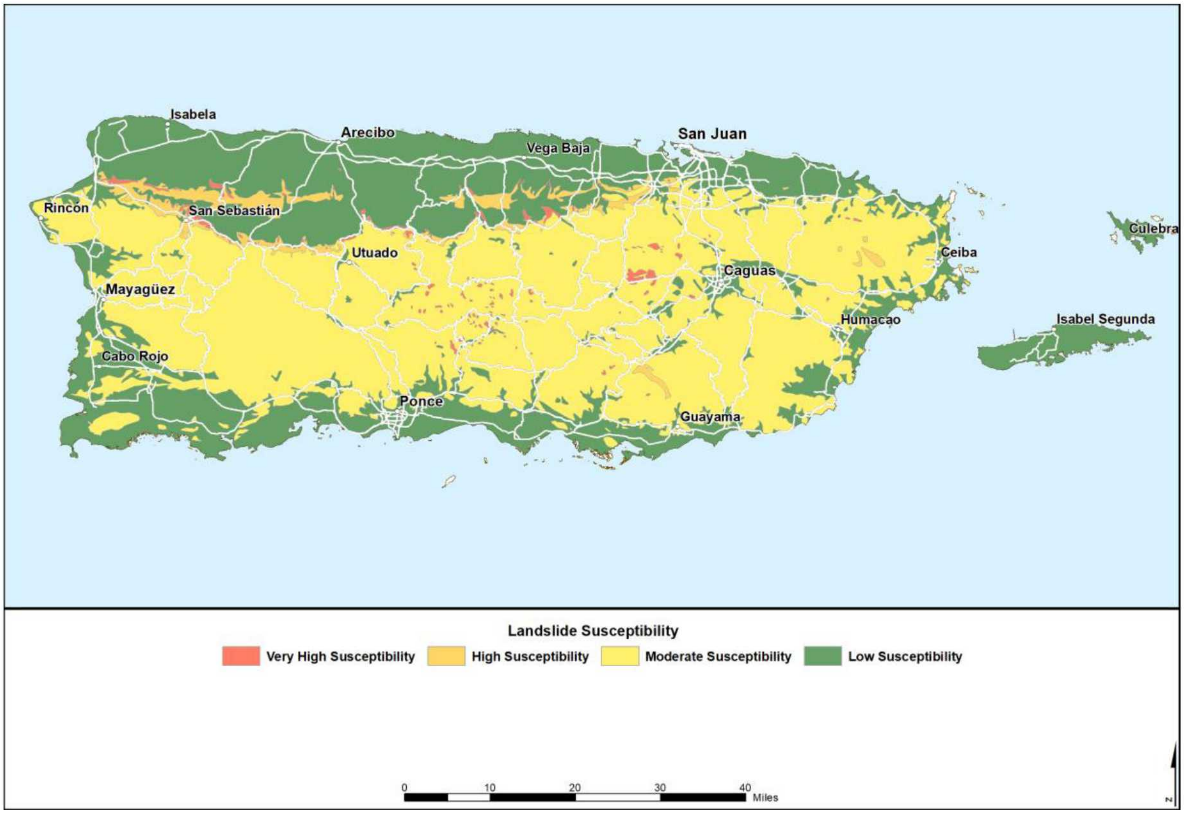

Figure 4. Landslide Susceptibility for Puerto Rico

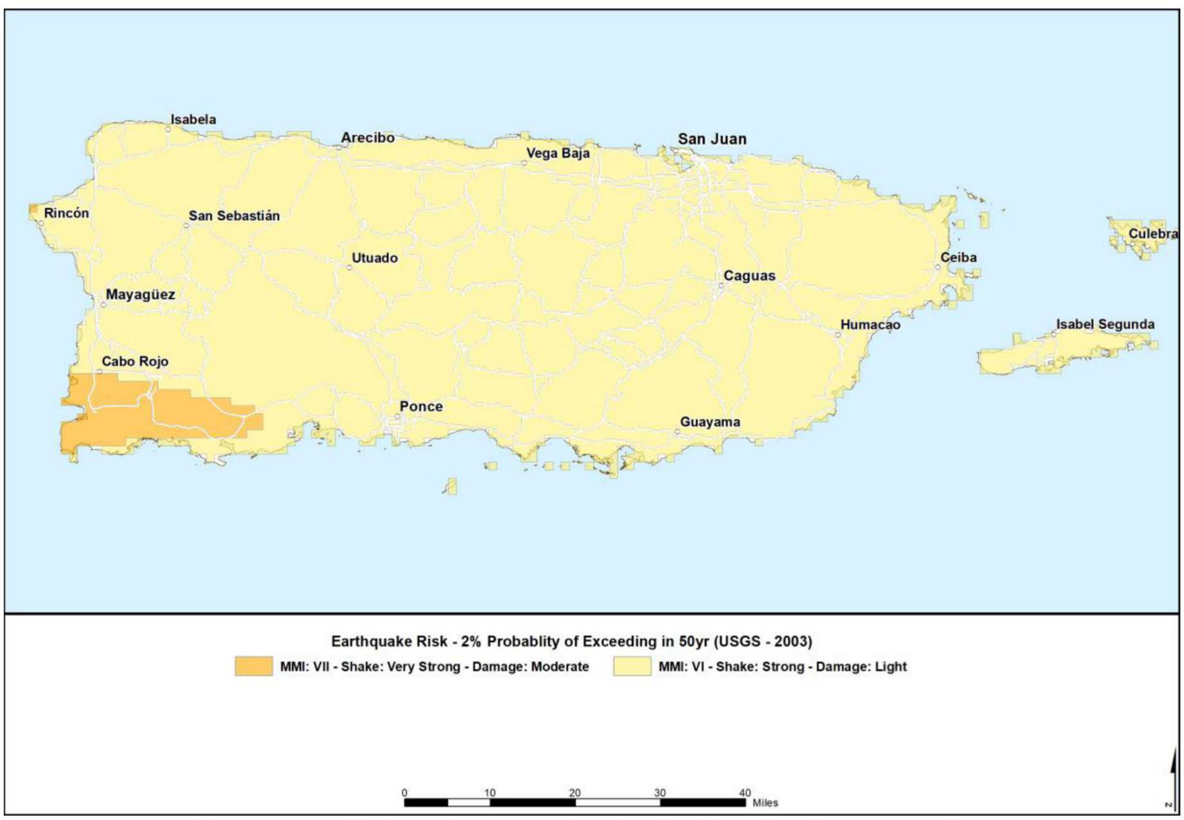

Figure 5. USGS Earthquake Risk Map for Puerto Rico

For planning purposes, seemingly rare events are conceivable over a reasonably near-term planning horizon. For example, the probability that Puerto Rico observes at least one event at or above the 100-year intensity over the course of 30 years is 26%. For the 500-year event this probability is approximately 6%. This probability is calculated taking the rate of return (e.g. once in 100 years) as the counting rate in a Poisson distribution:

$$P_t(r) = \frac{(\mu\, t)^r}{r!} e^{-\mu t} \tag{1}$$

Where r is the total number of occurrences (in this case we subtract the probability of seeing exactly zero occurrences over the 30 years from a probability of 1), t is the planning horizon (30 years), and μ is the rate of return (1/100, 1/500, etc.).

The infrastructure sectors Sandia has considered map to a smaller number of infrastructure services, as indicated in Table 1. For example, pharmacies may be the primary providers of medications during an emergency, but minor conditions may be able to be treated with over-the-counter medications available at larger grocery stores or even gas stations. In this case, pharmacies are designated a high contributor of medication services, while grocery stores and gas stations are designated as a low contributor of these services. In the analysis of microgrid siting, points are awarded to each infrastructure asset based on the levels of service they provide. The range of service contribution need not be confined to three categories; for instance infrastructure in the high and low categories can be designated as extra high or extra low and be assigned more or fewer points accordingly.

Table 1. Infrastructure to Community Service Mapping

Community Service	Level of Contribution by Infrastructure Sector		
	High	**Medium**	**Low**
Communications	Cell Towers; Wire Centers; Internet		Microwave Transmitters
Emergency Logistics	Local Emergency Operations Center; PEP	AM Radio Station Transmitters; FM Radio Station Transmitters	Evacuation Sites ; Points of Distribution; Official Shelters; Unofficial Shelters; Wire Centers; Cell Towers
Evacuation	Evacuation Sites; PEP; Airports	Wire Centers; Rail Stations; Bus Main Stations; Cruise Terminals	Police Stations; Local Emergency Operations Center; Cell Towers; Rail Operations and Maintenance; Bus Garages; Ferry Terminals
Finance	Bank Mains	Bank Branches	Wire Centers
Food	Points of Distribution; Large Grocery Stores; Airports	Small Grocery Stores	Official Shelters; Unofficial Shelters; Hotels; Gas Stations; Pharmacies; Cruise Terminals
Fuel	Gas Stations; Fuel Storage		
Medical Services	Hospitals; EMS	Air Ambulances; Medical Centers	Fire Stations; Pharmacies
Medications	Pharmacies	Hospitals	Points of Distribution; Official Shelters; Unofficial Shelters; Gas Stations; Large Grocery Stores; Medical Centers
Restoration	Electric Utility Control Center; Electric Utility Equipment Yard	Airports	Fuel Storage
Safety	Fire Stations; PSAP	EMS	Wire Centers; Cell Towers
Security	Police Stations; PSAP		Wire Centers; Cell Towers
Shelter	Official Shelters; Hotels	Unofficial Shelters	
Transportation	Rail Stations; Bus Main Stations; Airports	Rail Operations and Maintenance; Bus Garages; Ferry Terminals	Cruise Terminals
Waste Management	Sewer Treatment Plants	Sewer Pumps	Official Shelters; Unofficial Shelters
Water	POD; Water Main Office and Repair Yard	Large Grocery Stores; Water Purification; Water Pumps; Water Storage Tanks	Official Shelters; Unofficial Shelters; Hotels; Gas Stations; Small Grocery Stores; Pharmacies; Airports; Cruise Terminals

3. RESILIENCE METRIC DESIGN

Sandia employed the resilience metric described in Figure 6 to evaluate community resilience subject to major disruptions in Puerto Rico. This metric measures the burden on members of the community to satisfy their basic needs. A more resilient community will better prepare for, withstand, respond to, and recover from extreme shocks, therefore decreasing the burden imposed on its citizens following a disruption. Burden is a function of the effort required to satisfy each need, as well as each individual's ability, as indicated by the function: $B_C = \sum_{inf} \sum_{pop} \frac{E_{inf,pop}}{A_{pop}}$, where B_C is the burden for a community, which is defined as a spatially explicit sum over population (*pop*) and each infrastructure service (*inf*) of the effort (*E*) required for each individual to acquire each infrastructure service, divided by that individual's overall ability (*A*). This metric can be calculated as a snapshot in time (e.g. the initial day following a disruption) or over time (e.g. integrated over the recovery period).

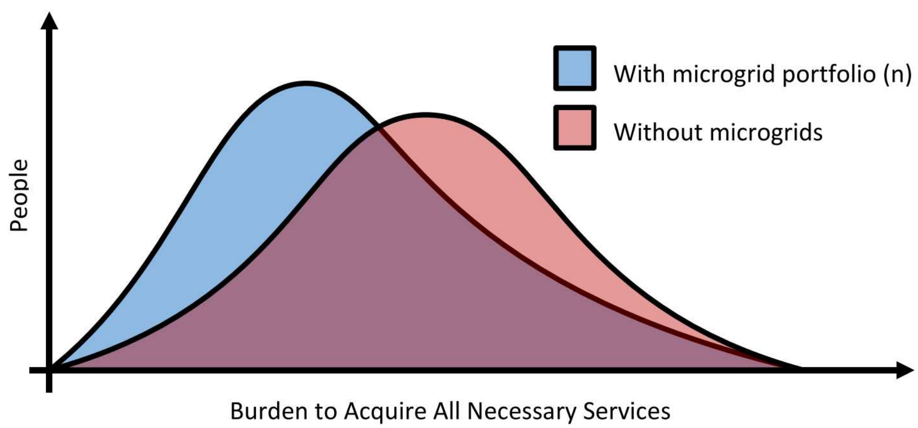

Figure 6. A Community Resilience Metric for Puerto Rico Describes the Burden to the Population of Accessing Critical Services

Using a metric of social burden allows planners to gain quantitative insight into how grid improvements impact the community, especially those in the population that have fewer means to acquire services even on a blue-sky day. It also allows for the grid's impact on a variety of services to be combined into a single dimension, which itself can be compared to the cost to build each alternative portfolio of advanced microgrids. Figure 7 illustrates the percentage of families below the poverty level throughout Puerto Rico, which can be an indicator of ability within the burden equation.

For this analysis, Sandia has further refined and implemented the methodology to calculate the burden metric for any given portfolio of microgrids and localized backup solutions. Sandia is in the process of documenting and validating this methodology. In the calculation of burden, infrastructure facilities that are on microgrids or backup power deliver a service or multiple services to the surrounding area as outlined in Table 1, and this service declines with the distance a person is from the facility. The reciprocal of this service is directly proportional to effort in the burden calculation. Services from all providing facilities within each service category are summed for each discrete spatial aggregation of population, and this number is inverted to determine the effort for that population aggregate. Ability is assumed to be directly proportional to the median household income within each population aggregate. In future calculations, Sandia will explore the use of other factors such as age and the percentage of population with vehicles.

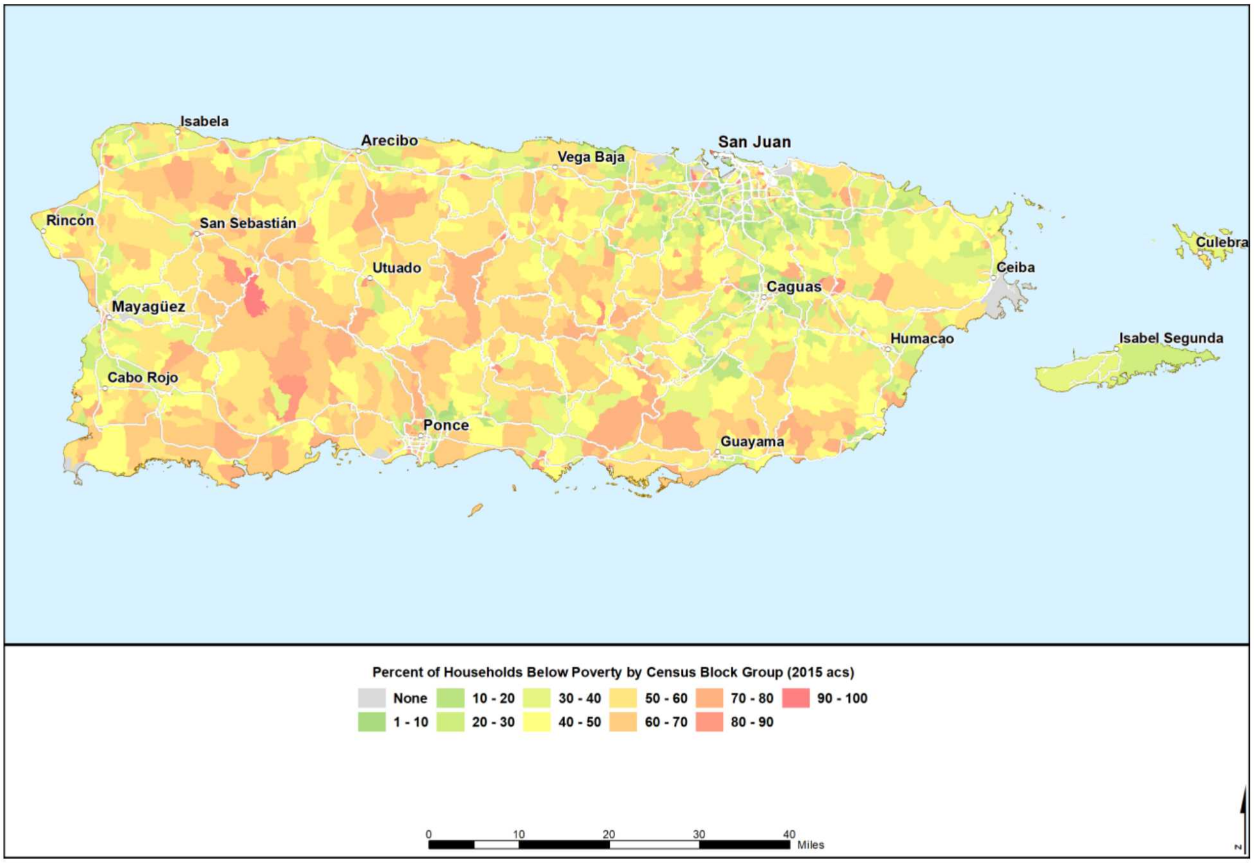

Figure 7. Percent of Families Below Poverty Line in Puerto Rico

Sandia is using census block groups as the spatial aggregation of population in this analysis. Demographic data from the 2015 American Community Survey (US Census Bureau 2015) provides information such as population, household median income, and age for each census block group.

An example histogram of burden to acquire all services for the population across the census block groups throughout Puerto Rico for a portfolio of 80 microgrids is shown in Figure 8. To complement the histogram, burden can be shown in detail for each census block group, and further broken down as illustrated in Figure 9. The effort term of the burden calculation can also be extracted and plotted, as illustrated in Figure 10.

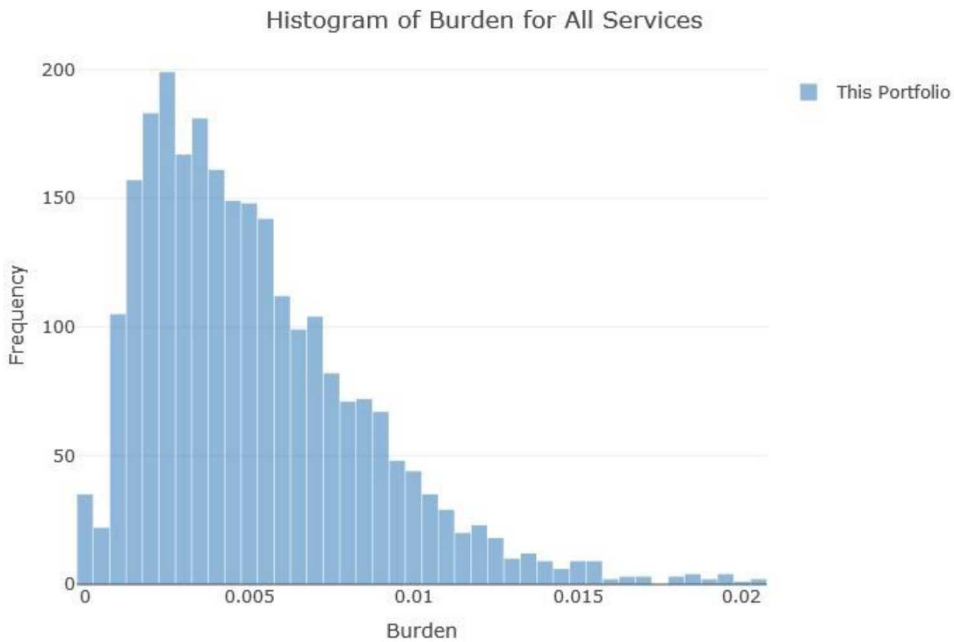

Figure 8. Illustrative Histogram of Societal Burden to Acquire All Infrastructure Services across Census Block Groups in Puerto Rico for a Random Portfolio of 80 Microgrids

Figure 9. Example Map of Societal Burden to Acquire All Services by Census Block Group for a Random Portfolio of 80 Microgrids

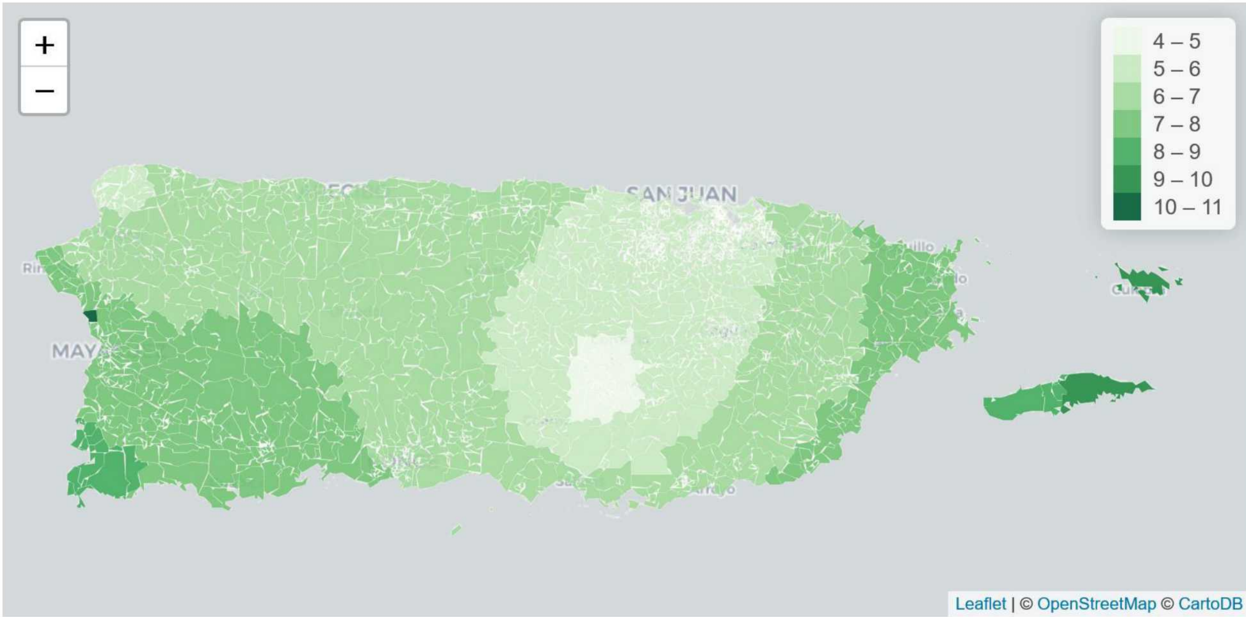

Figure 10. Example Map of Effort to Acquire All Services by Census Block Group for a Random Portfolio of 80 Microgrids

The metric described as a distribution in Figure 6 and histogram in Figure 8 accounts for variability across a population for a single disruption. Risk minimizing planners may also choose to account for the uncertainty inherent in future disruptive events by populating a probability distribution instead of or in addition to the population distribution. For example, the design basis threat for earthquake in this analysis has a 2% chance of occurrence over 50 years. Compare this to the 500 year flood, which using equation 1 has a 9.5% chance of occurrence over 50 years. Sandia used these occurrence probabilities to guide how the different threats were considered in development of microgrids. If planners have a more continuous estimate of threat probabilities, they may choose to calculate full probability densities of burden as suggested by Watson et al (2014).

In addition to the burden metric, Sandia is using a proxy metric that is a key determinant of burden, which is the fraction of services throughout Puerto Rico that have power and can operate in islanded mode after the disruption along each of the service categories in Table 1. Both the burden metric and the proxy metric are calculated at a single point in time which represents the system immediately following a disruption. Calculating these metrics over a dynamic restoration period involves an understanding of how microgrids aid or hinder recovery over the broader distribution system, which is an item for future analysis.

4. ASSESSMENT METHODS AND DATA COLLECTION

The Resilient Node Cluster Analysis Tool (ReNCAT), developed at Sandia, was used to analyze the critical infrastructure throughout Puerto Rico and find dense groupings of buildings that lend themselves to the development of resilience nodes. A resilience node is a region within a populated area where a microgrid or localized backup generation can be deployed to ensure critical assets are available to residents in the aftermath of a natural disaster. Particularly with regards to microgrids, buildings that are co-located tend to be an easier and more cost-effective target for a microgrid, especially if they are on the same electrical distribution feeder. A high-level depiction of the ReNCAT analysis process is shown in Figure 11. First all critical infrastructure data is entered into the tool and are associated with design basis threats that are of concern for the area. Once the data is entered the program calculates areas of the city that provide a high concentration of critical services that aren't susceptible to threat, and generates a visualization and report of the available resilient nodes. ReNCAT has been updated since the preliminary Puerto Rico report in June to be more user friendly and easily deployable. The application can be installed on any computer and a user manual will be provided as a separate deliverable.

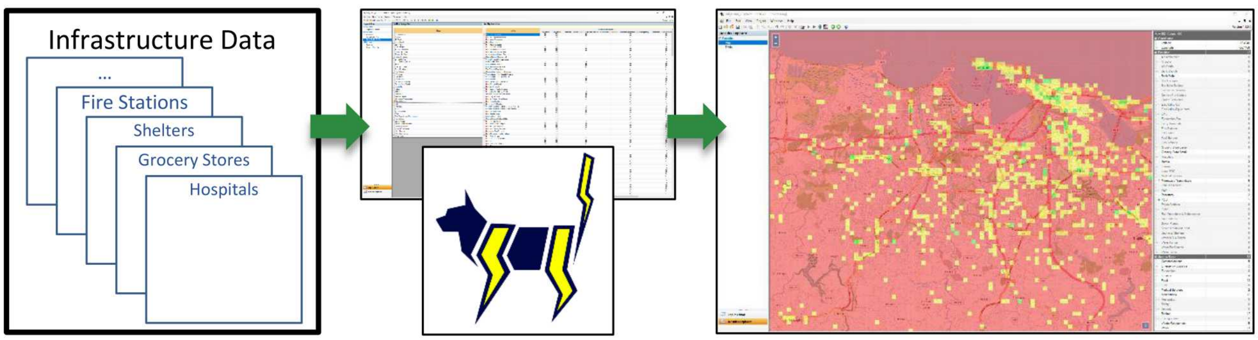

Figure 11. Depiction of the ReNCAT Analysis Process

In the absence of PREPA data on the electric utility's most critical restoration and recovery assets, multiple primary and supplementary data sources were used to generate and verify the critical infrastructure data needed to run ReNCAT, including HSIP Gold 2015; HIFLD Open; Open Street Map (OSM); GRIT, Inc.; the FCC, data from two emergency management websites; data from the Puerto Rican Government; and data manually gathered from Google and Google Maps. Each infrastructure sector and its data source(s) is shown in Table 2.

ReNCAT analyzes the available buildings by creating a spatial grid with squares whose size is designated by the analyst, and computes a score for each grid cell using the infrastructure to service score mapping in Table 1. For most urban areas, a grid size of 1000ft x 1000ft provides a size large enough to encompass multiple buildings while remaining small enough to span only one to two distribution feeders. Two additional grid sizes of 1500ft x 1500ft and 2000ft x 2000ft were analyzed to glean additional insights. The tool also uses a minimum service score to determine whether an area provides enough services to justify considering a microgrid. Critical infrastructure in Puerto Rico is shown in Figure 12 and Figure 13 with an overlay of the 100-year and 500-year FEMA flood plains. In all, there are 6,643 individual infrastructure assets that were considered in this analysis across Puerto Rico.

Table 2. Data Sources by Sector

Infrastructure Category	Primary Data Source(s)	Verification Source
Air Ambulances	HSIP Gold 2015	
Airports	FAA; HIFLD Open; Google Maps	
AM Radio Transmitters	FCC Antenna Database	
Bank Branches	OSM; Google Maps; HSIP Gold 2015	Google Maps; Navteq
Bank Main Locations	HSIP Gold 2015	Google Maps
Bus Garage and Offices	Google; Google Maps	
Cell Towers	FCC Antenna Database	
Cruise Terminals	Google; Google Maps	
Electric Utility Control Center	Google; Google Maps	
Electric Utility Equipment Yard	Google; Google Maps	
EMS	HSIP Gold 2015	
EOC	Google; Google Maps	
Evacuation Sites	http://redsismica.uprm.edu/English/tsunami/mapa/info/index.php?tw=san_juan	
Ferry Terminals	Google; Google Maps	
Fire Stations	HSIP Gold 2015	Google Maps
FM Radio Station Transmitters	FCC Antenna Database	
Gas Stations	OSM; Google Maps	Google Maps; Navteq
Grocery Stores - Large	OSM; Google Maps	Google Maps; Navteq
Grocery Stores – Small	OSM; Google Maps	Google Maps; Navteq
Hospitals	HSIP Gold 2015; OSM; Google Maps	Google Maps; Navteq
Hotels	OSM; Google Maps	Google Maps
Internet Centers	GRIT, Inc.; Google; Google Maps	
Main Bus Stations	Google; Google Maps	
Medical Centers	Google	
Microwave Transmitters	FCC Antenna Database	
Official Shelters	HIFLD; Puerto Rican Government	Google Maps
PEP Transmitters	FCC; Google Maps	
Pharmacies	OSM; Google Maps	Google Maps; Navteq
Points of Distribution	https://www.fema.gov/news-release/2017/09/26/federal-teams-continuing-deliver-supplies-puerto-rico-and-us-virgin-islands	Google Maps
Police Stations	HSIP Gold 2015; Google Maps	Google Maps
PSAP Facilities	Google; Google Maps	
Rail Operations and Maintenance Yard	Google; Google Maps	
Rail Stations	Google; Google Maps	
Refined Fuel Storage	EIA; Google	Google Maps
Sewer Pumps	Puerto Rican Government	Google Maps
Sewer Treatment Plants	Puerto Rican Government	Google Maps
Unofficial Shelters	OSM, HSIP Gold 2015; HIFLD	Google Maps
Water Pumps	Puerto Rican Government	Google Maps
Water Purification	HIFLD; Puerto Rican Government	Google Maps
Water Purification Main Office	Puerto Rican Government	Google Maps
Water Storage Tanks	Puerto Rican Government	Google Maps
Wire Centers	GRIT, Inc.; Google Maps	

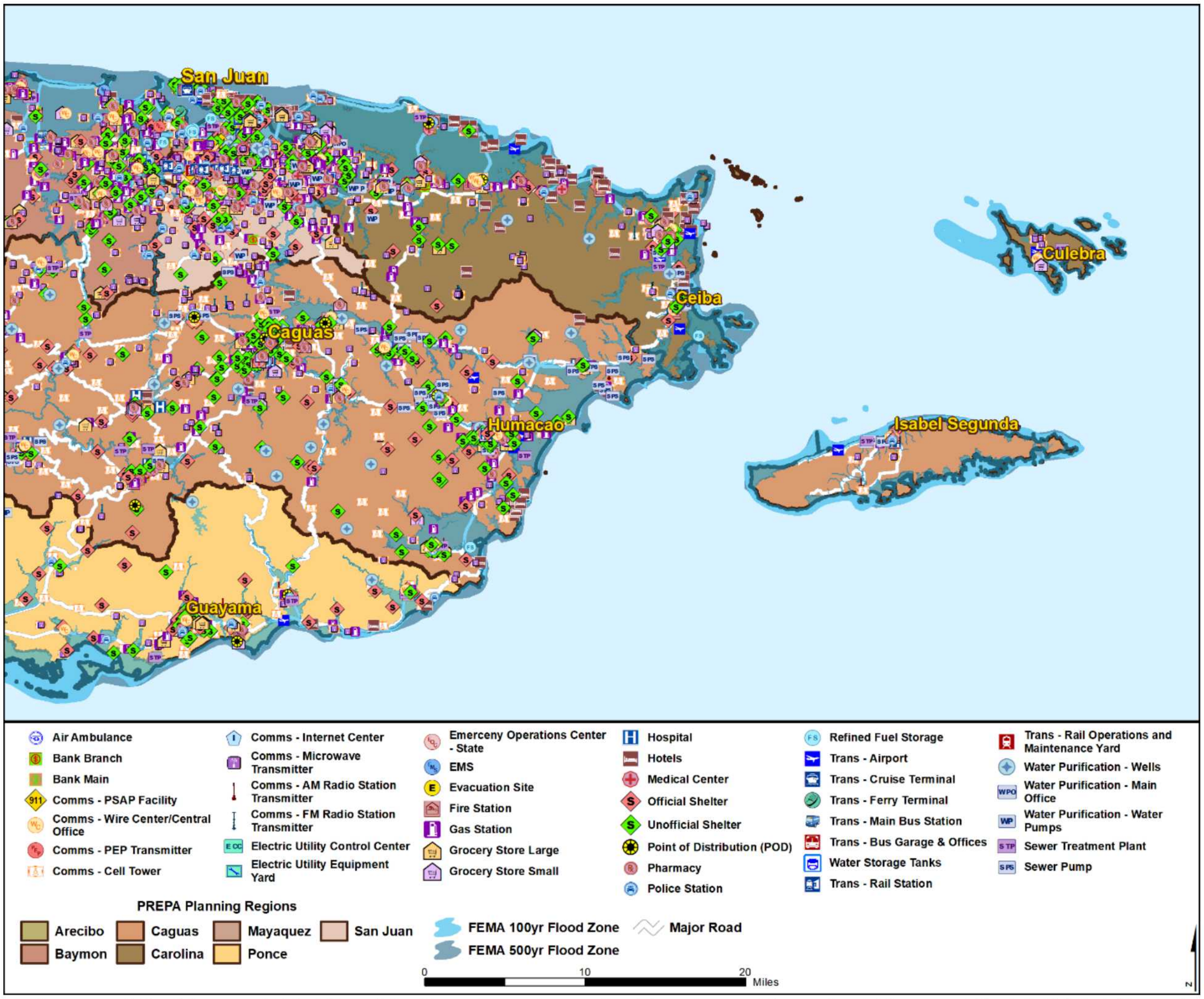

Figure 12. Map of Critical Infrastructure in Eastern Puerto Rico with FEMA Flood Contour Overlay

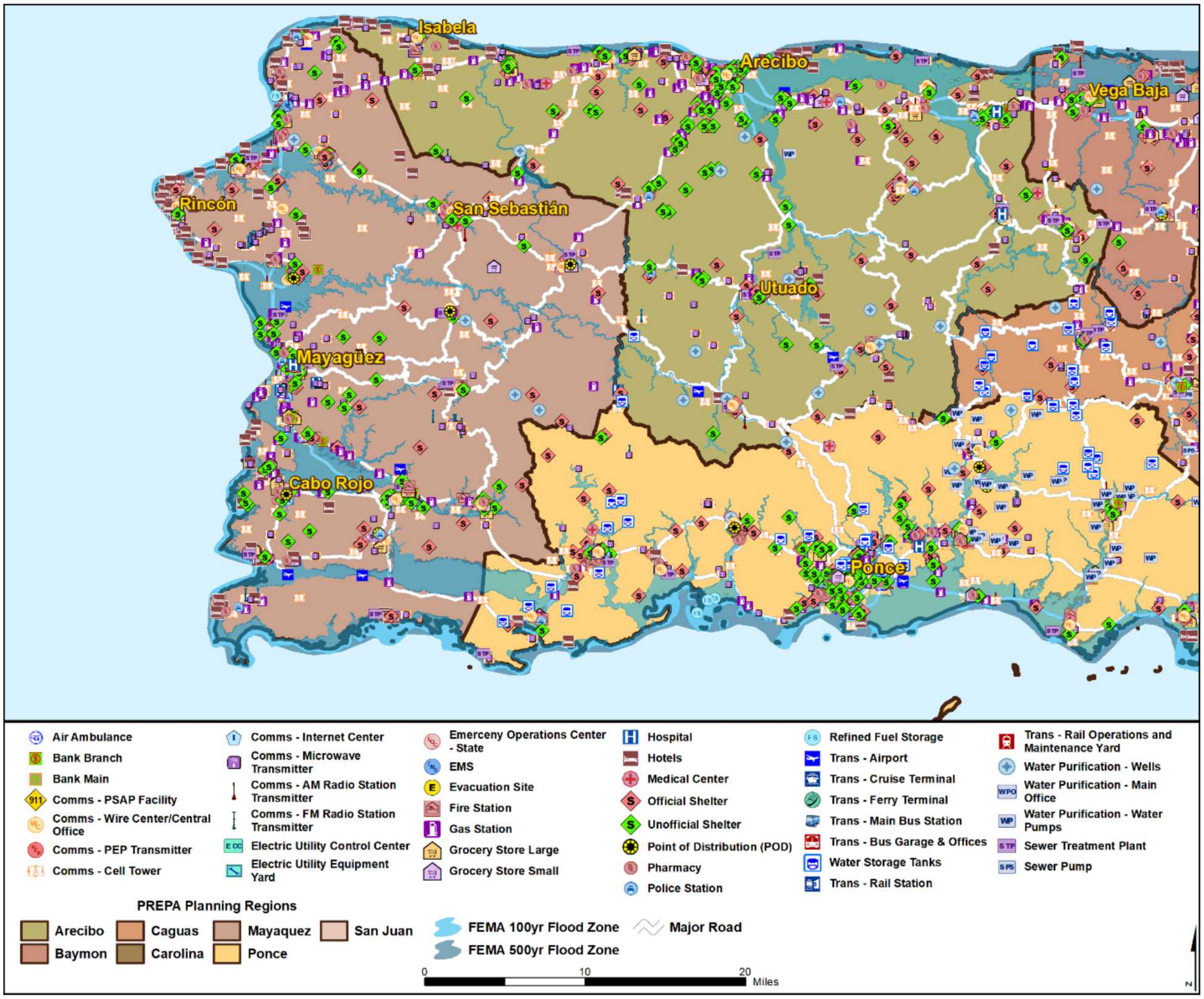

Figure 13. Map of Critical Infrastructure in Western Puerto Rico with FEMA Flood Contour Overlay

5. BASELINE RESILIENCE

The baseline resilience for Puerto Rico is defined as an evaluation of the resilience metric if no additional grid investments are made. An important component of assessing baseline resilience is an understanding of the risk of outage across the power system to future major disruptions. Sandia conducted a preliminary analysis of power outage susceptibility to hurricanes for this study.

There are a number of methods to assess the vulnerabilities of the power system infrastructure in a given region, and they all depend on the availability of high-quality data sources. Metrics such as the system average interruption duration index (SAIDI), the system average interruption frequency index (SAIFI), and the customer average interruption duration index (CAIDI) are all useful measures of the overall reliability of a power system. However, these metrics are calculated as an average over a period of time, often a year, and they typically leave out large-scale outage events caused by extreme events, such as a named tropical cyclone. Thus, their utility in assessing vulnerability to adverse weather is limited. For Puerto Rico, Sandia was provided access to these reliability metrics for the year 2015. Although we do not currently have detailed local weather data to match up with these reliability metrics, we can still observe some interesting patterns across the island.

There is a long tail in the distributions of all three metrics, showing that, at least for the year 2015, there were parts of the island that were performing significantly worse than average, as shown in Figure 14. To improve overall system performance, it might make sense to further investigate the feeder locations that have exceptionally high CAIDI, SAIDI, or SAIFI values.

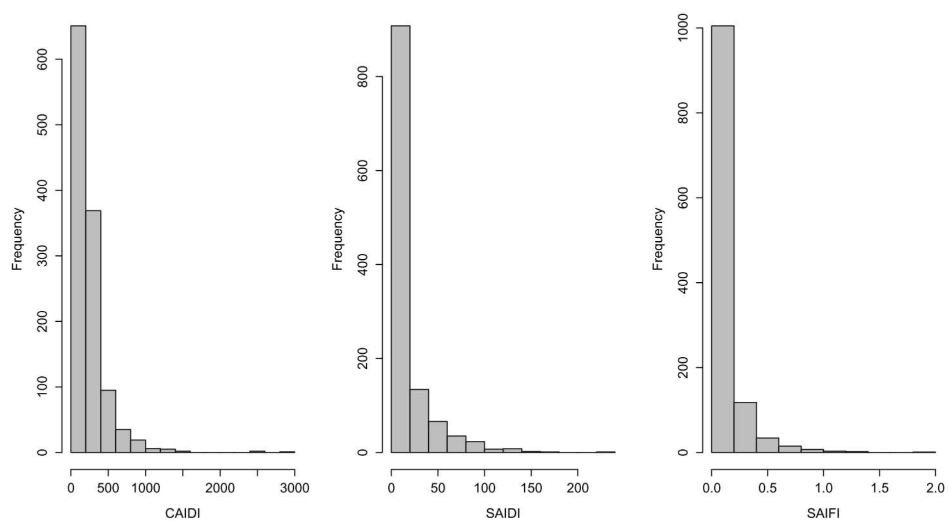

Figure 14. Histograms of CAIDI, SAIDI, and SAIFI values across all available feeders in Puerto Rico for the year 2015. Most feeders have high reliability indices, but the long tail is indicative of at-risk locations or grid components that are especially prone to failure.

The maps shown in Figures Figure 15 throughFigure 17 portray the locations of the feeders with especially high metric values. The SAIDI values are most noticeable for having the worst offenders located inland, far from the coasts of the island. CAIDI and SAIFI values, on the other hand, show less of a clear pattern. There are high values in and around San Juan, as well as dispersed throughout the inland regions.

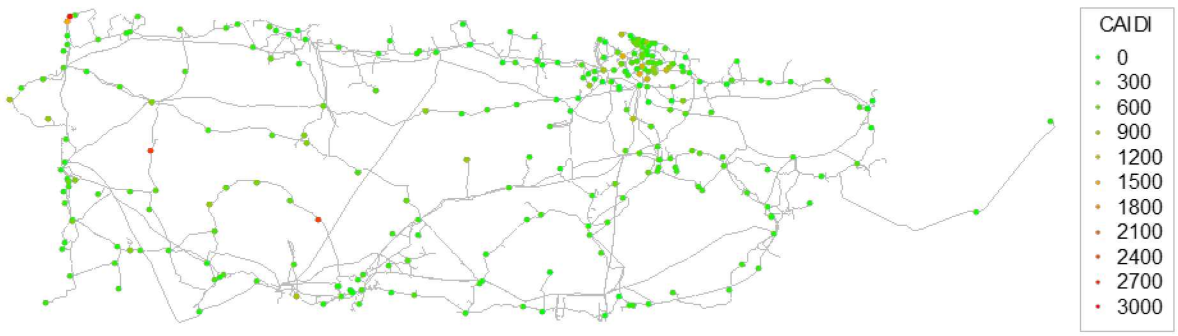

Figure 15. CAIDI plotted at the bus level, based on the maximum value for the metric found at that feeder location.

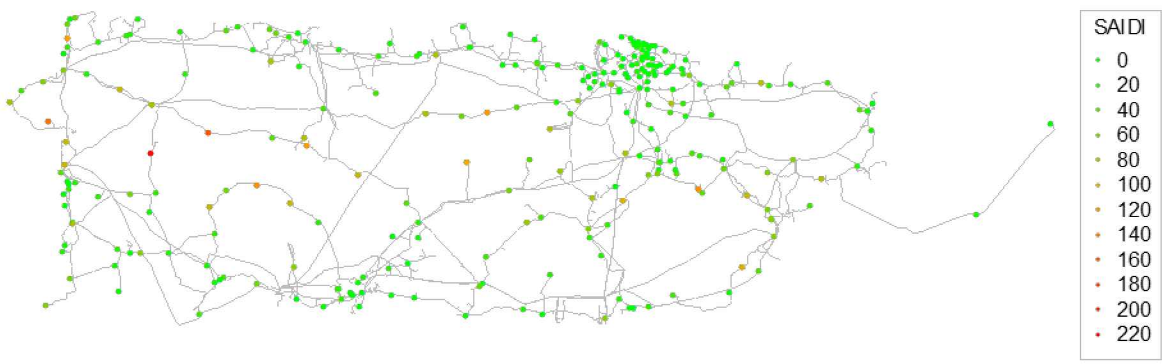

Figure 16. SAIDI plotted at the bus level, based on the maximum value for the metric found at that feeder location.

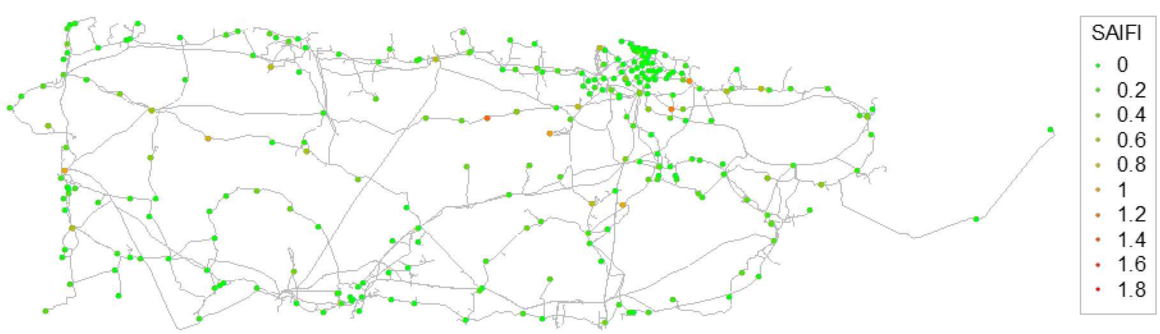

Figure 17. SAIFI plotted at the bus level, based on the maximum value for the metric found at that feeder location.

While these reliability metrics are useful for gaining insight into overall trends, they cannot tell us anything about the vulnerability to adverse weather events. Regardless of the fact that extreme events are left out of the calculations, these annual averages lack the temporal detail needed to attribute outages of any sort to a specific weather event. To truly evaluate the risks to the Puerto Rico power system, we need detailed threat and consequence modeling, which both rely on historical data of past weather events and subsequent outages.

For much of the continental United States, this data is starting to be used to build up trustworthy models of potential power outages. See, for example, work by Guikema *et al.* on predicting hurricane outages (Guikema et al. 2014). Their models rely on detailed wind field estimates of an oncoming storm, as well as historical data on the likelihood of failure based on storm strength and duration. There are now more options available for accessing power outage data, with the Department of Energy's Eagle-I tool being one of them.* This database of historical outages allows researchers to couple consequences to threats; estimates of a hurricane track and intensity can be used to inform failure models of distribution and transmission system line outages. Unfortunately, the Eagle-I data is currently only available for the continental U.S. We suggest that data of this sort be collected for Puerto Rico and made available for researchers to advise on risk analysis. For an example of what can be done with such data, see Figure 18. Combined with weather characteristics of the storm, researchers may be able to build reliable statistical models that link wind speeds, flooding, and other regional characteristics to the likelihood of power outages. This can be used both for essential real-time planning and crew positioning in advance of a storm and for much longer-term threat analysis, evaluating the impact of repeated storms over the lifetime of installed power system components or upgrades (Staid et al. 2014).

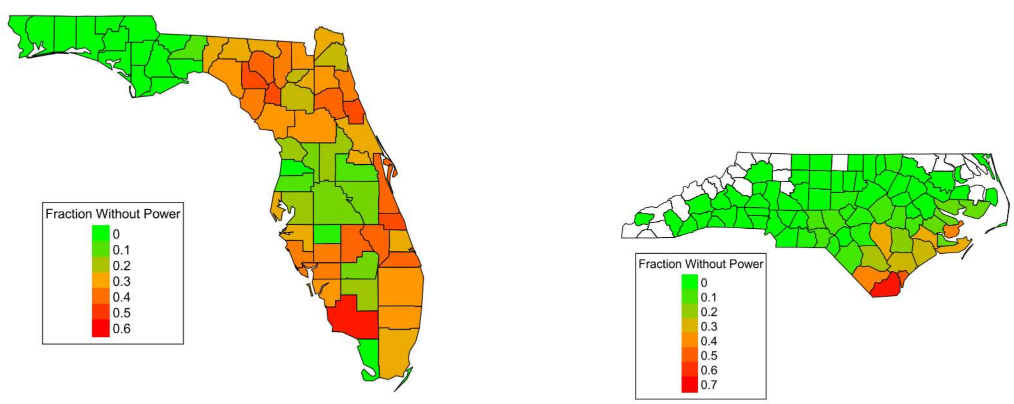

Figure 18. Outage maps for Florida (left) and North Carolina (right) showing the fraction of customers without power for a snapshot of time in the aftermath of Hurricane Irma (left) and shortly after landfall of Hurricane Florence (right).

* https://eagle-i.doe.gov

In order to provide detailed consequence modeling for future storms, we would need:

1. Historical power outage data for all of Puerto Rico from past tropical cyclones and other adverse weather events, both at the transmission and distribution level
2. Weather parameters for the corresponding weather events, ideally measured at local areas across Puerto Rico
3. Stochastic threat models of plausible future storms

With these pieces in place, we can build up models of potential grid impacts as a result of weather conditions. We can also use this to evaluate the reduction in outages based on specific infrastructure upgrades, by simulating consequences under potential future storm scenarios. This would allow for a detailed evaluation of the resilience benefits to be gained from improvements to Puerto Rico's power system infrastructure going forward.

The conclusion from the power system vulnerability analysis is that more in-depth modeling is required to understand the likelihood of power outage – both directly caused by damage and indirectly caused by power system collapse – across the island subject to the threats considered. For the baseline, this analysis assumes that all locations in Puerto Rico are equally likely to suffer extended power outages over a fifty year planning horizon. This assumption is clearly a simplification. Furthermore, we assume that none of the infrastructures considered within the resilience metric have reliable backup power. This conservative assumption could be revisited if additional data on existing or planned local backup power resources were provided.

These assumptions are useful in that they allow simple comparisons. For instance, without power to any services island-wide the baseline percentage of services with power in the days immediately following an extreme event is essentially zero for all categories. This does not necessarily mean that no services would be provided, only that the infrastructures will not have power from the grid.

The baseline burden metric summed across all service categories for each census block group is illustrated in Figure 19. Because the burden metric accounts for household income status, many of the low-income census block groups have especially high burden in this scenario. Within the burden calculation, it is assumed that infrastructures without power are still able to serve at $1/100^{th}$ of capacity – therefore areas with higher concentration of infrastructure such as San Juan municipality do have a lower effort than the outlying regions of the map in Figure 19.

Notably, the histogram of burden to acquire all services across the census block groups demonstrates a thick upper tail as indicated by Figure 20. Often it is an planners' desire to eliminate extremely high consequence to members of the public. Therefore, microgrid portfolios can be designed to decrease the tail of this distribution, to decrease the mean, or a combination of both.

Figure 19. Map of Total Burden to Acquire All Services in the Baseline Scenario

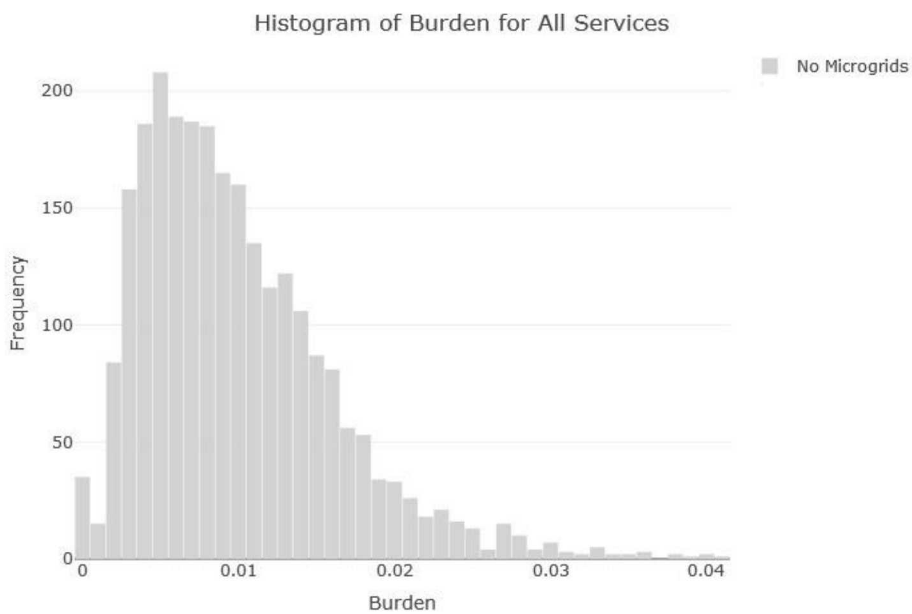

Figure 20. Histogram of Burden to Acquire All Services in the Baseline Scenario

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6. MICROGRIDS TO ENHANCE COMMUNITY RESILIENCE

Proposed distribution energy resilience improvements for the island of Puerto Rico consider both the set of critical services needed across the region and the cost of implementation in order to strategically select a set of resilience investments. The recommended resilience improvements from this analysis include sets of resilience nodes, implemented through microgrids, supplemented with localized backup generation to critical assets in locations that may not warrant an microgrid but are deemed necessary for the community. These recommendations for advance microgrids and backup generation are directly sited in the Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico report in December 2017. These distributed energy resilience improvements are intended to complement and work in tandem with generation, transmission and other distribution resilience improvement recommendations in the overall multi-lab study as well as those discussed in the Build Back Better report.

Microgrids

Microgrids enable resilience nodes to utilize automated controls to tie a collection of critical facilities within a relatively small geographical area using one or more points of common coupling (PCCs) to the utility. These PCCs are switching devices that can automatically segregate and form the microgrid from the distribution system in an outage situation or when operational. Within the microgrid there are sets of distributed energy resources (DERs) that are integrated to provide stable power to buildings associated with key infrastructures. The DERs can consist of a suite of generation supply including sources such as fossil fuel based diesel and natural gas units, renewables like PV and Wind, and Battery Energy Storage. In order to make microgrids resilient to major events, the distribution infrastructure should be locally hardened and/or reconfigured in order to connect the microgrid to the key infrastructure assets. Finally, sufficient fuel resources and storage tanks must exist for the microgrid to function during the duration of the expected major event. microgrids can also provide added services when tied to the grid (grid-tied operation), such as peak shaving, renewable energy integration, and demand response.

Localized Backup Generation

Building-tied backup generators are the most common method of supplying power to a facility to keep key infrastructure assets powered during utility outages. This option may also include provisions for backup generation (e.g., pin and sleeve portable generator connection) that are not housed on-site, but are moved on-location before or during an outage so that a collection of mobile backup generators can supply multiple facilities. Based on the results of this analysis, new backup generation or improvements to existing backup generation are recommended for a subset of key infrastructure assets that aren't in areas that warrant a microgrid. Improvements can include replacement of existing generators, increasing the fuel tank sizes, and hardening the equipment associated with preventing wind and water damage in order to guarantee they will function until restoration is complete.

6.1. Microgrid Considerations

Main categories of technology in these microgrids include:

- New Distributed Generation – Distributed generation, renewables and energy storage sources necessary to supply loads within each microgrid

- Points of Common Coupling – Switching devices that isolate and form the microgrid from the PREPA distribution system
- Hardened Distribution Lines – Hardening overhead distribution lines to expected wind damage and falling trees, or converting overhead lines to underground
- Reconfiguring Distribution Lines – In some cases to build a microgrid, the existing distribution may need to be reconfigured so that critical buildings are all on the same distribution feeder in order for the microgrid to be able to form a seamless transition during a major event
- Fuel Infrastructure and Supply – Adequate diesel, natural gas, or other fuels, as well as storage and supply infrastructure to support the microgrid for the duration of the major event
- Controls – Controls include the communications, infrastructure, and protocols for switching, generation, and operating load devices that detect system conditions, monitor, and operate the microgrid
- System Protection – System protection includes modifications of the protection scheme when the loads connected to the distribution feeder are connected to the microgrid
- Cyber Security – Cyber security includes both administrative and engineered cyber protections included in control and protection, as well as the hardening of any other hardware that may be possible to interface with to harden with which they interface

All of these technology categories contribute to the outlay cost of a microgrid. Depending on the existing state of the distribution system, Sandia experience estimates total microgrid cost on the order of $1.3-$2M per MW of peak load required for the microgrid. For example, if lines need to be placed underground and the grid needs extensive reconfiguration the costs will be likely toward the higher end of this range. A conservative rough order of magnitude estimate for a typical 5MW microgrid is $10M.

Microgrids are recommended as one of the suite of grid modernization solutions of interest for PREPA and the Commonwealth of Puerto Rico. Over small areas, for example 50 square miles, microgrids are highly effective at providing resilient infrastructure services to a population. Resilience nodes in the form of these microgrids supplemented by backup generation to a select set of facilities offer a cost-effective solution in cases where large portions of the community do not evacuate, and where large portions of the population need a wide array of services. Using resilience nodes, a relatively small amount of backup generation and localized hardening can provide several key services to a large population as compared to the generation and hardening required to keep the entire grid online. Once these nodes are specified, planners can begin to co-locate other beneficial resources such as shelter facilities, points of distribution, or post-storm evacuation sites within the nodes.

7. MICROGRID SITING ANALYSIS

When siting microgrids, Sandia assumed most of the infrastructure assets in Table 1 are buildings that are robust to high winds, yet will be unusable when flooded, damaged by earthquake, or damaged by landslide. For assets such as cell towers, this assumption may be revisited based on feedback from Puerto Rico stakeholders. For this analysis, ReNCAT excludes infrastructure assets from consideration that exceed a threshold risk of being damaged. The exclusion profiles in Table 3 were used for setting these thresholds.

Table 3. Asset exclusion profiles for incorporating asset damage risk within ReNCAT analysis

Exclusion Profile	Wind Exclusions	Flood Exclusions	Earthquake Exclusions	Landslide Exclusions
Risk Averse	-	In 500 yr zone	Medium and higher damage zones	Medium and higher susceptibility zones
Risk Accepting	-	In 100 yr zone	High and higher damage zones	High and higher susceptibility zones
100 yr Flood	-	In 100 yr zone	-	-
500 yr Flood	-	In 500 yr zone	-	-
Landslide Med	-	-	-	Medium and higher susceptibility zones
Landslide High	-	-	-	High and higher susceptibility zones
Earthquake Med	-	-	Medium and higher damage zones	-

Figure 21 illustrates the fraction of services available from infrastructure assets outside of the exclusion zones for the Risk Averse and Risk Accepting asset exclusion profiles. Across all service types, a significant number of assets are impacted by the Risk Averse assumptions as compared to the Risk Accepting assumptions. Upon examination, this is largely driven by the significant fraction of assets within the Medium Landslide Susceptibility zone. The use of planning scenarios mapped to exclusion zones maximizes the likelihood that the improved infrastructure will be operational in the aftermath of predicted future major events.

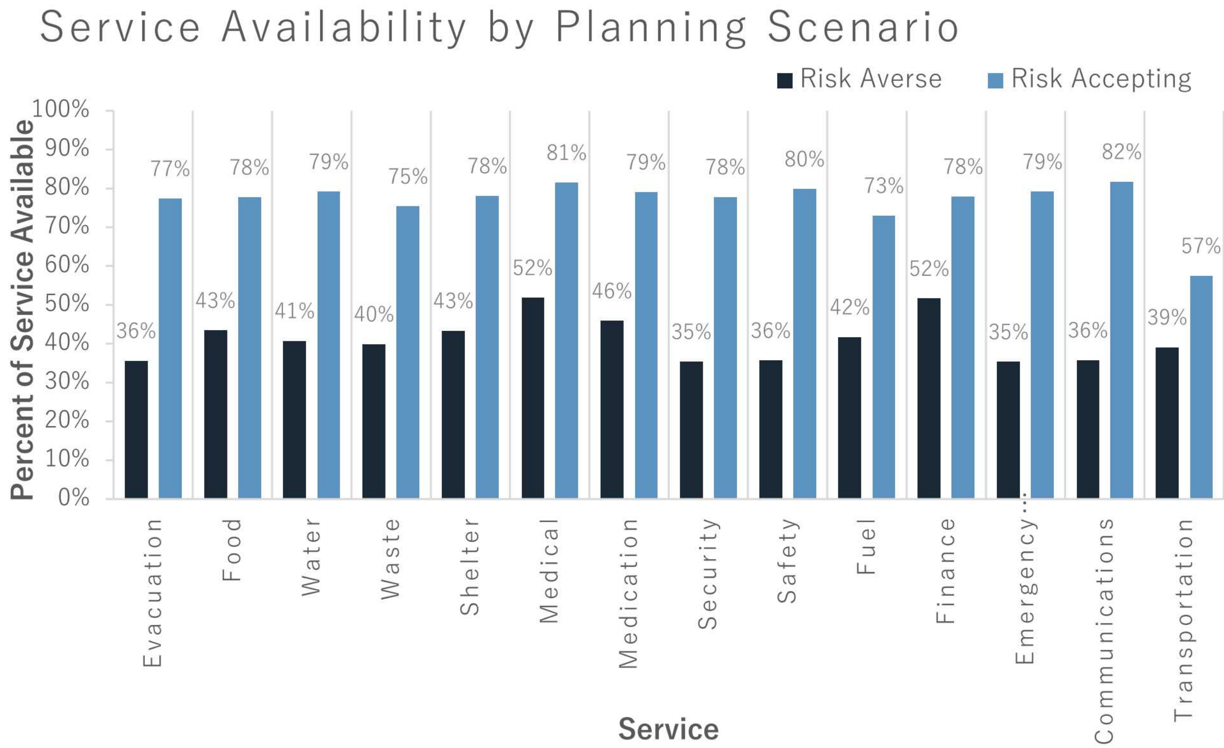

Figure 21. Percentage of Each Service Category Outside of the Risk Averse and Risk Accepting infrastructure exclusion zones.

Before the ReNCAT analysis, infrastructure assets are evaluated within each threat category as to their forecasted level of risk/damage/susceptibility using geospatial techniques. This table is input to ReNCAT, and the exclusion profiles from Table 3 are programed to exclude the appropriate subsets from consideration. The initial runs of ReNCAT were performed with a grid size of 1000ft x 1000ft to determine an appropriate minimum service score. The service score is based on a mapping of infrastructure asset type to the 15 service categories (shown in Table 1). Results are shown in Figure 22 through Figure 24 for minimum service scores of 40, 30, and 20 with inundated assets excluded based on the 500-year flood exclusion profile. Grid cells that meet the service score thresholds are shown in green and are potential resilience nodes. Grid cells with some level of service below the threshold are shown in yellow. Analysts may use groupings of yellow cells as resilience nodes, especially in areas with high service need and low number of green cells. Red grid cells either do not contain assets or contain assets that fall within the chosen exclusion profile. Using a minimum service score of 40 generated 47 potential resilience nodes, a score of 30 generated 118 potential resilience nodes, and a score of 20 generated 392 potential resilience nodes. Note that more resilience nodes are identified in the interior of the island as the service score requirement is lowered. This reflects the lower critical infrastructure density present in those areas. Based on this sensitivity analysis, a minimum service score of 30 was used as a starting point for investigating potential resilience node locations.

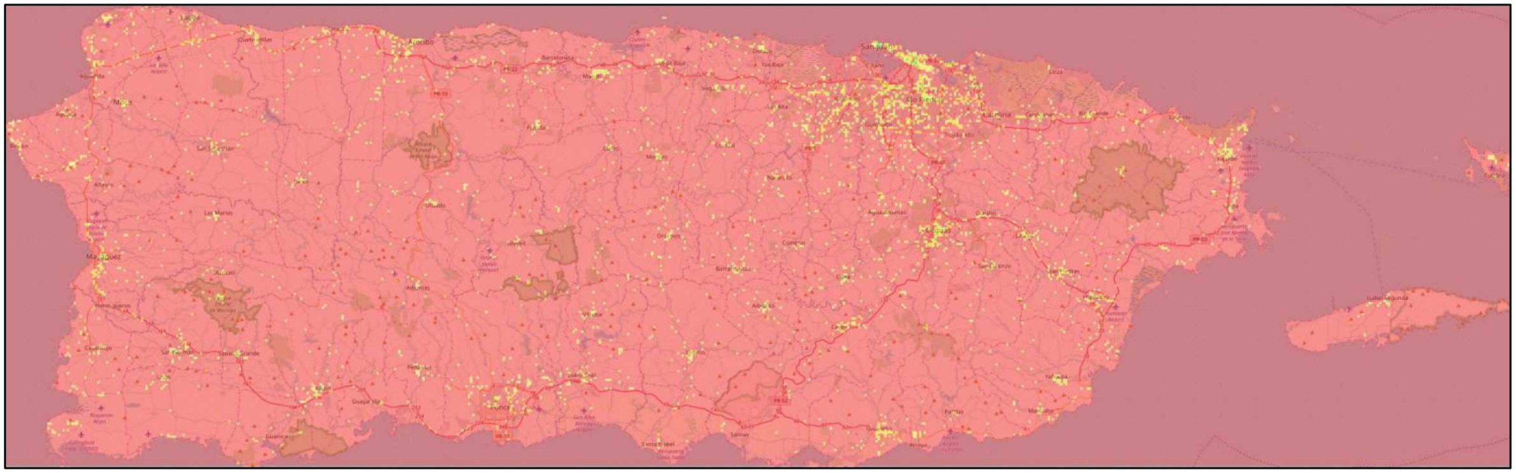

Figure 22. Minimum Service Score of 40 for 1000ft x 1000ft Grid Cell

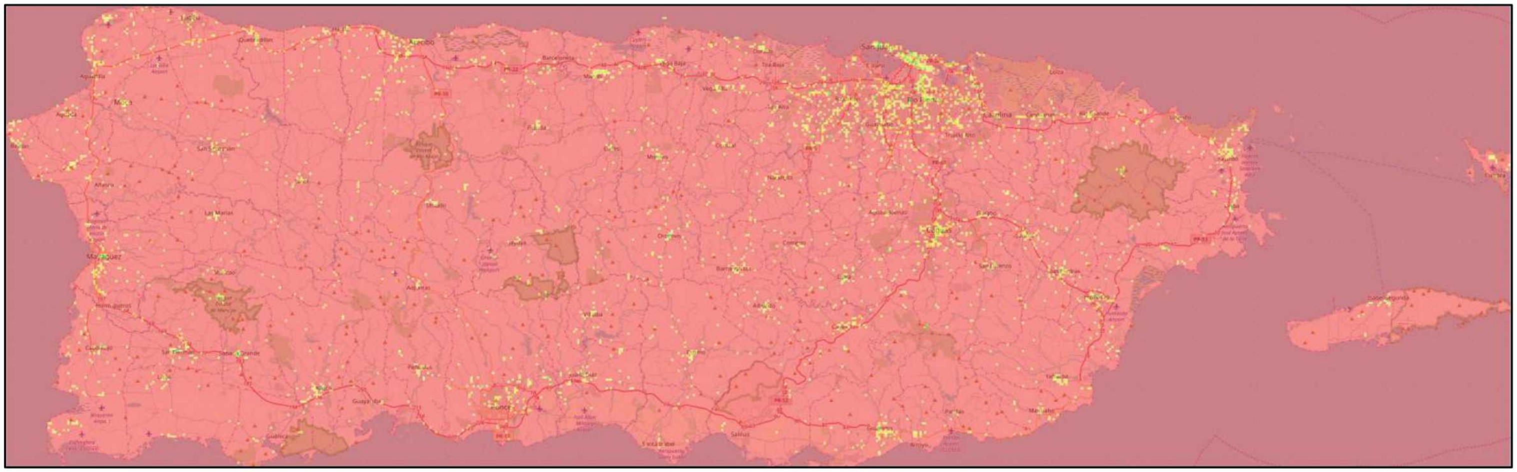

Figure 23. Minimum Service Score of 30 for 1000ft x 1000ft Grid Cell

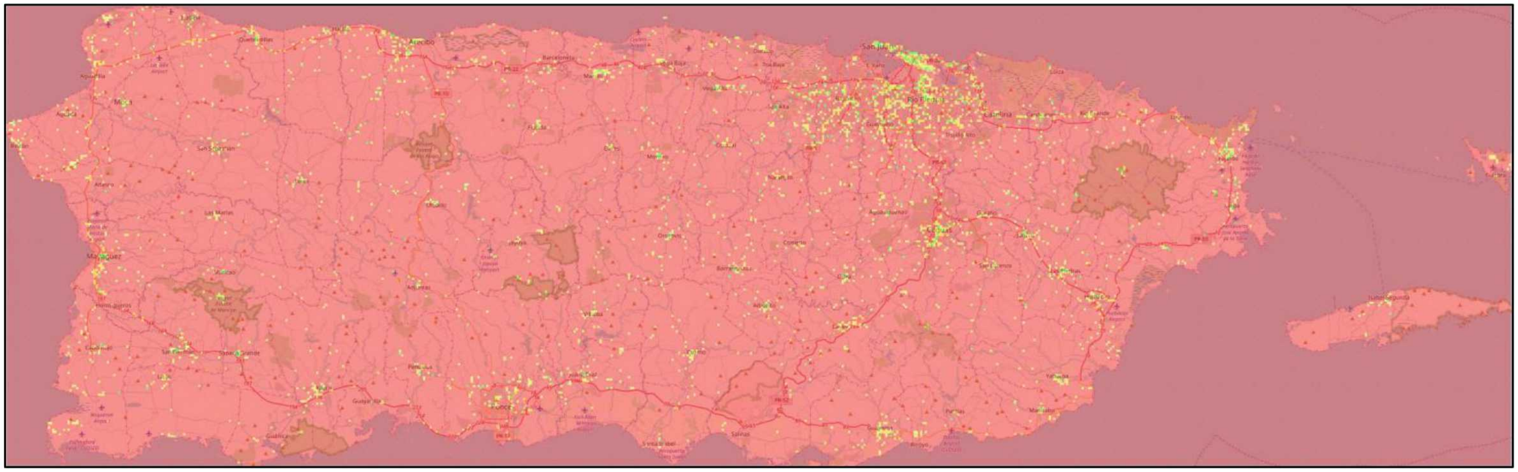

Figure 24. Minimum Service Score of 20 for 1000ft x 1000ft Grid Cell

ReNCAT was run with a service score threshold of 30 for each asset exclusion profile to determine the impact of risk tolerance on the number of potential microgrids available. Figure 25 shows the number of microgrids by asset exclusion profile for grid cell sizes of 1000ft x 1000ft. Note that infrastructure in certain regions of the island may become unavailable depending on the design basis threat profile applied in the analysis. For example, the interior of the island is highly susceptible to landslides and has little to no buildings available that are classified as low susceptibility. A comparison of the ReNCAT output is show in Figure 26 for the 100-year Flood exclusion profile and the Landslide Med exclusion profile for a minimum service score of 30. There is a near-complete absence of green or even yellow areas in the interior for the low landslide profile meaning that there are either no buildings available in the area or that all buildings have exceeded the landslide susceptibility threshold.

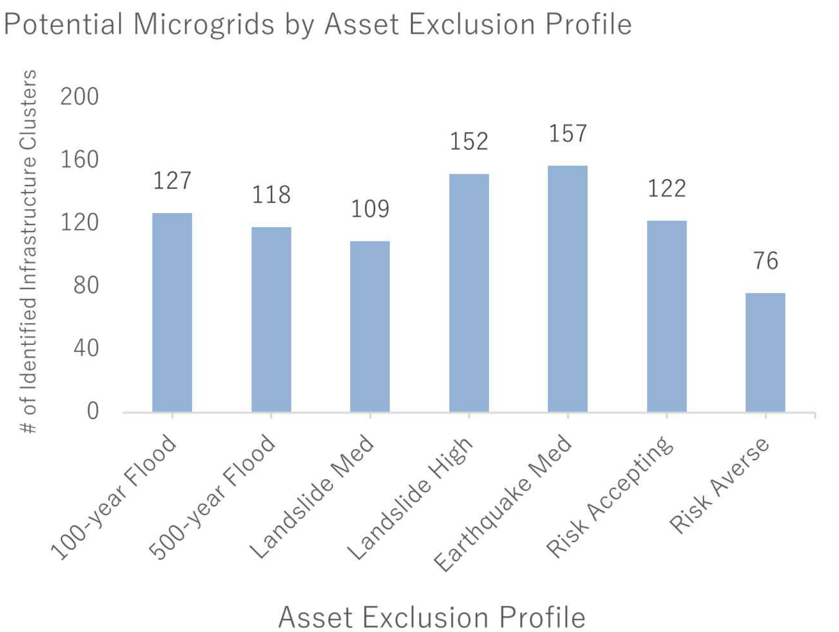

Figure 25. Number of Potential Resilience Nodes for Each Asset Exclusion Profile

Sandia used a minimum service score of 30 and expanded the grid size to 2000ft x 2000ft and then to 3000ft x 3000ft to examine the impact of different grid cell sizes on the number of resilience nodes. This allowed the analysts to identify additional potential resilience nodes in less densely populated areas. This analysis was done for the “risk accepting” threat profile since it is more restrictive than using individual threats, but not as restrictive as the “risk averse” threat profile. Since the larger areas include more buildings, the potential resilience nodes increased from the baseline of 122 for the 1000ft x 1000ft case, to 244 for 200ft x 2000ft, and then to 315 for 3000ft x 3000ft. A comparison is shown in the graphic in Figure 27.

Figure 26. Change in Infrastructure Availability Between 100-yr Flood Exclusion Profile and Landslide Med Exclusion Profile

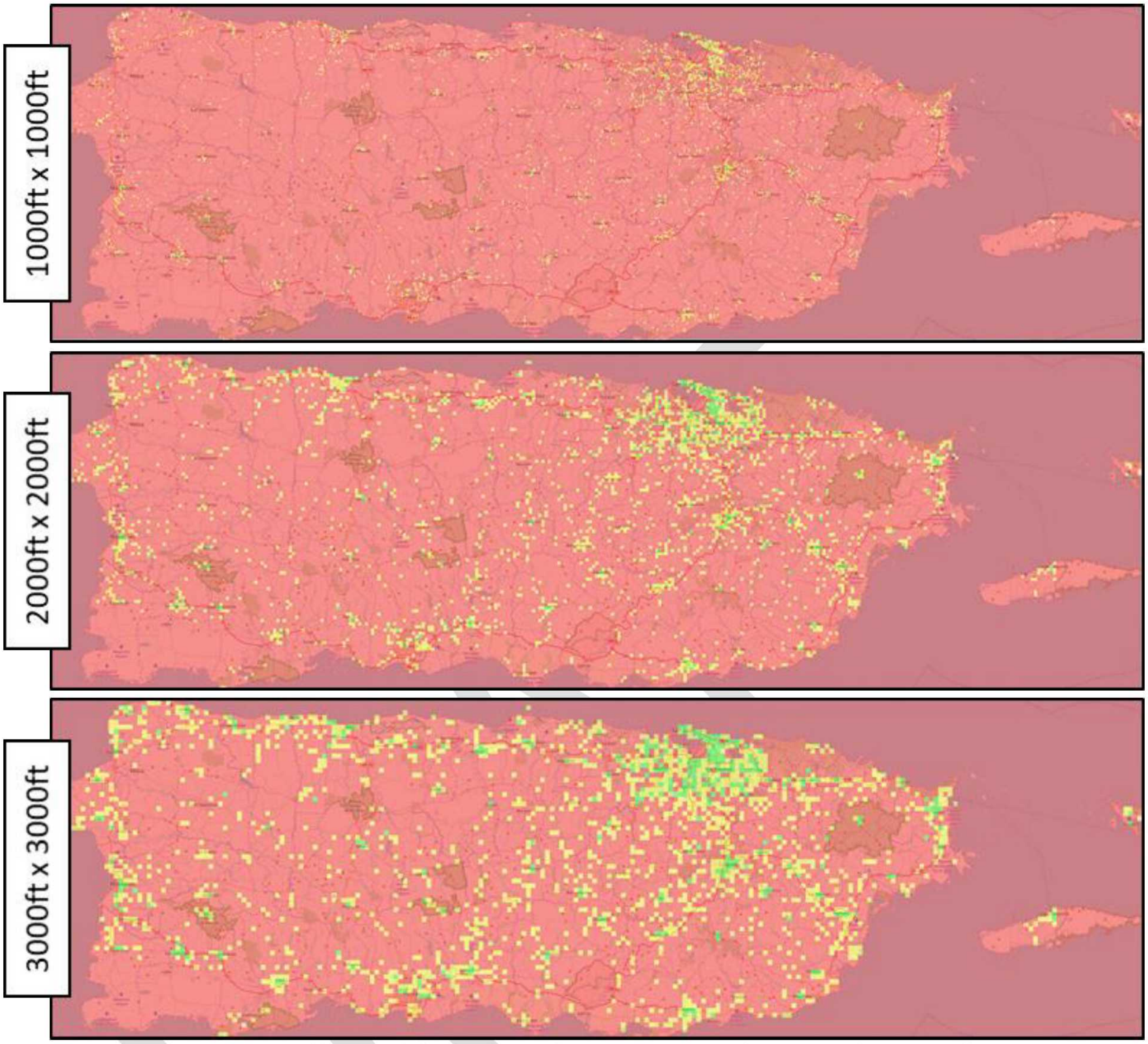

Figure 27. Effect of Grid Size for Minimum Service Score of 30

The resilience node grid cells determined using ReNCAT were used as the starting point for the next phase of the analysis in which the team took each potential resilience node and further analyzed considerations for microgrids—taking into account factors such as population density, infrastructure present on neighboring microgrids, details of the distribution system, and coverage of both urban and remote regions throughout Puerto Rico. Specifically, each suggested resilience node from ReNCAT was closely analyzed within a Geospatial Information System platform, building-by-building and feeder-by-feeder, to determine which existing feeders could be hardened and sectionalized to form a microgrid. In many cases, a single feeder was found to serve much of the critical infrastructure, and often this feeder picks up other critical infrastructure outside of the ReNCAT-suggested node – for example, oblong microgrid areas that follow a radial feeder. In cases where feeders are heavily meshed and infrastructure density is high, for example in Old San Juan, the team assumed microgrids could be formed by running new underground conductor or by reconfiguring multiple existing feeders.

Once initial siting based on ReNCAT-suggested nodes was complete, the team ran an initial burden calculation and looked for areas of especially high burden. In these areas grid cell size was increased and additional potential microgrid areas were identified. Some areas of Puerto Rico did not have infrastructure available once certain design basis threat profiles were applied, such as the interior of the island which is susceptible to landslides as discussed earlier. In some of these special cases, the team identified nodes are in threat areas and are denoted as such. These microgrids may not provide benefits during landslide events.

The results of microgrid siting based on the ReNCAT suggestions and additional considerations are illustrated in Figure 28 and Figure 29. Sandia identified 159 locations with strong potential for microgrid application, a significant increase over the 66 locations identified in the previous iteration of this report. Some of these locations suggest a much larger microgrid than others. Some regions, such as central Bayamón, have high population but fewer suggested resilience nodes. In these cases, it may be more beneficial to site backup generation at a set of facilities than to build sprawling microgrids. The latitudes and longitudes of buildings suggested under each of the 159 candidate microgrids is included as a separate addendum to this report.

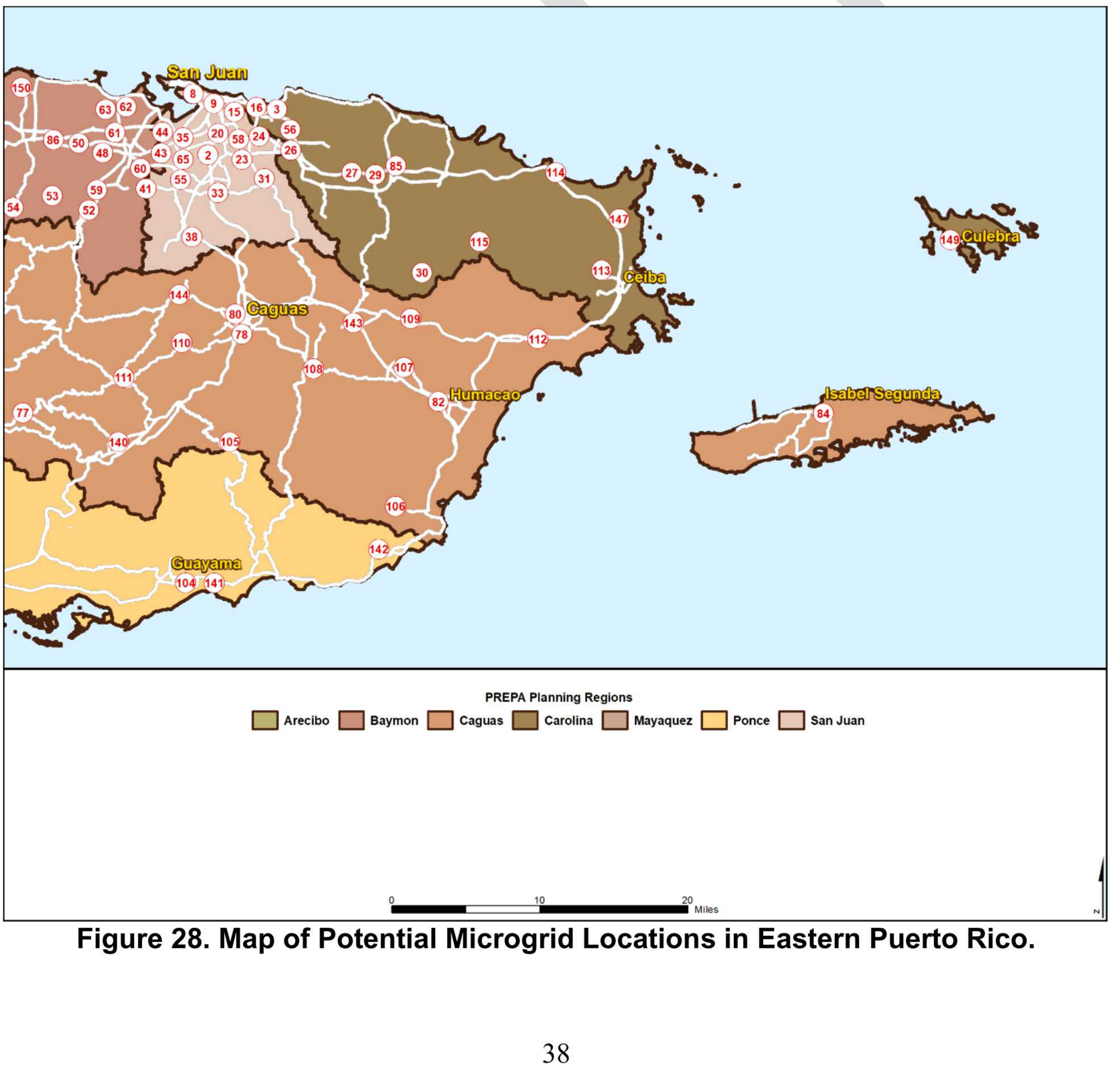

Figure 28. Map of Potential Microgrid Locations in Eastern Puerto Rico.

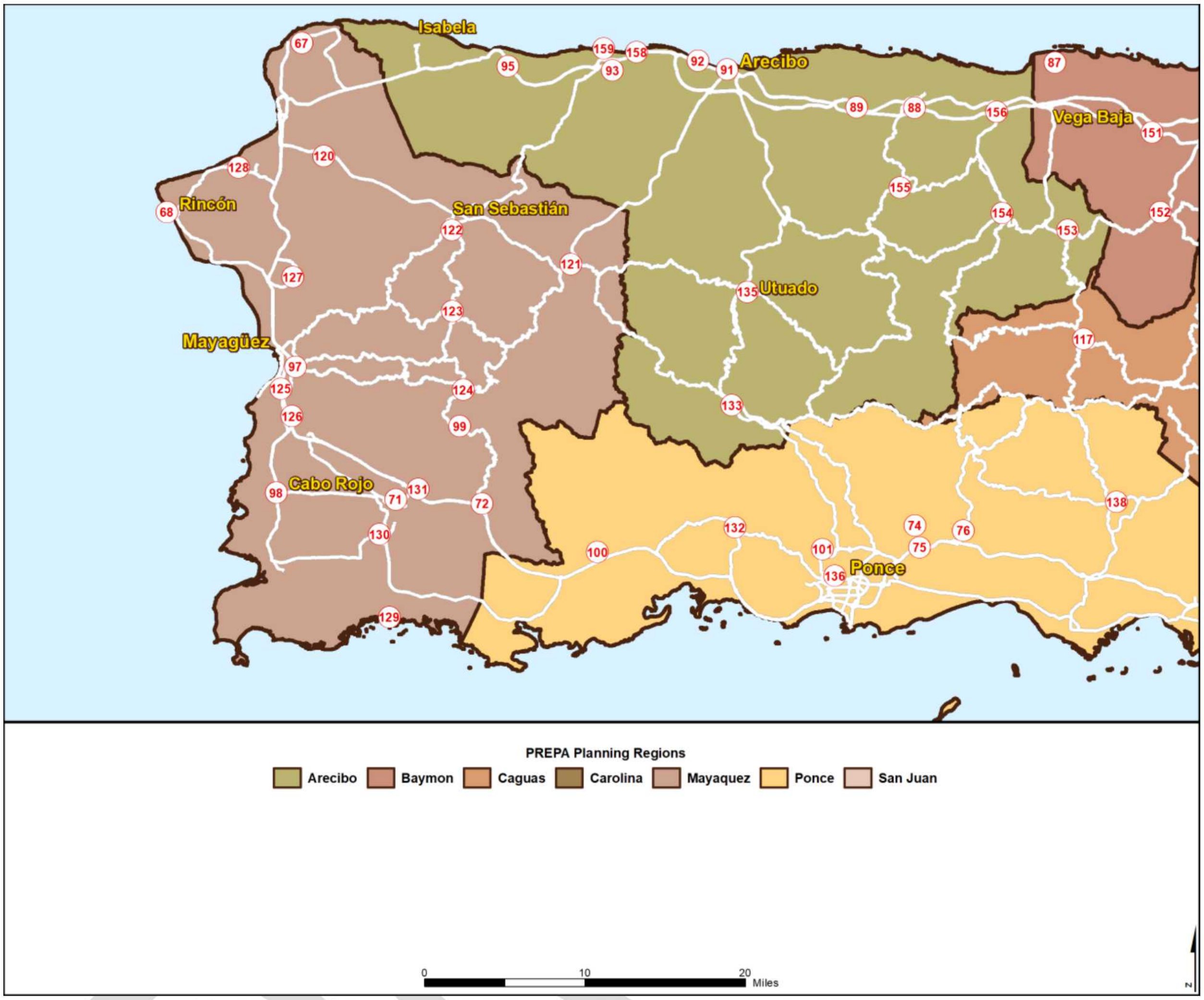

Figure 29. Map of Potential Microgrid Locations in Western Puerto Rico

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8. COST BENEFIT TRADEOFF ANALYSIS

The cost to build all 159 microgrids is significant, and therefore various methods to balance tradeoffs between cost and benefits has been refined for this project. Sandia has generated high-level cost estimates for each microgrid and each region given assumptions that should be refined in cooperation with Puerto Rico stakeholders. The first step in determining the potential costs for each of the regions within Puerto Rico is to determine the amount of generation required for each microgrid. This in turn involves estimating the load demand requirements for the set of critical and non-critical buildings within each microgrid. Direct feeder demand data and building peak demand and energy use data associated with each customer tied to the distribution system would be the best and most accurate way to obtain this data to determine the amount of generation required to serve these loads. Given that this data is not directly available in the time frame to conduct this study, the next best method to estimate building loads is to estimate demand on a square footage basis based on the service type of the building based on the best building surveys and models which are available, so this is the approach taken to do these estimates.

Detailed methodology on the cost estimation approach is included as Appendix A to this report. Costs for each of the 159 microgrids is included as Table 7 for four different scenarios that span different assumptions about how generation might be sized at each microgrid. In total, a conservative estimate to serve only critical loads across the entire 159-microgrid portfolio (cost scenario B1 in Appendix A) is $1,165M. The two largest microgrids - numbers 2 and 3 - contribute 42% of this total. Note the total population-normalized burden for the do-nothing portfolio is approximately 25.26, while the burden score for the entire 159-microgrid portfolio is 8.88.

Ideally, all infrastructure services would have at least some level of service enabled by resilient power solutions, which is a threshold that can be set by Puerto Rico planners. This is one area where the societal burden metric can support decision-making. To explore the space of potential microgrid portfolios – e.g. subsets of the 159 microgrids – Sandia selected 1000 combinations from the 159-microgrid set at random and calculated their overall societal burden score against the portfolio cost, illustrated as a scatter plot in Figure 30**Error! Reference source not found.**. Not all portfolios are covered, but this gives insight into the impact of portfolio selection on the burden metric. While the individual impacts of each microgrid may help to prioritize investments, these microgrids should not be viewed completely independently. Many of the suggested nodes are highly complementary to one another, and conversely two highly ranked microgrids may be spatially redundant. The overall system of microgrids has been designed to decrease the burden of accessing critical services to the entire population of Puerto Rico.

To reflect a sensible investment strategy, all of the portfolios illustrated in Figure 30 contain between 60 and 100 microgrids. Within this range there are groupings where the portfolios appear to cluster, most likely due to the presence of one or two specific microgrids or the inclusion of a specific service in an area that is lacking that service. Sandia more closely examined the bottom left region of this scatter plot to filter down to portfolios that are most cost effective for resilience. Of the 34 individual portfolios that cost less than $400M and have a total burden score less than 12, there were individual microgrids that appeared more often, and some that appeared much less often. The most frequent inclusions are microgrids 14, 33, 44, 58, 62, 64, 73, 89, 93, and 124. The least frequent inclusions are 3, 16, 19, 24, 46, 52, 65, 88,133, and 135.

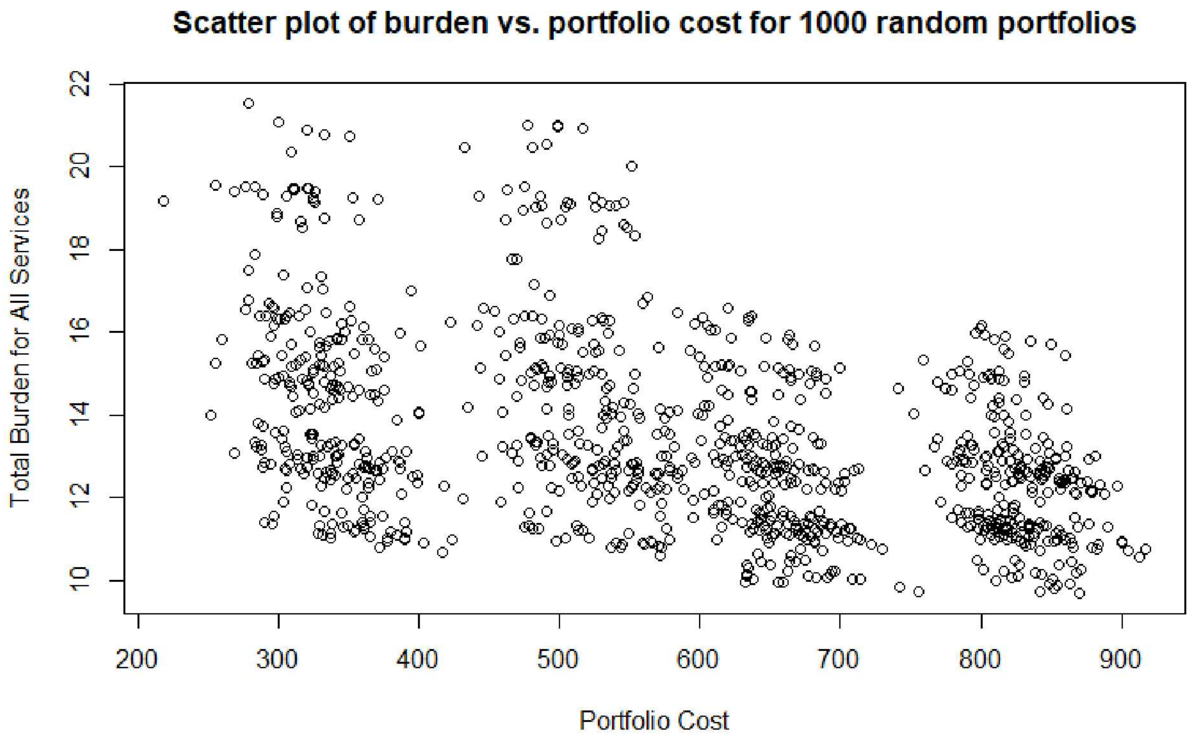

Figure 30. Total Burden to Acquire All Services vs. Cost (in Million US Dollars) for 5000 Random Microgrid Portfolios

Sandia has developed an interactive results explorer for further exploration of these microgrid portfolios. This Microgrid Portfolio Explorer (MPEx) allows users to upload portfolios and compare across the dimensions of the societal burden metric. In coordination with stakeholders, the burden metric can be plotted spatially as shown in Figure 31, and in a histogram as shown in Figure 32. This can also be used to find which specific services (e.g. food, water, shelter) are contributing most to the burden score, so additional microgrids can be found that improve portfolios. Additionally, effort can be explored separately from burden, and locations of the microgrids in each portfolio dynamically update on a separate map when a user changes portfolios. As users compare different portfolios, a history is saved so that "better" portfolios may be identified. As illustrated in Figure 33, a previous portfolio the user analyzed has a better performance for similar cost to the current portfolio under consideration. MPEx can be packaged and delivered to project stakeholders as a compliment to this report.

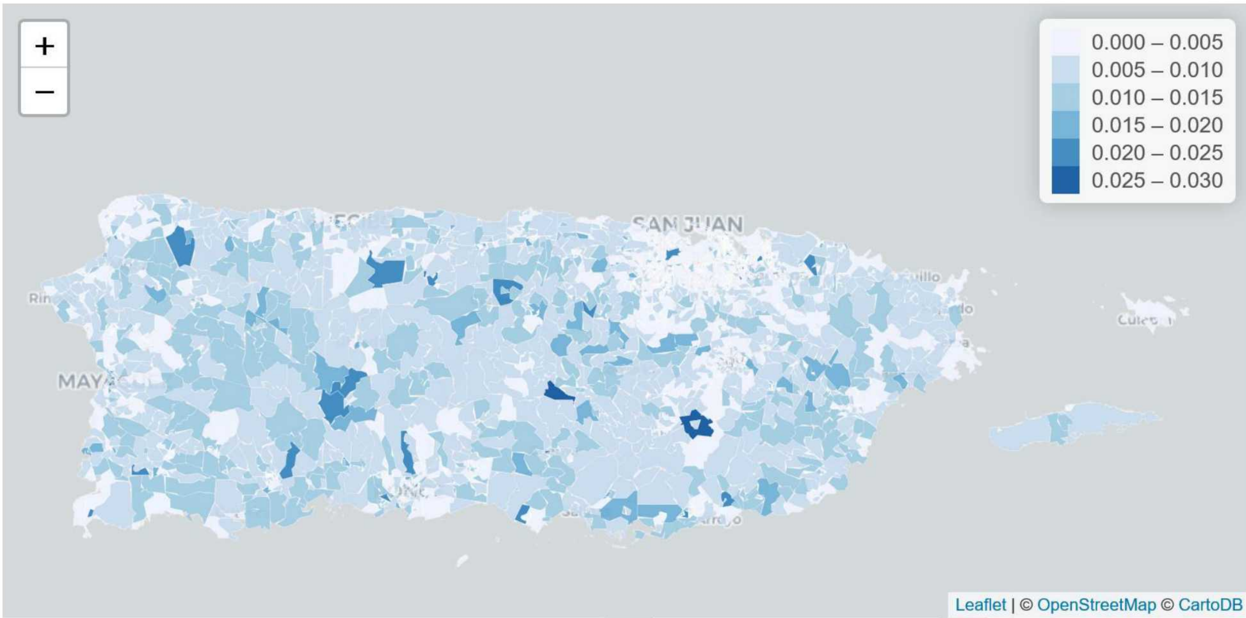

Figure 31. Map of Burden to Access All Services for One of the Most Cost Effective Portfolios

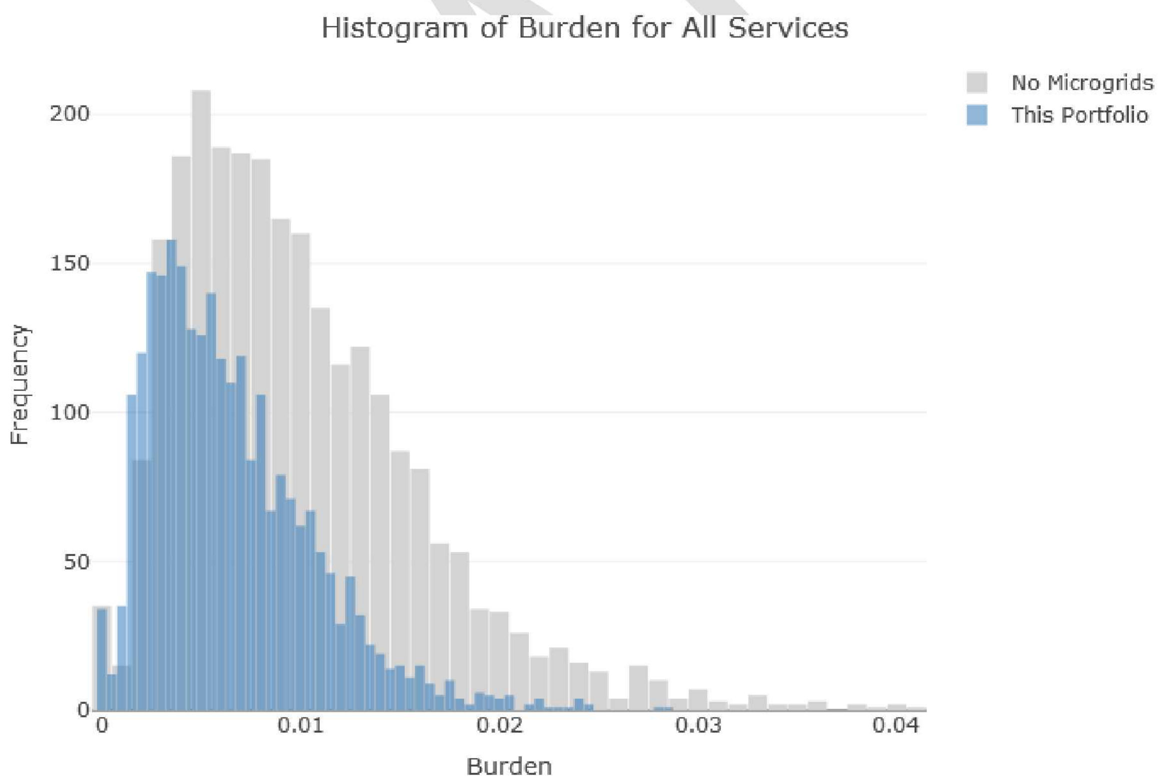

Figure 32. Histogram of Burden to Access All Services for One of the Most Cost Effective Portfolios.

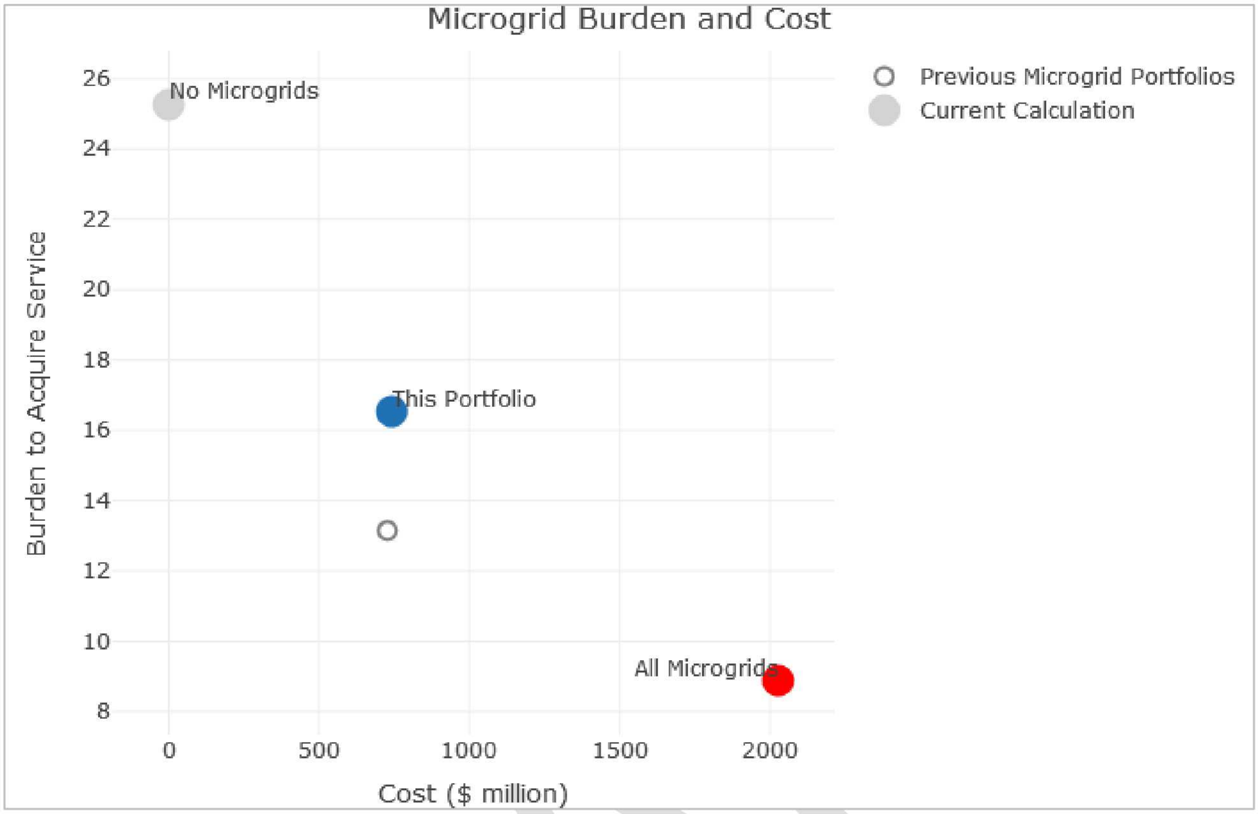

Figure 33. Comparing microgrid portfolios by their relative burden score and cost using MPEx.

9. CONCLUSIONS AND FUTURE WORK

These results provide siting of microgrids explicitly to improve a community-focused and risk-informed resilience metric. With the high-level cost estimation performed, the system of all 159 potential resilience nodes would cost $1,165M if only the critical loads were served by these microgrids, and approximately $2,027 to serve both critical and non-critical load. A large cluster of portfolios achieves performance benefits close to the do-everything scenario at greatly reduced cost: on the order of $300-$400M. Microgrids 14, 33, 44, 58, 62, 64, 73, 89, 93, and 124 appear most often in this cluster of portfolios that have the most cost-effective impact to societal burden. These portfolios should be studied in more detail for commonalities. We stress that the societal burden calculations have not been validated, and the confidence in these recommendations is low without additional work and stakeholder interaction. Steps to validation and verification include:

- Sensitivity analysis of burden and cost calculations to understand the most sensitive parameters and improve confidence in model outputs
- Working with Puerto Rico stakeholders such as PREPA distribution system planners, State officials, and city officials to validate assumptions made in the calculation of societal burden
- Improved cost estimates based on size of microgrid, facility types, building loads, characteristics of local distribution system, existing generation, and other factors
- Collecting additional data on the relative reliability and resilience of individual feeders, especially those feeders that are within microgrid boundaries
- Working with infrastructure owners and the academic community to better incorporate the fragility of infrastructure assets such as cell towers to wind speed and other hazards not included herein

Two additional bodies of analysis accompany this report. Appendix B describes a method to calculate economic resilience metrics, which can complement the societal metric used herein. Appendix C discusses design considerations for planners once they have chosen a particular microgrid for potential investment.

Additional work is being performed on this project to deliver actionable tools to Puerto Rico and federal stakeholders. Tasks include:

- The ReNCAT and MPEx tools are relatively robust and ready to use by analysts outside Sandia. Training material will be generated on use of these tools.

In the long-term, over the course of the next year Sandia plans to incorporate other considerations that will support inclusion of microgrids into the overall grid modernization portfolio for Puerto Rico, such as:

- Microgrids can be used to improve grid restoration, and therefore should be considered within system level models of outage restoration dynamics. Interdependencies between infrastructures during restoration periods should also be considered.
- At the scale of all 159 microgrids suggested, a networked microgrid approach could further improve service provisions at minimal cost. To start, two microgrids could be linked together via a hardened feeder that picks up additional infrastructures. As this

system expands, it becomes a grid of microgrids with additional features such as reconfigurability, improved generation/load balancing, and improved dispatchability on the transmission system.

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APPENDIX A: MICROGRID COST METHODOLOGY

The US Energy Information Agency (EIA) conducts a periodic survey of the stock of US commercial buildings known as the Commercial Buildings Energy Consumption Survey (CBECS) (R1). The CBECS classifies building types in to the principle building activity, such as education, food sales, health care, mercantile, office, etc. Each building type category is further subdivided into sub-categories to facilitate CBECS questionnaires upon which energy data is obtained (R2). For example, the building type category Education, has subcategories for elementary, middle and high schools, college or university, preschool, adult education etc. We utilized energy use tables from the most recent data available in 2012 (R3) to develop load estimates for buildings based on load type for these microgrids.

The CBECS reports kWh per square footage usage for each building category. It also reports broad data of the same per unit square footage data for different ranges of size in buildings (1,001 to 5,000, 5,001 to 10,000, etc., up to buildings over 500,000 square feet). Across the different range of sizes of buildings, there isn't a clear relationship like a linear increase or decrease in per unit usage as sizes increase, so we didn't utilize this information in our load estimates. The CBECS also discriminates survey information by the region it resides in, which is further reflective of the type of climate each region reflects based on annual temperature and precipitation. Puerto Rico is classified to be closest to the South climate region. Based on building data, we increased the average usage of Puerto Rico buildings by ~13.5% to reflect the higher average use of the South climate region relative to the average of all regions.
With this data we developed estimates for average yearly use per kWh of critical buildings by mapping this 2012 data from the CBECS categorized by building types to the infrastructure types we considered for inclusion in our microgrids adjusted by the climate region associated with Puerto Rico as noted. For non-critical buildings within microgrids, we used average yearly use data of the average for all buildings in the 2012 CBECS data set.

To determine the generation requirements for microgrids, we need to estimate the energy kW demand for the buildings, or the estimated peak usage for these buildings since this reflects the amount of generation required to supply the load during a peak condition. Since we don't know when an event may occur, the best approach is to design the microgrid generation to meet or exceed the peak demand for buildings associated with the microgrid.

To translate the energy use data into peak demand data for each building we used another set of available data. DOE Office of Energy Efficiency & Renewable Energy (EERE) in conjunction with three national laboratories has developed 16 commercial reference buildings (R4) which serve as benchmark models which represent up to 70% of commercial buildings in the United States. This data set (R5) is maintained as part of the Open Energy Information (Open EI) is a community which provides content and data for a variety of energy topics including energy building models (R6). Available buildings types include representations for various size offices, warehouse, commercial retail, primary and secondary schools, supermarkets, restaurants, hospitals, healthcare, hotels and apartment complexes. Each building type has a representative floor area, number of floors. These building types are broken down into applicable climate zones. Each building type has a set of 1-hour energy demand profiles for one-year duration. This data set allowed us to calculate what the expected peak demand would be relative to the average demand for each of these building types for buildings modeled in climate zones that are closest to Puerto Rico in climate. For example, the peak demand for the supermarket model building is approximately 2X the average demand for the yearly model. Like the CBECS data set, we mapped building types to our critical infrastructure types to determine the demand factor for each critical infrastructure type. For buildings with no clear association with the critical infrastructure type as well as for non-critical buildings, we used the average demand factor of the buildings to develop calculations.

Based on these data sets, Table 4 below shows the energy use and peak demand values we used to estimate buildings contained in each microgrid area. We used an average demand of 6kW and a peak demand of 12kW for AM & FM transmitters, cell and microgrid towers, since these assets don’t track easily to square footage.

Table 4. Energy Use and Demand Estimates for Critical Infrastructure Types

Critical Infrastructure Type	CBECS Building Activity (for Energy Use Calculation)	OPEN EI Building Model (For Demand Factor Calculation)	Energy Use (kWh/1000 sqft/year	Peak Demand (kW/1000 sqft/year
Shelter	Education	Primary School	12495	3.9938
Grocery Store	Food Sales	Supermarket	55318	12.6296
Hospital	Health Care Inpatient	Hospital	35213	5.6276
Medical Center	Heath Care Outpatient	Outpatient Health Care	21241	4.6071
Pharmacy	Retail other than mall	Average Demand	17266	4.5332
Bank	Office	Office	18061	5.1543
Evac Site	Public Assembly	Average Demand	16470	4.3244
Police, Fire, EMS, EOC	Public Order and Safety	Average Demand	16925	4.4437
Gas Station	Service	Average Demand	9428	2.4754
Other Infrastructures	Other	Average Demand	32146	8.4401
Non-Critical	Average	Average Demand	16584	4.3542

Microgrid Cost Estimation

In advanced microgrids, all distributed generation resources - renewables, energy storage, diesel or natural gas gen-sets, etc. - are connected on the local distribution system, as well as connected to the sub-transmission system through one or more points of common coupling (PCC). As shown in Figure 34 below, there is flexibility in the size of the microgrids, from a partial feeder, full feeder, multi-feeder, or even a full substation microgrid, depending on local needs.

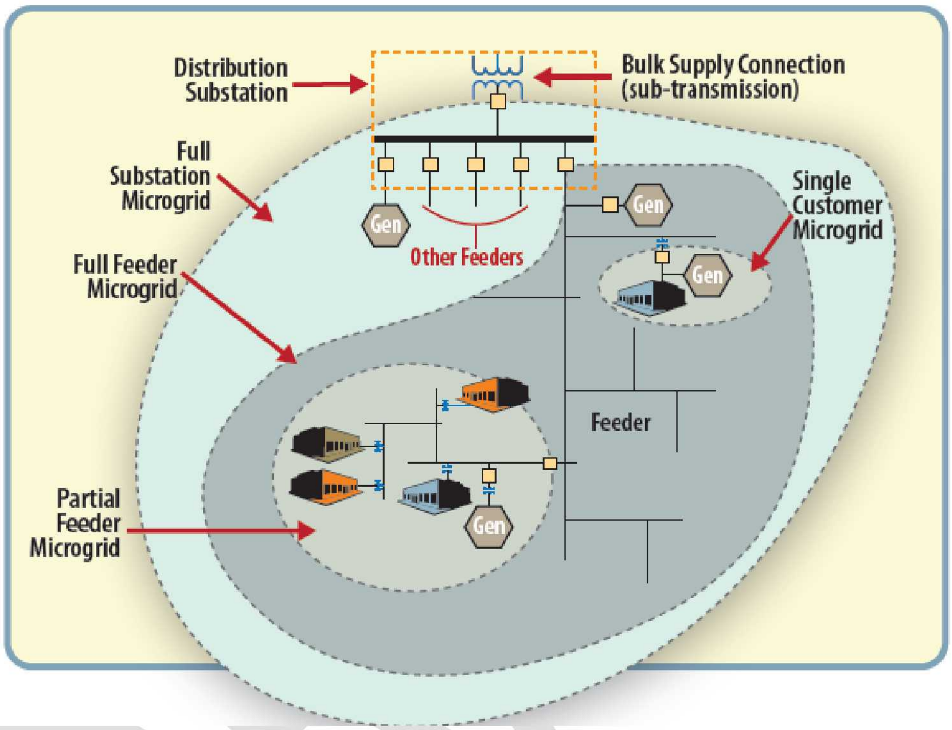

Figure 34. Microgrids can vary in size depending on how much of a feeder is utilized

The major operational benefit of a microgrid is that the distributed generation can operate when tied to the grid to reduce peak load, etc., but also operate independently during a power outage to safely support local critical loads. In this way, energy costs are minimized by using lower cost utility power most of the time, but using the renewable and distributed generation resources when appropriate – power outages, peak shaving of power demand to lower energy costs, etc. This optimizes the operation of the distributed generation and lowers operational costs. This is often the lowest cost, highest reliability approach, supporting 20-40% of renewable penetration without expensive energy storage.

There are usually minimal additional operations and maintenance costs associated with microgrids since the existing distribution system infrastructure is often used. This approach has the most flexibility in managing loads and generation resources as situations vary, improves local energy assurance and resiliency in both short and extended power outages, enhances the utilization of renewables to provide emergency power, and enables load shedding and other grid services with distributed and renewable generation. Microgrids can be a relatively cost-effective option, often paying for themselves in a single major power outage because of the avoided economic loss of critical operations or services, by reducing costs through load shedding, and by generating income by providing ancillary services to the local utility when needed.

A microgrid essentially works as an integrated energy system consisting of loads and distributed energy resources (DERs) operating as a coherent unit, either in parallel with or islanded from the power grid, and either utilizing elements from the existing grid (power lines, transformers, switches, etc.,) or operating as a separate unit which can tie to or be isolated from the power grid. A microgrid should have capabilities designed to make the microgrid operate with flexibility and efficiency. Some important capabilities include:

- Flexibility in placement and technologies associated with generation resources including distributed generation, renewables and energy storage by development of plug-and-play capabilities. Plug-and-play also provides for reduction of engineering costs of these resources and increased reliability through their shared use among multiple facilities within the microgrid. This is compatible with a range of different sizes of generation resources in the microgrid.
- Power quality and reliability are enhanced through intentional islanding and autonomous control of generation resources.
- Robustness of the system is enhanced through the ability of generation resources to share all energy resources to meet the needs of the loads. The microgrid provides for continuous operation during loss of the utility grid, and compensates for loss of generation resources by sharing loads between units.
- Because the total generation is matched to the microgrid load, with a slight excess for contingencies, the generation resources are run more efficiently so only the backup generation required for the microgrid is utilized, therefore less yearly emissions during power outages will occur.

Generation resources (also referred to as distributed energy resources (DERs)) are distributed to enhance reliability by minimizing disruptions during power outages and providing distributed power to critical resources when islanded. If generation resources are designed to carry continuous loads, they can supply these loads and any excess can be sold back to the utility to balance costs while grid connected. Generation resources can also be potentially used as peak shaving devices. Typical generation sources used in todays advanced microgrids include diesel and gas engines, microturbines, fuel cells, PV, wind, biomass, etc. depending on the capabilities and interests of the site.

Microgrids are designed to distribute existing and new generation resources among critical buildings to meet critical energy needs. They therefore require the following types of alterations of the existing utility grid to implement the microgrid:

Microgrids are collections of buildings connected to the existing distribution feeders which form by isolating portions of the feeders connected to these buildings during a major event using points of common coupling (PCCs) and serving these loads with sufficient generation to be able to supply the loads for the duration of the event. Microgrids can supply all the buildings it connects or only the set of critical buildings needed during the event. Since it may be cost prohibitive to supply generation to all the buildings during an event, it is possible to employ automated switches which can shed supply to non-critical buildings during the event to reduce the cost of generation, with the added cost of the load shedding switches.

Microgrids that use either diesel or natural gas generation coupled with photovoltaics (PV) and battery energy storage are still the most prevalent forms of energy supply used in microgrids today so we consider combinations of these in the microgrid options we consider. To make microgrids effective, it is often necessary to either replace or refurbish existing overhead or underground lines to make them more resilient to expected events, therefore these costs need to be considered as well. Per unit installed equipment costs estimates for these items are listed in Table 5 below.

Table 5. Microgrid Installed Equipment Cost Estimates

Equipment Item	Installed Equipment Cost	Unit
Natural Gas Generation	1.2	$/W
Diesel Generation	0.6	$/W
Battery Energy Storage	1.0	$/WH
Photovoltaics (PV)	1.5	$/W
Point of Common Coupling (PCC)	100	$K/unit
Switch to shed non-critical building (SW)	50	$K/unit
Overhead Line	700	$K/kilometer
Underground Line	2800	$K/kilometer
Overall Estimated Cost	2X	2 times total installed equipment cost

Note that these costs are high level averages for actual costs associated with a particular installation which necessarily requires detailed cost estimation for validation. To account for the additional control infrastructure, auxiliary equipment, permitting, engineering, design, construction, overhead, etc. costs which would also have to be estimated in detail, we use a factor of 2X these installed equipment cost calculations to account for these costs. The purpose of the cost estimates, is to provide information about the general relative costs that should be anticipated for both a collection of microgrids as well as particular microgrids considered, which can be compared to determine which microgrids are the most feasible for further performance and cost analysis selection.

To simplify the analysis, we consider cost comparisons of four options listed in Table 5 below. We use either diesel or natural gas generation to supply all loads critical and non-critical in each microgrid area (Option A1 or A2) or diesel or natural gas generation to only critical service loads in each microgrid area (Option B1 or B2). In these options, the diesel or natural gas generation is sized to serve 80% of the load, and a combination of 40% PV and 20% battery energy storage (1 hour) is included to supply the 20% during peak demand periods. Inclusion pf PV and battery energy storage allows these resources to recover costs when microgrids are not operating by supplying power and ancillary services to the existing distribution system. For each option, we assume that 4 PCCs are required to isolate the microgrid from the existing distribution system. For service of critical loads only (Option B1 or B2) 10 switches to shed non-critical loads are included in each option. Given that it requires further detailed analysis within each microgrid to specify generation, PV, the amount of PCCs and SWs required to employ, as well as actual customer load data to more accurately assess costs for these options, we have taken the approach to apply the same requirements for each microgrid to come up with some initial cost estimates for these microgrids. These options do not include those associated with replacing or refurbishing existing overhead or underground lines, but the generic costs per km for both types provides a sense of what additional costs would be entailed to the extent that parts of these feeders would have to be refurbished or replaced in the microgrid implementations.

Figure 35 below shows an example load duration curve obtained from averages of the 16 EERE commercial reference buildings discussed in the building load section above. A load duration curve shows the percentage of time the load will be expected to be at a certain level during the year. In this example, the load will be greater than or equal to 50% of peak load, approximately 60% of the time (red dotted line), and greater than or equal to 80% approximately 17% of the time (blue dotted line). This indicates that the load will only be greater than 80%, 17% of the time periods which in our microgrids would require PV and battery energy storage to supplement the diesel or gas generation in each microgrid.

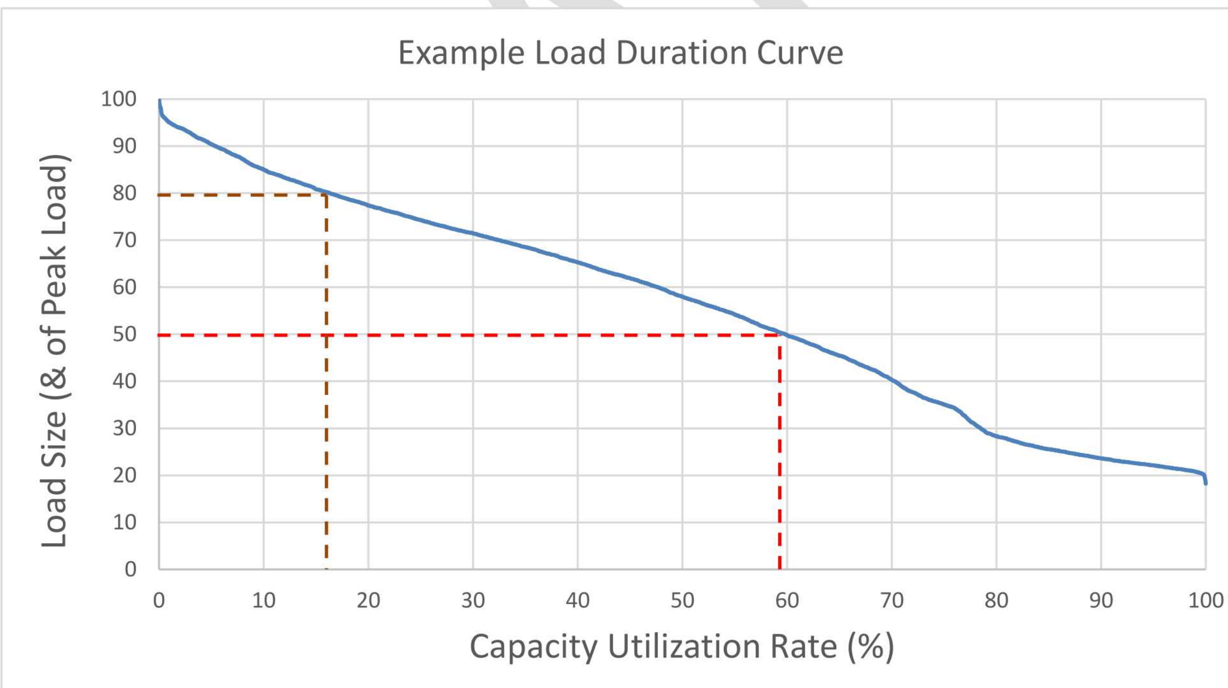

Figure 35. Example Load Duration Curve

Table 6. Microgrid Options Considered

Option A1	80% Diesel, 40% PV, 20% Energy Storage (1 hour), 4 PCCs serving all loads
Option A2	80% Natural Gas, 40% PV, 20% Energy Storage (1 hour), 4 PCCs serving all loads
Option B1	80% Diesel, 40% PV, 20% Energy Storage (1 hour), 4 PCCs, 10 SWs serving critical loads only
Option B2	80% Natural Gas, 40% PV, 20% Energy Storage (1 hour), 4 PCCs, 10 SWs serving critical loads only

Based on the load and cost estimate methods used, each of the four options considered in Table 6 is applied to each microgrid area, which also includes the amount of critical and non-critical demand estimated based on the square footage of buildings contained within them. Given that we are working with both high level load estimates and cost estimate methods, this data should be viewed as high level comparative cost information for the microgrids, based primarily on their sizes which can then be further analyzed to in more detail with more complete data to obtain more accurate estimates of each. But the data should provide information about the relative sizes and costs that might be expected for these microgrids.

Table 7 displays the cost estimates based on the critical and non-critical demand estimates (kW) for the 159 candidate microgrids identified throughout Puerto Rico based on the load estimate and cost estimate methodology employed. Table 8 illustrates the same demand estimates for both critical and non-critical loads as well as the energy use in gigawatt-hours (109 Watt-hours, GWH) per year based on the same load estimate methodology. Table 8 also shows the amount of communication towers included in each microgrid (AM & FM transmitters, cell and microgrid towers).

In many of the microgrids the critical building asset loads represent approximately 40% of the loads for each microgrid. This means that approximately 60% additional generation must be included to supply each microgrid for non-critical loads. Depending on the case, above a threshold it then becomes more cost effective to shed non-critical loads and supply generation to critical loads when the microgrid is operated as indicated by Option B costs. For smaller microgrids, it may be more advantageous to supply generation to both critical and non-critical loads indicated by Option A.

There is a great range in size with the microgrids, so the costs for given microgrids vary widely. It may be possible to further reduce the size of larger microgrids like microgrid 2, the Hospital Complex, or microgrid 3, the International Airport, by splitting them into smaller microgrids or serve a smaller subset of critical loads. In any case the results presented show load and cost comparative information which can be further analyzed to determine which ones are the most important and critical for service to Puerto Rico during major events.

Table 7. Microgrid Cost Estimates for each Microgrid Area

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Option A1 ($M)	Option A2 ($M)	Option B1 ($M)	Option B2 ($M)
1	San Juan City Hall	1079	4630	15.42	20.90	4.56	5.60
2	Hospital Complex	70049	9323	203.99	280.19	181.13	248.37
3	International Airport	122315	12805	346.71	476.42	314.93	432.35
4	Muelle De Viejo Ferry and Cruise Terminals	4202	4069	21.97	29.91	12.56	16.59
5	Calle Cuervillas	1201	4250	14.75	19.99	4.87	6.03
6	Doctors Hospital Center	2164	2097	11.71	15.80	7.34	9.42
7	Centro Comunal El Gandel	456	1100	4.78	6.28	2.97	3.41
8	Conservatoria de Musica de Puerto Rico	2655	886	9.86	13.26	8.60	11.15
9	Pavia Hospital Complex	2032	14882	44.10	60.34	7.00	8.95
10	Avenida Wilson	1579	10464	31.63	43.19	5.84	7.36
11	Avenida Doctor Ashford	2902	14966	46.54	63.70	9.23	12.02
12	University Sacred Heart	1332	3019	11.94	16.12	5.21	6.49
13	FRD Airport and Convention Center	7774	21268	75.15	103.03	21.70	29.16
14	Sagrado Corazon	1377	3848	14.18	19.19	5.33	6.65
15	Avenida Borinquen	862	2833	10.26	13.81	4.01	4.83
16	Avenida Isla Verde	6892	3251	26.77	36.50	19.44	26.06
17	Universidad del Este	1685	1271	8.37	11.21	6.11	7.73
18	Coliseo de Puerto Rico Jose Miguel Agrelot	8840	16189	64.87	88.90	24.43	32.92
19	Pavia Hato Rey	1555	8376	26.22	35.76	5.78	7.27
20	Domenech	1445	2911	11.95	16.13	5.50	6.89
21	Pinero	3703	3015	18.00	24.45	11.28	14.83
22	Rio Piedras	1361	6785	21.65	29.47	5.28	6.59
23	Escuela Republica de Colombia	2338	6961	24.61	33.53	7.79	10.03
24	The Mall of San Juan	1565	684	6.56	8.72	5.81	7.31
25	Plaza Escorial	3952	4403	22.19	30.21	11.92	15.71
26	Avenida 65 de Infanteria	338	3140	9.70	13.04	2.67	2.99
27	Los Colobos	1371	1892	9.15	12.29	5.31	6.63
28	Canovas	386	2087	7.13	9.50	2.79	3.16
29	Green Carribbean	1082	206	4.10	5.33	4.57	5.61
30	Radio Station Mountain	108	93	1.31	1.51	2.08	2.18
31	Plaza Trujillo	3052	4924	21.22	28.88	9.61	12.54
32	Senorial Plaza	741	1161	5.67	7.50	3.70	4.41
33	Avenidos Las Cumbres	876	2055	8.30	11.12	4.04	4.88
34	Avenidos de Diego	139	984	3.67	4.75	2.16	2.29
35	Estacionamiento de Plaza Caparra	4924	7794	33.36	45.57	14.41	19.13

Table 7: Microgrid Cost Estimates for each Microgrid Area (Continued)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Option A1 ($M)	Option A2 ($M)	Option B1 ($M)	Option B2 ($M)
36	Profession Hospital & Wire Center	778	83	3.00	3.83	3.79	4.54
37	Guaynabo Municipal Stadium	1099	5050	16.54	22.44	4.61	5.67
38	Club Gallistico de San Juan, La Muda	48	255	1.58	1.87	1.92	1.97
39	Fraternidad Phi Eta Mu	72	14	1.02	1.10	1.98	2.05
40	WQII-AM San Juan	60	7	0.97	1.04	1.95	2.01
41	WKVM-AM San Juan	72	26	1.05	1.14	1.98	2.05
42	Esc. Juan Ponce de Lein	215	493	2.61	3.29	2.35	2.56
43	Jardines	602	67	2.51	3.15	3.34	3.92
44	Ft Buchanan	129	2744	8.15	10.91	2.13	2.25
45	Bayamon	1256	1294	7.33	9.78	5.02	6.22
46	Parque Robert Junghanns	1886	3325	14.14	19.14	6.63	8.44
47	Sec Los Viejito Hato Tejas	64	1553	4.94	6.49	1.96	2.03
48	Drive in Plaza	649	2294	8.33	11.16	3.46	4.08
49	PR-863	322	613	3.19	4.09	2.62	2.93
50	Adriel Nissan	17	779	2.84	3.60	1.84	1.86
51	Cell Tower Radio Ridge	72	18	1.03	1.12	1.98	2.05
52	Escuela Maria Vazquez de Umpierre	425	410	2.94	3.74	2.89	3.30
53	Radio Cell Tower Hill	36	0	0.89	0.93	1.89	1.93
54	Plaza Aquarium Mall	923	719	5.00	6.58	4.16	5.05
55	Avenidos Esmeralda	274	894	3.79	4.91	2.50	2.76
56	Supermercados Econo	5249	3217	22.47	30.60	15.24	20.28
57	University of Puerto Rico- Medical Sciences	7524	1042	22.73	30.95	21.06	28.28
58	Miguel Such	2500	321	8.02	10.73	8.20	10.60
59	Rexville Towne Center	645	3293	10.88	14.66	3.45	4.07
60	Cola-Cola Land	304	2737	8.58	11.50	2.58	2.87
61	Riverview Bayamon	301	83	1.78	2.15	2.57	2.86
62	Levittown Toa Baja	889	1376	6.60	8.77	4.08	4.93
63	Club Atletico Levitown	890	363	4.01	5.21	4.08	4.93
64	Train Yard & PSAP	3517	2112	15.21	20.61	10.80	14.18
65	Hospital Metropolitano	3463	5604	24.01	32.72	10.67	13.99
66	Calle San Augustin	573	3203	10.47	14.09	3.27	3.82
67	Aguadilla Airport	1465	5281	18.07	24.55	5.55	6.96
68	Rincon City Center	150	1499	5.02	6.61	2.19	2.33
69	Mayaguez Calle Mendez	170	728	3.10	3.96	2.23	2.40

Table 7: Microgrid Cost Estimates for each Microgrid Area (Continued)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Option A1 ($M)	Option A2 ($M)	Option B1 ($M)	Option B2 ($M)
70	Mayaguez Hospitals	409	1376	5.37	7.08	2.85	3.24
71	San German Avenida Universidad	785	943	5.22	6.88	3.81	4.56
72	Sabana Grande City Center	1021	4461	14.83	20.10	4.41	5.39
73	Ponce Aven Tito Castro	239	1198	4.48	5.86	2.41	2.64
74	Ponce Carretera Central	79	399	2.02	2.48	2.00	2.08
75	Ponce Hospital San Cristobal	204	2194	6.94	9.24	2.32	2.52
76	Juana Diaz Casa Alcaldia	599	1585	6.39	8.49	3.33	3.91
77	Aibonito City Center	2031	1312	9.36	12.57	7.00	8.95
78	Caguas Ave Degetau	207	1461	5.07	6.67	2.33	2.53
79	Caguas CDT Atencion	414	2468	8.18	10.94	2.86	3.26
80	Caguas Centro Ambulatorio	418	2083	7.20	9.60	2.87	3.27
81	Humacao Hima San Pablo	549	2406	8.37	11.20	3.21	3.73
82	Humacao Aven Font Martelo	135	855	3.33	4.28	2.14	2.27
83	Ceiba Aven Lauro Pinero	270	2667	8.32	11.14	2.49	2.75
84	Isabela Segunda Avenida El Tamarindo	108	1602	5.18	6.82	2.08	2.18
85	Canovanas Communications	0	809	2.87	3.65	1.80	1.80
86	Baymon Communications	10	317	1.63	1.95	1.82	1.83
87	Puerto Nuevo Communications	0	8	0.82	0.83	1.80	1.80
88	Barceloneta Communications	0	147	1.18	1.32	1.80	1.80
89	Carretera 2 Rd Communications	0	638	2.43	3.05	1.80	1.80
90	Arecibo Hosp Metropolitano	329	1442	5.34	7.04	2.64	2.96
91	Arecibo Hosp Manuel Figueroa	727	2254	8.43	11.29	3.66	4.36
92	Arecibo Aven Miramar	170	4590	12.98	17.55	2.23	2.40
93	Camuy Communications	0	357	1.71	2.06	1.80	1.80
94	Quebradillas Calle Socorro	600	720	4.18	5.45	3.34	3.91
95	Quebradillas City Center	697	2467	8.90	11.94	3.58	4.25

Table 7: Microgrid Cost Estimates for each Microgrid Area (Continued)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Option A1 ($M)	Option A2 ($M)	Option B1 ($M)	Option B2 ($M)
96	Isabela City Center	854	1896	7.84	10.48	3.99	4.81
97	Mayaguez Casa Alcaldia	647	1856	7.21	9.61	3.46	4.08
98	Cabo Rojo City Center	502	2150	7.59	10.13	3.09	3.57
99	Bosque Estatal de Maricao Comms	0	191	1.29	1.47	1.80	1.80
100	Yauco City Center	1419	6125	20.11	27.35	5.43	6.79
101	Madrigal Community Center	205	398	2.34	2.92	2.33	2.52
102	Guayama City Center	234	396	2.41	3.02	2.40	2.62
103	Guayama Escuela Francisco	75	1085	3.77	4.88	1.99	2.06
104	Plaza Guayama	1770	6733	22.57	30.73	6.33	8.03
105	Bosque Estatal de Carite Comms	0	109	1.08	1.18	1.80	1.80
106	Yabucoa Catalina Morales	951	7646	22.81	31.06	4.23	5.15
107	Las Piedras Centro Medico	525	4526	13.73	18.58	3.15	3.65
108	San Lorenzo Carr Estatal	684	965	5.02	6.61	3.55	4.21
109	Pueblita del Rio	10	214	1.37	1.59	1.82	1.83
110	El Paraiso	149	457	2.35	2.94	2.18	2.33
111	Cidra City Center	384	2236	7.51	10.02	2.78	3.15
112	Casa Alcaldia de Naguabo	264	800	3.53	4.55	2.48	2.73
113	Cerro Corozal Communications	0	212	1.34	1.55	1.80	1.80
114	Luquillo City Center	844	714	4.79	6.28	3.96	4.77
115	Bosque El Yunque Communications	0	40	0.90	0.94	1.80	1.80
116	Orocovis Calle Juan Rivera Santiago	173	517	2.57	3.23	2.24	2.41
117	Orocovis Casa Alcaldia	402	810	3.90	5.07	2.83	3.22
118	Aguadilla West Parade	427	2350	7.91	10.57	2.89	3.30
119	Moca Hosp San Carlos Borromeo	289	1134	4.44	5.81	2.54	2.82
120	Moca Calle Mon Torres	194	671	3.02	3.85	2.30	2.48
121	Lares City Center	331	1294	4.96	6.52	2.65	2.97
122	San Sebastian	133	1118	4.00	5.20	2.14	2.27
123	Las Marias	188	892	3.57	4.60	2.28	2.46

Table 7: Microgrid Cost Estimates for each Microgrid Area (Continued)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Option A1 ($M)	Option A2 ($M)	Option B1 ($M)	Option B2 ($M)
124	Maricao	234	691	3.17	4.06	2.40	2.62
125	Mayaguez Advanced Cardiology	423	4906	14.44	19.56	2.88	3.29
126	Mayaguez Mall	1380	13842	39.77	54.38	5.33	6.66
127	Anasco	199	1687	5.63	7.44	2.31	2.50
128	Aguada	1030	1006	6.01	7.96	4.44	5.42
129	La Parguera	612	1291	5.67	7.50	3.37	3.96
130	Lajas	242	3513	10.41	14.02	2.42	2.65
131	San German Plaza del Oeste	1249	2309	9.91	13.32	5.00	6.20
132	Penuelas	253	829	3.57	4.61	2.45	2.69
133	Adjuntas	510	511	3.41	4.39	3.11	3.60
134	Utuado South	199	676	3.04	3.88	2.31	2.50
135	Utuado North	204	603	2.86	3.64	2.32	2.52
136	Ponce Calle Victoria	312	821	3.70	4.79	2.60	2.90
137	Juana Diaz Mall	710	2935	10.13	13.63	3.62	4.30
138	Coamo	575	2126	7.71	10.31	3.27	3.82
139	Cayey South	333	2059	6.92	9.22	2.65	2.97
140	Cayey North	507	274	2.80	3.55	3.10	3.58
141	Guayama East	698	2397	8.72	11.69	3.59	4.26
142	Maunabo	158	1132	4.10	5.34	2.20	2.36
143	Juncos	641	1369	5.95	7.88	3.44	4.06
144	Aguas Buenas	169	863	3.44	4.43	2.23	2.39
145	Caguas South	1318	2826	11.41	15.39	5.18	6.44
146	Plaza de Fajardo	176	876	3.49	4.50	2.25	2.42
147	Fajardo Av Valero	129	536	2.50	3.14	2.13	2.25
148	Culebra South	35	511	2.20	2.72	1.89	1.92
149	Culebra North	507	532	3.46	4.46	3.10	3.58
150	Dorado	417	1524	5.77	7.63	2.87	3.27
151	Vega Alta	642	1639	6.64	8.83	3.44	4.06
152	Corozal	167	1906	6.11	8.09	2.23	2.39
153	Morovis	268	881	3.74	4.85	2.49	2.74
154	Ciales	249	285	2.17	2.68	2.44	2.68
155	Florida	510	2436	8.34	11.17	3.11	3.60
156	Manati	364	3987	11.94	16.12	2.73	3.08
157	Arecibo Hosp Cayetano Coll	637	1724	6.84	9.11	3.43	4.04
158	Hatillo City Center	599	2846	9.62	12.93	3.33	3.91
159	Camuy	175	1806	5.87	7.77	2.25	2.42
	Total	**343455**	**398567**	**2027**	**2739**	**1165**	**1495**

Table 8. Supplemental Demand, Energy Use and Total Communication Equipment for Microgrids

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Critical Energy Use (GWH/year)	Non-Critical Energy Use (GWh/year)	Total Comm Towers
1	San Juan City Hall	1079	4630	3.95	17.64	4
2	Hospital Complex	70049	9323	436.33	35.51	6
3	International Airport	122315	12805	465.72	48.77	3
4	Muelle De Viejo Ferry and Cruise Terminals	4202	4069	15.85	15.50	1
5	Calle Cuervillas	1201	4250	4.77	16.19	2
6	Doctors Hospital Center	2164	2097	10.36	7.99	5
7	Centro Comunal El Gandel	456	1100	0.88	4.19	17
8	Conservatoria de Musica de Puerto Rico	2655	886	10.77	3.37	3
9	Pavia Hospital Complex	2032	14882	9.83	56.68	6
10	Avenida Wilson	1579	10464	6.08	39.85	1
11	Avenida Doctor Ashford	2902	14966	15.83	57.00	2
12	University Sacred Heart	1332	3019	4.14	11.50	1
13	FRD Airport and Convention Center	7774	21268	29.33	81.00	6
14	Sagrado Corazon	1377	3848	4.95	14.66	2
15	Avenida Borinquen	862	2833	3.84	10.79	4
16	Avenida Isla Verde	6892	3251	26.26	12.38	7
17	Universidad del Este	1685	1271	5.28	4.84	4
18	Coliseo de Puerto Rico Jose Miguel Agrelot	8840	16189	32.45	61.66	5
19	Pavia Hato Rey	1555	8376	9.23	31.90	3
20	Domenech	1445	2911	5.11	11.09	2
21	Pinero	3703	3015	16.33	11.48	8
22	Rio Piedras	1361	6785	4.32	25.84	11
23	Escuela Republica de Colombia	2338	6961	13.05	26.51	1
24	The Mall of San Juan	1565	684	4.67	2.61	6
25	Plaza Escorial	3952	4403	17.15	16.77	1
26	Avenida 65 de Infanteria	338	3140	1.28	11.96	2
27	Los Colobos	1371	1892	5.20	7.21	8
28	Canovas	386	2087	1.17	7.95	3
29	Green Carribbean	1082	206	4.37	0.79	5
30	Radio Station Mountain	108	93	0.00	0.35	9
31	Plaza Trujillo	3052	4924	12.05	18.75	3
32	Senorial Plaza	741	1161	2.79	4.42	2
33	Avenidos Las Cumbres	876	2055	3.58	7.83	4
34	Avenidos de Diego	139	984	0.37	3.75	3

Table 8: Supplemental Demand, Energy Use and Total Communication Equipment for Microgrids (Cont)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Critical Energy Use (GWH/ year)	Non-Critical Energy Use (GWh/year)	Total Comm Towers
35	Estacionamiento de Plaza Caparra	4924	7794	19.25	29.68	1
36	Profession Hospital & Wire Center	778	83	4.56	0.32	3
37	Guaynabo Municipal Stadium	1099	5050	4.23	19.24	4
38	Club Gallistico de San Juan, La Muda	48	255	0.00	0.97	4
39	Fraternidad Phi Eta Mu	72	14	0.00	0.05	6
40	WQII-AM San Juan	60	7	0.00	0.03	5
41	WKVM-AM San Juan	72	26	0.00	0.10	6
42	Esc. Juan Ponce de Lein	215	493	0.61	1.88	2
43	Jardines	602	67	1.94	0.25	1
44	Ft Buchanan	129	2744	0.04	10.45	10
45	Bayamon	1256	1294	4.58	4.93	1
46	Parque Robert Junghanns	1886	3325	7.86	12.66	1
47	Sec Los Viejito Hato Tejas	64	1553	0.11	5.92	3
48	Drive in Plaza	649	2294	2.66	8.74	2
49	PR-863	322	613	0.88	2.33	4
50	Adriel Nissan	17	779	0.02	2.97	1
51	Cell Tower Radio Ridge	72	18	0.00	0.07	6
52	Escuela Maria Vazquez de Umpierre	425	410	1.37	1.56	1
53	Radio Cell Tower Hill	36	0	0.00	0.00	3
54	Plaza Aquarium Mall	923	719	3.91	2.74	2
55	Avenidos Esmeralda	274	894	1.15	3.40	0
56	Supermercados Econo	5249	3217	22.51	12.25	0
57	University of Puerto Rico- Medical Sciences	7524	1042	42.22	3.97	0
58	Miguel Such	2500	321	8.03	1.22	0
59	Rexville Towne Center	645	3293	2.68	12.54	0
60	Cola-Cola Land	304	2737	1.27	10.42	1
61	Riverview Bayamon	301	83	1.12	0.32	2
62	Levittown Toa Baja	889	1376	3.78	5.24	1
63	Club Atletico Levitown	890	363	3.64	1.38	0
64	Train Yard & PSAP	3517	2112	13.30	8.04	2
65	Hospital Metropolitano	3463	5604	20.34	21.34	0
66	Calle San Augustin	573	3203	2.51	12.20	0
67	Aguadilla Airport	1465	5281	5.53	20.11	2
68	Rincon City Center	150	1499	0.55	5.71	0

Table 8: Supplemental Demand, Energy Use and Total Communication Equipment for Microgrids (Cont)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Critical Energy Use (GWH/year)	Non-Critical Energy Use (GWh/year)	Total Comm Towers
69	Mayaguez Calle Mendez	170	728	0.59	2.77	1
70	Mayaguez Hospitals	409	1376	2.56	5.24	2
71	San German Avenida Universidad	785	943	2.92	3.59	0
72	Sabana Grande City Center	1021	4461	3.82	16.99	0
73	Ponce Aven Tito Castro	239	1198	0.79	4.56	0
74	Ponce Carretera Central	79	399	0.30	1.52	1
75	Ponce Hospital San Cristobal	204	2194	1.28	8.36	2
76	Juana Diaz Casa Alcaldia	599	1585	2.28	6.04	0
77	Aibonito City Center	2031	1312	7.69	5.00	1
78	Caguas Ave Degetau	207	1461	0.80	5.57	2
79	Caguas CDT Atencion	414	2468	1.97	9.40	1
80	Caguas Centro Ambulatorio	418	2083	2.07	7.93	1
81	Humacao Hima San Pablo	549	2406	2.55	9.16	1
82	Humacao Aven Font Martelo	135	855	0.47	3.26	3
83	Ceiba Aven Lauro Pinero	270	2667	0.91	10.16	3
84	Isabela Segunda Avenida El Tamarindo	108	1602	0.36	6.10	5
85	Canovanas Communications	0	809	0.00	3.08	5
86	Baymon Communications	10	317	0.04	1.21	7
87	Puerto Nuevo Communications	0	8	0.00	0.03	5
88	Barceloneta Communications	0	147	0.00	0.56	3
89	Carretera 2 Rd Communications	0	638	0.00	2.43	11
90	Arecibo Hosp Metropolitano	329	1442	1.71	5.49	5
91	Arecibo Hosp Manuel Figueroa	727	2254	3.04	8.59	4
92	Arecibo Aven Miramar	170	4590	0.59	17.48	3
93	Camuy Communications	0	357	0.00	1.36	4
94	Quebradillas Calle Socorro	600	720	2.60	2.74	1

Table 8: Supplemental Demand, Energy Use and Total Communication Equipment for Microgrids (Cont)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Critical Energy Use (GWH/ year)	Non-Critical Energy Use (GWh/year)	Total Comm Towers
95	Quebradillas City Center	697	2467	2.56	9.40	0
96	Isabela City Center	854	1896	3.19	7.22	0
97	Mayaguez Casa Alcaldia	647	1856	2.45	7.07	1
98	Cabo Rojo City Center	502	2150	1.91	8.19	4
99	Bosque Estatal de Maricao Comms	0	191	0.00	0.73	6
100	Yauco City Center	1419	6125	5.74	23.33	1
101	Madrigal Community Center	205	398	0.64	1.51	0
102	Guayama City Center	234	396	0.84	1.51	1
103	Guayama Escuela Francisco	75	1085	0.23	4.13	2
104	Plaza Guayama	1770	6733	7.66	25.64	2
105	Bosque Estatal de Carite Comms	0	109	0.00	0.42	21
106	Yabucoa Catalina Morales	951	7646	3.84	29.12	1
107	Las Piedras Centro Medico	525	4526	1.95	17.24	0
108	San Lorenzo Carr Estatal	684	965	2.92	3.68	1
109	Pueblita del Rio	10	214	0.04	0.81	2
110	El Paraiso	149	457	0.48	1.74	5
111	Cidra City Center	384	2236	1.50	8.52	0
112	Casa Alcaldia de Naguabo	264	800	0.92	3.05	1
113	Cerro Corozal Communications	0	212	0.00	0.81	12
114	Luquillo City Center	844	714	3.17	2.72	1
115	Bosque El Yunque Communications	0	40	0.00	0.15	6
116	Orocovis Calle Juan Rivera Santiago	173	517	0.56	1.97	0
117	Orocovis Casa Alcaldia	402	810	1.49	3.08	0
118	Aguadilla West Parade	427	2350	1.61	8.95	1
119	Moca Hosp San Carlos Borromeo	289	1134	1.56	4.32	0
120	Moca Calle Mon Torres	194	671	0.64	2.56	0
121	Lares City Center	331	1294	1.28	4.93	0
122	San Sebastian	133	1118	0.45	4.26	0
123	Las Marias	188	892	0.72	3.40	2
124	Maricao	234	691	0.84	2.63	1

Table 8: Supplemental Demand, Energy Use and Total Communication Equipment for Microgrids (Cont)

Microgrid #	Microgrid Name	Critical Demand (kW)	Non-Critical Demand (kW)	Critical Energy Use (GWH/ year)	Non-Critical Energy Use (GWh/year)	Total Comm Towers
125	Mayaguez Advanced Cardiology	423	4906	2.23	18.69	5
126	Mayaguez Mall	1380	13842	5.83	52.72	0
127	Anasco	199	1687	0.71	6.43	1
128	Aguada	1030	1006	4.24	3.83	0
129	La Parguera	612	1291	2.28	4.92	0
130	Lajas	242	3513	0.87	13.38	0
131	San German Plaza del Oeste	1249	2309	5.38	8.79	0
132	Penuelas	253	829	0.90	3.16	0
133	Adjuntas	510	511	1.94	1.95	0
134	Utuado South	199	676	0.71	2.57	0
135	Utuado North	204	603	0.67	2.30	1
136	Ponce Calle Victoria	312	821	1.12	3.13	0
137	Juana Diaz Mall	710	2935	3.01	11.18	0
138	Coamo	575	2126	2.13	8.10	0
139	Cayey South	333	2059	1.37	7.84	0
140	Cayey North	507	274	1.88	1.04	0
141	Guayama East	698	2397	2.91	9.13	3
142	Maunabo	158	1132	0.56	4.31	0
143	Juncos	641	1369	2.39	5.22	0
144	Aguas Buenas	169	863	0.63	3.29	1
145	Caguas South	1318	2826	5.77	10.76	0
146	Plaza de Fajardo	176	876	0.64	3.34	1
147	Fajardo Av Valero	129	536	0.49	2.04	1
148	Culebra South	35	511	0.12	1.95	3
149	Culebra North	507	532	1.88	2.03	0
150	Dorado	417	1524	1.69	5.80	0
151	Vega Alta	642	1639	2.76	6.24	1
152	Corozal	167	1906	0.64	7.26	1
153	Morovis	268	881	0.98	3.36	0
154	Ciales	249	285	1.45	1.09	0
155	Florida	510	2436	1.94	9.28	4
156	Manati	364	3987	1.83	15.18	0
157	Arecibo Hosp Cayetano Coll	637	1724	2.93	6.57	0
158	Hatillo City Center	599	2846	2.59	10.84	0
159	Camuy	175	1806	0.56	6.88	0
	Total	**343455**	**398567**	**1524.52**	**1518.01**	**388**

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APPENDIX B: MICROGRID DESIGN CONSIDERATIONS

The microgrid siting analysis based on RenCAT presented here has identified an initial set of microgrids, along with a load estimate of the set of critical and non-critical assets as well as associated cost estimates for these microgrids.

When the burden calculation the potential benefits of different portfolios of these potential microgrid selections, along with the initial load and cost estimates determined, a subset of these microgrids that are considered as feasible potential options to consider will be selected to do further detailed analysis on.

The analysis takes these initial microgrids and further develops them into microgrid conceptual designs which continue to refine the boundaries of each microgrid and evaluate more detailed performance and cost tradeoffs for each microgrid. Below is a brief outline of some important steps to consider for each microgrid conceptual design considered.

Microgrid boundary Characterization

Development of a microgrid conceptual design first involves refinement of the boundaries for the microgrid, first identified as a candidate resilience node with RenCAT which bounds the scope of what sets of critical services and assets are to be included in the microgrid. This involves initially determining how the existing distribution feeders and switches can connect to energize the critical services and assets within the microgrid to provide the initial boundaries for each microgrid. Later steps will evaluate options for additional switching, feeders, generation, etc. to further refine the boundaries and evaluate the tradeoffs for various options.

Design option considerations

Next, development of a conceptual design includes a set of high level considerations which frame what needs to be considered and included in evaluating each option. Some example design considerations:

- The design basis threat (DBT) the microgrid is designed to operate on and the associated minimal time the microgrid will be required to be functional for (such as 72 hours, 7 days, etc.)
- Type of equipment hardening such as for flood, earthquake, landslide, extreme wind conditions or to increase reliability to faults such as converting overhead lines to underground to meet DBT conditions as necessary if applicable to where the microgrid is placed
- How existing backup generation is to be utilized with the microgrid, whether it will be utilized and how it will be upgraded for microgrid use if necessary
- The types of distributed generation, renewables (PV, wind, hydro, biogas, etc.), and energy storage will be considered as part of the microgrid options
- Maximum allowable renewable penetration allowed in a microgrid, if renewables are considered as an option
- If the microgrid will utilize existing infrastructure or further add to the infrastructure to create dedicated microgrid feeder
- If new switches will be considered to further bound the microgrid in addition to the use of existing switches

- If the microgrid will be implemented at low voltage (LV) or medium voltage (MV)
- If a particular control algorithm should be used to ensure electrical transient stability and energy management dispatch.
- If a particular control algorithm should include how to implement load shedding to prioritize critical asset loads over non-critical load in cases when microgrid generation is limited
- If switching algorithms should be automated or may include some manual switching operations
- How backup fuel needs will be addressed for the microgrid such as sizing of both bulk and individual generator storage tanks adequately and how fuel will be provided during emergency conditions
- Regional standards, permitting and regulations that will influence both the feasibility of design, and operational features of the microgrid as well as the time to implement

Electrical Facility Characterization

The conceptual design needs to characterize the existing electrical distribution system connected to and utilized within the microgrid. The electric facility characterization can be split into two categories: analysis of physical equipment, and load data. For the physical equipment, one-line drawings, both low voltage (LV) and medium voltage (MV) are invaluable. One-line drawings show how the existing electrical distribution system is laid out and what equipment is currently in the field (including feeders, buses, transformers, switches, normally-open/normally-closed, conductor size, and shunt compensation) to scope out if the microgrid can be situated within the existing distribution system and the degree in which additional switches and controls will be needed to make the microgrid feasible.

The conceptual design also needs to characterize the load profiles for both the critical and non-critical assets that will function in the microgrid. Load data should include both peak load and individual load profiles, for both the electrical distribution system, as well as for individual critical and non-critical assets.

If possible, load profiles for individual facilities should be at 15-minute or 1-hour intervals for the duration of 1-year to characterize the energy dispatch of the system. A year of data increases confidence that the microgrid designed will be capable of providing expected peak demands for assets within the microgrid. If this is unavailable, then feeder data with 15-minute or 1-hour intervals that can be distributed across a set of facilities according to their estimated use is the next best option. If neither is available, load profiles need to be created based on peak demand measurement information of feeders or individual buildings but the load profiles will be less accurate reflections of the energy dispatch for the system. If this data is not available, either metering needs to be deployed, or estimates will be calculated. The load profiles are used to evaluate the amount of generation required for the microgrid as well as the best way to dispatch them based on the modeling performed.

The gathered information from the electric facility characterization is utilized to build models to analyze performance and cost options for each conceptual design.

Generation Resource Characterization

The conceptual design requires detailed information on both existing and proposed new options for backup generation, and distributed generation to be considered as options including size, location, ratings (voltage and power), fuel used, and fuel storage capacity as it exists in the existing system which will be used in the microgrid. Similar detailed information on any proposed new generation to be included in the microgrid to supplement existing generation needed to meet load demand requirements is included also.

The conceptual design also requires existing as well as proposed new options for renewable energy resources photovoltaic (PV), wind, biomass, etc. (make, size, location, and ratings) as well as battery energy storage that may impact the loads on the system which may be utilized in the microgrid needed to meet load demands or other performance requirements is included also.

The gathered information from the generation resource characterization is utilized to build models to analyze performance and cost options for each conceptual design.

Initial Design Options and Performance Requirements

Once conceptual microgrid boundaries have been determined, design option considerations have been made, the electric facility loads and generation resources have been specified in enough detail, the microgrid conceptual design is able to be assessed. The next step is to perform analysis in which the option space and range of potential costs/benefits based on the design space can be evaluated. The evaluation serves as a screening process to narrow the microgrid design options by elucidating key relationships between critical asset loads, renewable generation, energy storage, fossil generation and other design parameters/decisions as well as costs to evaluate the best most optimal options to consider. The conceptual design evaluation results in the ability to quantify the range of cost/benefit tradeoffs of these various options to evaluate each microgrid conceptual design.

Microgrid design toolkit (MDT) Analysis

The Sandia Microgrid Design Toolkit (MDT) is decision support software tool that illustrates one software tool capable of imputing the microgrid facility models, loads and generator options thus described to create a microgrid conceptual design which multiple performance and cost tradeoff can be evaluated for microgrid options considered for each microgrid conceptual design. Employing powerful algorithms, MDT searches the trade space of alternative system designs in terms of user-selected objectives, such as performance, reliability, and cost. It then produces a Pareto frontier of efficient system solutions—or, the efficient tradeoffs that can be made among multiple user-defined objectives. A range of interactive displays and charts help designers understand the implications of different decisions and tradeoffs on the quality of a system design. The MDT can also function as a means of evaluating baseline system performance and reliability.

MDT Model Inputs

To produce solutions, the MDT requires several inputs detailing the system to include descriptions of the aspects of the system that are variable. A variable aspect is a feature of the design that is in question. That may include the introduction of new technologies, new topology features, changes to existing technologies and features, etc.

Generally, a substantial data collection effort must be undergone before the MDT can provide actionable results. Examples of minimal data that must be collected or estimated include:

- load data
- existing and potential equipment characteristics
- cost information
- details of threats the system must endure
- current and anticipated topology (1-line diagrams for example)

Consider the diagram below of an example MDT model.

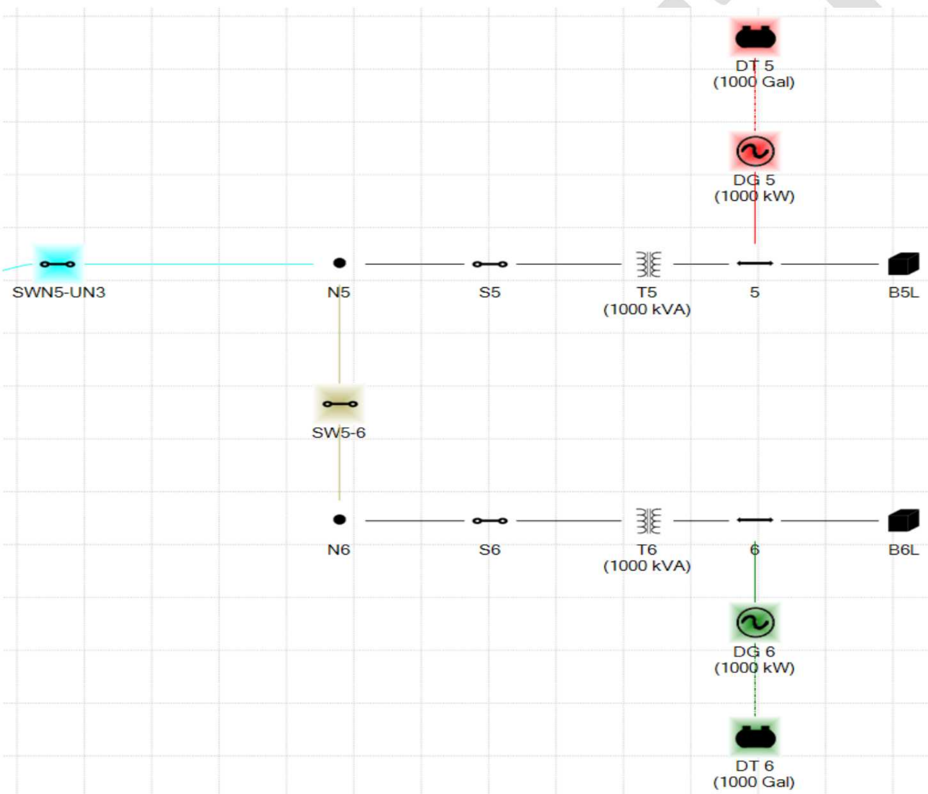

Figure 36. Example MDT One-Line Diagram

There are several pieces of equipment represented in the diagram including switches, generators, transformers, and conductors. In addition to the equipment, there are 2 load sections, B5L and B6L. Each of these elements must be configured in the MDT. For equipment, common information includes purchase cost, operational cost, and failure modes. In addition, each specific asset requires some specific configuration such as capacities, line lengths, performance characteristics, etc. Most of these inputs can be ignored if they are not relevant to the problem at hand.

MDT Model Outputs

The MDT produces a Pareto set of solutions that embodies the efficient trade-offs that can be made among the design decisions. Depending on the problem, there can be many candidate solutions in the set. Views and features provided by the MDT help designers more fully explore the trade space to answer important questions, such as:

- What solution characteristics perform well along a tradeoff dimension?
- What technology decisions have been ruled out as undesirable?
- What is the cost of realizing a 10% performance improvement over that of a baseline solution?

To generate a trade-space, the user must express their design goals in the form of metrics and objectives. The MDT provides many pre-defined metrics to choose from. Examples include energy availability, fuel used, purchase and operational cost, efficiency, etc. When performing an optimization, a user can select any or all the available metrics to include as optimization objectives. The output of the performance and cost trade space developed by MDT can be further refined and evaluated to determine which microgrid conceptual design options are most feasible for further development.

Electrical Modeling Results

The same electrical infrastructure information use to create a conceptual design can be used to create simple electrical network models using standard analysis software tools like MATLAB/Simulink to that ensure that all sources operate within their power limits and that other equipment (like transmissions lines and transformers) are not overloaded are essential requirements of a microgrid. A load flow study, also referred to as a power flow study, is a common tool used for AC analysis of a power system in steady state and to ensure that all requirements discussed above are met during the planning stages of a power system. Similar analysis is used for heat generation, flow, and consumption. Electrical modeling results complement and further elucidate the feasibility of conceptual design options analyzed with software tools such as MDT.

Additional Analysis and Results

The conceptual design analysis will also include the initial analysis of existing communication and control systems, protection schemes, and cyber security used in the existing electrical system in which the microgrid will be implemented within. These results can include requirements and recommendations for communications, controls, protection and cyber security to specify for the conceptual design options to be considered.

Functional Requirements for Conceptual designs

After analyzing various conceptual design options, a recommended optimal preliminary design is agreed upon by stakeholders based on performance and cost parameters evaluated and selected for further specification for the conceptual design considered. The requirements document the key microgrid design decisions based on selection of the most suitable option chosen for the preliminary microgrid design. The microgrid owner/operator who will ultimately operate as well as maintain the fully functional microgrid as well as other identified key stakeholders are critical contributors to ensuring the microgrid is implemented and meets functional requirements as specified for the microgrid preliminary design.

Once all the functional requirements for a specific conceptual design have been developed, the next step is the development of a request for information (RFI) or request for quote (RFQ) which captures the information developed by a conceptual design and puts it in a form in which an entity has enough specificity about the microgrid to bid on the project and produce detailed designs and construction implementation plans for each conceptual design.

APPENDIX C: ECONOMIC EVALUATION METHODOLOGY

Introduction

We investigate placement of microgrids as an option in hurricane disruption preparation and as an option for normal operations. The former would alleviate the hardship caused by the disruption, and the latter may improve business operations if normal power provision is unreliable and increase households access to reliable power.

To optimize such investments, three pieces of information are necessary: 1) a description of disruption scenarios; 2) system behavior under different disruption scenarios and normal conditions and effects or microgrids on the system behavior; and 3) preferences of decision makers, affected population, and other stakeholders. The disruption scenarios (1) are necessary to bound the problem and allow probabilistic treatment of uncertainties involved. The system behavior and the microgrids effects (2) are necessary to quantify what would actually happen as a result of microgrids placement. For example, the economic benefits of microgrids would be different in the scenario where everyone is evacuated and the economic activity ceases with the scenario where people stay in place and the economic activity continues if the electric power is available. The preferences of various stakeholders (3) are necessary because there is not necessarily a single "best" microgrids placement solution. Instead we recognize that microgrids placement to achieve the most reliable industrial power may be different from microgrids placement to achieve the most reliable utilities services provisions during the hurricane. Both can be different from microgrids placement to ensure reliable power during normal non-disruption conditions. Various tradeoffs involved in comparisons of different alternatives cannot be evaluated purely in a research model. Instead, we see the purpose of this modeling effort to inform the decision makers of different alternatives and tradeoffs involved to allow actual investments to be done on the basis of locality-specific evaluation of alternatives and tradeoffs. This paper describes a framework for evaluating tradeoffs associated with different alternatives and provides preliminary examples using limited subset of available Puerto Rico data. At this point, the results presented here should be treated as example analyses. We expect that the next iteration of this report will provide a thorough quantitative investigation of different investment options and scenarios.

We specifically investigate the following example scenarios:

- A hypothetical hurricane disruption scenario centered around San Juan. For this scenario, we investigate the placement of a single microgrid in one of the affected municipalities and show that different locations provide substantially different avoided economic losses.
- A hypothetical normal operations scenario partially informed by the available data on SAIDI/SAIFI metrics for different municipalities in Puerto Rico

These two example analyses demonstrate that a substantial variability associated with different microgrids placements schemas within and across different scenarios even when the evaluation metric is the avoided costs and the metric is calculated in the same way across different scenarios. It calls out the need for the stakeholders to evaluate different alternatives and potentially negotiate compromise solutions. This would become even more necessary if the evaluation metrics would include non-economic metrics such as measures of access to basic utility and economic services, clean water, food provisions, etc.

The rest of this report outlines the economic impacts calculation methodology based at the RDEIM model created at Sandia, outlines evaluation of different resilience-enhancing options within an optimization framework, and presents two example case studies.

Methodology

This section is based, in certain parts verbatim, on Outkin and Bixler (2017)[†]. The model outlined here is a modification of a model for estimating the economic impacts of disruptions, called RDEIM (Regional Disruption Economic Impacts Model) created by Sandia National Laboratories for the NRC (Nuclear Regulatory Commission). This model has been adapted to represent the disruptions by such events as hurricanes and to estimate the resilience benefits of different distributed grid investments.

RDEIM calculates the indirect losses using "net total requirements" (NTR) multipliers based on the Regional I-O Modeling System (RIMS II) data. It uses employment by county, value added[‡] and gross output by industry, total requirements tables, final demand value added multipliers (RIMS II model) provided by the U.S. Bureau of Economic Analysis (BEA), as well as other data provided by the Bureau of Labor Statistics and other sources.
The total economic impact (loss) caused by a disruption is typically grouped into three categories (BEA, 2012):

- Direct[§] GDP impacts occur due to a loss of final demand, which occurs in the context of an accident because they are located in the affected area and their production is curtailed which represents a loss of the value added created by the affected firms.
- Indirect GDP impacts occur because the loss of final demand will also affect the supplier firms as their input to the curtailed production is no longer required. In the context of an accident, supplier firms are outside the affected area. GDP impacts represent value added losses to indirectly affected firms.
- Induced GDP impact relates to the spending of workers whose earnings are affected by the disruption.[**]

The GDP loss calculated by RDEIM estimates the losses accrued over time at the local scale of the impacted area and at the national scale. It also allows the recovery schedules for local and national scales to be varied independently of each other with the proviso that local recovery is never faster than national recovery.

[†] Outkin, Alexander V. and Nathan E. Bixler (2017), Economic Model For Estimation Of GDP And Tangible-Asset Losses In The MACCS Offsite Consequence Analysis Code. NRC Draft Letter Report. NRC-HQ-60-15-T-0006.
[‡] Value added is defined as the sum of labor compensation, capital income, and net indirect taxes (producer taxes, import tariffs minus subsidies).
[§] The notion of direct (and by extension indirect and induced) impacts in this application does not map directly to the existing literature, due to the nature of disruption, where all industries are shut down for a particular area. Therefore, the impacts in the directly affected area that would've been indirect if only one industry were shut down, are treated as direct given that all industries are shut down. This is the reason for using the net value added multipliers. The estimation of the value added multipliers is described in section 2.4.1 of this report.
[**] For example, employers may lay off workers to reduce their realized losses that in turn entrenches an induced loss from the reduced spending of their employees. The range of possible losses is estimated using Type I and Type II multipliers to calculate the direct, indirect, and induced components and thereby establish bounds for the likely total loss.

The scenario definition includes the analysis area represented by affected regions, response characteristics of the public, economic enterprises, and utilities, restoration schedules and certain other parameters.

The GDP losses and benefits of resilience enhancing investments are estimated as the difference between a baseline scenario and a disruption scenario. For direct GDP, the loss is simply the GDP that would have been produced in the area if it were open for business, as assumed in the baseline scenario. The direct GDP loss is represented by assuming the affected area is shut down either partially or completely for a specified period of time in the disruption scenario, and the GDP from the affected area is lost.

RDEIM calculates both the rational and national effects. While local recovery to pre-disruption level may never occur, it is assumed that after some period of time the national economy is able to recover to its baseline trajectory, as illustrated in the Figure 37. The duration of local recovery is estimated based on the disruption severity and expected recovery efforts.

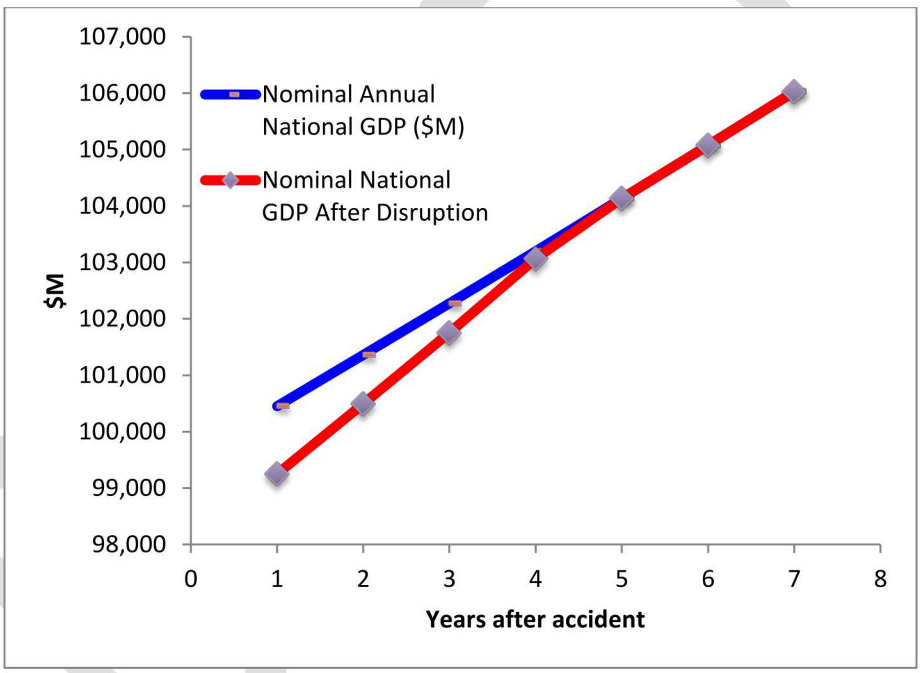

Figure 37. Nominal GDP recovery at the national scale assuming the GDP growth rate is higher than the social discount rate. Here the national GDP recovers to its pre-accident trajectory at the beginning of the 5th year after the accident.

Impacts Estimation Model

RDEIM uses lost GDP to represent the macroeconomic impacts of a disruption, where GDP is defined as the value of all final goods and services produced over a given time period. The avoided GDP loss as a result of resilience-enhancing investments is treated as benefit due to those investments and can be compared with the costs of such investments, thus producing a Pareto efficient frontier based on which the decision makers can make the investment decisions.

Uncertainty and scenario variability is an important part of such cost-benefit analysis. The original RDEIM model conducts a number of weather trials are generated to represent possible disruption parameters and to take into account the wind, precipitation, and other weather-related uncertainties. Impacts are then estimated for each weather trial for the corresponding affected area and then the overall impacts are calculated statistically for the set of weather trials. In particular, mean, median, 90th percentile, and other statistical values are calculated for the economic losses[††].

The following describes the impact estimation for a single scenario realization. The impacts are calculated on the level of individual affected counties or portions of those counties[‡‡]. Collections of complete and partial counties correspond to disrupted areas. In the context of the code framework, an impacted region corresponds to one or more grid elements. A grid element is a portion of the overall problem domain and could represent anything from a small fraction of a single county to a large collection of counties and partial counties. The response and recovery are defined at the level of the grid elements.

The affected area is represented as a set of grid elements $R = \{1, 2, ..., n\}$ and the set of all the industries as $I = \{1, 2, ..., k\}$. It is assumed that all industries in a grid element $r \in R$ are completely or partially shut down for a period of time at the level of $0 \leq s_r(t) \leq 1,\ 0 \leq t \leq T$, where the disruption level s_r takes values between 0 and 1, and the time is measured in years, where T is the maximum duration of local disruption, as determined by the "Maximum Duration of Local Economic Impact" parameter. The period of time t_r that the grid element is disrupted may differ across grid elements, depending on the level of damage and the time it takes to restore different grid elements to use. The disruption function s_r may also differ across different industries and maybe a function of the state and disruption level of a number of infrastructures, such as electric power, water, telecommunications, and other[§§]. It also depends on the labor and productive assets available.

The following notation is used in the subsequent discussion and equations:

[††] The same kind of analysis can be done based on different hurricane scenario and parameters, and can take into account the probabilistic uncertainty about recovery, preparation, response, and other parameters affecting the disruption losses.

[‡‡] Incomplete counties arise because disruption areas do not need to correspond to the county boundaries exactly. The relative importance of partial counties diminishes with the size of the accident and of the affected area.

[§§] Such dependency on multiple infrastructures, can be incorporated by using the Cobb-Douglas production function, as for example in Dauelsberg, Lori R. and Alexander V. Outkin (2005). Modeling economic impacts to critical infrastructures in a system dynamics framework, in Proceedings of the 23rd International Conference of the System Dynamics. Boston, Massachusetts.

i, j – industry indices

V_i – annual value added for industry i

ΔV_i - the direct value added change in industry i

$\Delta V_{i,r}$ - the direct value added change in industry i in the grid element *r*.

ΔV^D, ΔV^T, ΔV^{D+I}, ΔV^P – GDP (value added) losses, with indices *D*, *T, D+I, and P* denoting the total, direct, direct plus indirect, and induced losses respectively.

v_i – average value added per worker for industry *i*.

Y_i – annual national gross output for industry i.

E_i – national employment for industry i

g – expected real *GDP* growth rate.

ρ – social discount rate.

t – Gregorian calendar time, expressed as a real number, in units of year, so one-day time increment equals to 1/365.

t_0 – database year (starting time of base year). This is the year for which the data, such as on value added, gross output, and employment were collected or to which all those values were adjusted to.

t_I – accident year (starting time of accident year).

$m_i^{I,II}$ – the net total requirements multipliers of Type I or Type II[***].

$\tilde{m}_i^{I,II}$ – the final demand value added multipliers of Type I or Type II[†††] provided by the BEA.

$s_r(t)$ – disruption function representing the state of grid element *r*. This dimensionless parameter allows a faster recovery schedule for certain grid elements than the maximum duration of impacts parameter. It equals 1 when the grid element is completely disrupted and 0 when the grid element has been restored[‡‡‡].

$l_{i,r}$ – number of industry *i* affected employees in grid element *r*.

T_R – maximum duration of economic loss calculation for directly affected area.

T_N – maximum duration of economic loss calculation for indirectly affected area.

A disruption affects a local region composed of one or more full or partial county, resulting in a direct economic impact[§§§]. The average GDP per worker in industry i at time t_0 is estimated as follows:

[***] Superscript *I* indicates a Type I multiplier and superscript *II* indicates a Type II multiplier.
[†††] Superscript *I* indicates a Type I multiplier and superscript *II* indicates a Type II multiplier.
[‡‡‡] The formulation allows intermediate values as well; however, this option is not implemented in MACCS for disruptions due to radioactive releases.
[§§§] What represents direct and indirect losses in this model is defined differently from the normal uses of those terms. Specifically, given that an entire area is shut down for a period of time, all the losses in the area are deemed direct. In the input-output terminology, the losses due to inter-industry linkages inside of the affected area could also be considered to be indirect. However, calculating both direct and indirect losses inside of the affected area would introduce double counting. The section 2.4.2 of this report explains how such double counting was eliminated.

$$v_i = \frac{Y_i}{E_i} \tag{0}$$

where, Y_i and E_i are national annual gross output and employment for industry.

The number of affected employees for a particular county is obtained from the US Census Bureau. For grid elements that represent a fraction of a county, the number of the affected employees is estimated by multiplying the number of employees in the county by the value determined as a fraction of the land or population affected.

t_I is different starting year (accident year) than the base year. In this case it is necessary to adapt the GDP available for a year t_0 (base year) to GDP consistent with a particular accident year, t_I. This is accomplished by using an input GDP growth rate and calculating the accident year GDP as a function of the base year GDP assuming a constant growth rate. The concept of a social discount rate is also applied to discount[****]. The losses are adjusted for projected GDP growth in real terms between the last year of available data (the base year) and the accident year. This growth is reflected by the exponential term in Equation (2)[††††]. This allows for GDP calculations to be performed for the real GDP in years following the accident year. From Equation (2), it is clear that dollars are reported in base year dollars but account for real GDP growth between the base year and the accident year. For years beyond the accident year, the reported values account for additional GDP growth but are discounted back to the accident year. Employing a GDP growth rate in Equation (2) does not account for any structural changes in the economy, i.e., it assumes all sectors of the economy grow at the same rate.

Direct Economic Impact Estimates

Once the disruption scenario is specified, the calculation of direct losses is independent[‡‡‡‡] across different grid elements.

For clarity, we start with a single grid element calculation. The rate of direct value added losses for industry i at grid element r at time t_I can be found by multiplying the per-employee value added by the number of employees and projecting the GDP to the year of the accident:

$$v^D{}_{i,r} = e^{g(t_I - t_0)} v_i l_{i,r} \ , \tag{1}$$

[****] The social discounting rate is kept for consistency with the original RDEIM. It is unlikely to affect the immediate disruption losses significantly, however, it may affect the cost-benefit analysis over longer time scales.

[††††] The, GDP losses generally need to be calculated for variable time periods. However, the data and input parameters used by RDEIM to calculate GDP losses are available only for a specific year, which is defined as the "base year." To address this, GDP is treated as a continuous variable to simplify the treatment of time periods of arbitrary duration and arbitrary accident start times. This produces results that are slightly different than an approach where GDP is treated as a discrete annualized variable. However, where GDP growth rates, social discount rates, and their differences are small, this difference is also small.

[‡‡‡‡] Aside from implicit dependencies in 1) the multipliers, given that those generally depend on the size of the entire affected area; and 2) recovery speeds that likely are correlated with neighboring regions.

where $v_i l_{i,r}$ denotes the value added loss for industry i at grid element r. To calculate the cumulative scenario losses for industry i at grid element r starting from time t_I until time T §§§§, the above expression is integrated over time, taking into account the economy real GDP growth rate g, the social discount rate ρ, and that a specific grid element may be decontaminated sooner than T.

$$\Delta V^D_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} \int_{t_I}^{t_I+T} s_r(t) e^{(g-\rho)(t-t_I)} dt ,$$

where the disruption function $s_r(t)$ reflects the decontamination schedule and is more precisely defined in the Equation (3). By defining t as time relative to the start of the incident, the above can be further simplified as follows:

$$\Delta V^D_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} \int_0^T s_r(t) e^{(g-\rho)t} dt , \tag{2}$$

where the disruption function $s_r(t)$, takes the following form:

$$s_r = \begin{cases} 1, & t \le \mathrm{T}_r \\ 0, & t > \mathrm{T}_r \end{cases} , \tag{3}$$

where T_r is the recovery time for grid element r.

In the special case of $g = \rho$ the part of Equation (2) under the integral is the number of years the grid element r is disrupted. In general, it can be interpreted as an exponentially discounted number of years a grid element has been disrupted. It is therefore clear that the Equation (2) can be interpreted as the multiplication of the annual value added per grid element and industry by the effective number of years that industry was disrupted.

By introducing $S_r(t) = \int_0^T s_r(t) e^{(g-\rho)t} dt$, Equation (2) can be re-written as follows:

$$\Delta V^D_{i,r}(T) = e^{g(t_I - t_0)} v_i l_{i,r} S_r(T) \tag{4}$$

The direct losses for the entire affected area and for all industries are found by summing over all industries and grid elements:

$$\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} S_r(T) \tag{5}$$

The above equations involving integrals could be expressed as sums over years and the results would be the same provided that all losses are for complete years. The integral equations allow

§§§§ Time T is treated as an independent variable here that can vary between 0 and T_R. This allows representation of losses as they occur over time.

for partial years and so they provide more generality. The implementation of this economic model in MACCS uses the integral formulation expressed in the preceding equations and allows for partial years of GDP losses.

Total, Indirect, and Induced Losses

The total, indirect, and induced losses are calculated using the net total requirements multipliers. The net total requirements multipliers can be of Type I or Type II, representing either indirect or indirect plus induced losses, analogously to the BEA Type I and Type II multipliers. The net total requirements multipliers are calculated on the basis of national and regional (as in the directly affected region) multipliers. The primary differences from the value added multipliers are two-fold: 1) they attempt to eliminate the double-counting of losses[*****], and 2) adjust for the fact that direct losses are calculated as value added, not final demand losses.
The total impact includes direct, indirect, and induced losses, and can be calculated with the following equation:

$$\Delta V^T(T) = e^{g(t_l - t_0)} \sum_I v_i m^{II}{}_i \sum_R l_{i,r} \int_0^T s_r(t) s_N(t) e^{(g-\rho)t} dt \,, \tag{6}$$

where the time-dependent parameter $s_N(t)$ reflects the national recovery progress, which is expressed as follows:

$$s_N = \begin{cases} 1 - \dfrac{t}{T_N}, & t \le \mathrm{T}_N \\ 0, & t > T_N \end{cases} \tag{7}$$

By substituting Type I multipliers for Type II multipliers in equation (6), induced effects are excluded and the expression yields the combined direct plus indirect losses. The cumulative indirect losses can then be calculated by subtracting the direct losses, which are given by Equation (5). Thus the cumulative indirect losses are represented by the following equation:

$$\Delta V^I(T) = e^{g(t_l - t_0)} \sum_I v_i \sum_R l_{i,r} \int_0^T s_r(t)(s_N(t) m^I{}_i - 1) e^{(g-\rho)t} dt \,, \tag{8}$$

where $m^I{}_i$ are Type I multipliers.

The cumulative induced impacts $\Delta V^P(T)$ up to time T are evaluated by taking the difference, $\Delta V^T(T) - \Delta V^D(T) - \Delta V^I(T)$.

Time-dependent factors in Equations (6) and (8) allow different speeds for local and national recovery. The speed of the local recovery is represented to a degree by the parameter T and the speed of the national recovery is reflected in the functional dependency of $s_N(t)$ with respect to time. Zeroing national losses after a period of time T_N that is shorter than T allows national

[*****] This double counting arises because in a scenario when all industries in an area are shut down, some of the indirect impacts would also be direct, given that local industries use each other's production in part.

recovery to be faster than local recovery and alleviates the over-estimation associated with the static nature of I-O models.

Puerto Rico Model Initialization and Data

Some of the Puerto Rico specific data is not available in the data used for the 48 Contiguous United States RDEIM model. Instead, the data had to be obtained from other sources. The process of creating a Puerto Rico specific model is described in this section.

REDEIM is flexible in regards to the specific industries included and the industries aggregation level. Given that data sets provided by the BLS, BEA, and other organizations often have (slightly) different aggregation levels, it is necessary to aggregate these different data sets to a common industry denominator. The list of industries in RDEIM and the corresponding NAICS and BEA industries are show in the table below.

RDEIM_INDUSTRY_ID	INDUSTRY_NAME	NAICS	BEA
3	Agriculture forestry fishing and hunting	111 112 113 114 115	1 2
6	Mining	21	3 4 5
10	Utilities	22	6
11	Construction	23	7
12	Manufacturing	31-33	8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
34	Wholesale trade	42	27
35	Retail trade	44-45	28
36	Transportation and warehousing	48-49	29 30 31 32 33 34 35 36
45	Information	51	37 38 39 40 41
51	Finance and insurance	52	42 43 44 45
56	Real estate and rental leasing	53	46 47
60	Professional scientific and technical services	54	48
64	Management of companies and enterprises	55	49
65	Administrative and waste management services	56	50 51
69	Educational services	61	52
70	Health care and social assistance	62	53 54 55 56
75	Arts entertainment and recreation	71	57 58
78	Accommodation and food services	72	59. 60
81	Other services except government	81	61
83	Federal Civilian		
85	State and Local Government		

The data available for Puerto Rico at the County level provides less resolution on the industry level in particular in regards to the value added data than the data provided by the BEA for the 48 Contiguous States. Therefore, the set of industries from the industry map table has been reduced to a smaller subset of aggregated industries in the table below. This table does not necessarily imply that certain industries, such as utilities, are not present at the island. Instead, it generally means that those industries may have been reported as another industry. For example, utilities are reported as Transportation.

RDEIM_INDUSTRY_ID	INDUSTRY_NAME	VA	Empl	VA_Emp
	Total	101,564.80	1,025	99.1
3	Agriculture forestry fishing and hunting	816.4	17	48
6	Mining			
10	Utilities			
11	Construction	1,369.50	50	27.4
12	Manufacturing	46,971.40	94	499.7
34	Wholesale trade	2,819.10	22	128.1
35	Retail trade	4,808.50	207	23.2
36	Transportation and warehousing	946.5	28	33.8
45	Information	4,539.00	12	378.3
51	Finance and insurance	20,559.40	34	604.7
56	Real estate and rental leasing			
60	Professional scientific and technical services	9,880.30	339	29.1
64	Management of companies and enterprises			
65	Administrative and waste management services			
69	Educational services			
70	Health care and social assistance			
75	Arts entertainment and recreation			
78	Accommodation and food services			
81	Other services except government			
83	Federal Civilian	8,277.70	223	37.1
85	State and Local Government			

Investment Evaluation

We analyze a set of resilience enhancing options $(R_i, C_i)\ i \in \{1, K\}$, where R_i and C_i represent the specific investment configuration (such as a microgrid of a specific capacity and specific location in San Juan) and calculate the scenario losses and avoided losses associated with these investments. This gives us a vector of variables $[\Delta V_i^T(t), \Delta V_i^D(t), \Delta V_i^I(t), \Delta V_i^P(t)]$ and their distributions, if probabilistic analysis has been employed, for each investment option $(R_i, C_i)\ i \in \{1, K\}$. This information allows creating an approximation of a Pareto efficient frontier available to the decision makers and analyzing multi-objective tradeoffs between investment costs, disruption levels, recovery speeds, local vs. national losses, employment, and other variables. The goal of this analysis is to provide the decision makers with these options and facilitate their (options) analysis.

For this study, we've focused on a small set of Puerto Rico Municipalities shown in Table 9.

Table 9. Affected counties.

GEO.id	GEO.id2	Name
0500000US72127	72127	San Juan Municipio, Puerto Rico
0500000US72021	72021	Bayamón Municipio, Puerto Rico
0500000US72061	72061	Guaynabo Municipio, Puerto Rico
0500000US72033	72033	Cataño Municipio, Puerto Rico
0500000US72029	72029	Canóvanas Municipio, Puerto Rico
0500000US72135	72135	Toa Alta Municipio, Puerto Rico
0500000US72137	72137	Toa Baja Municipio, Puerto Rico
0500000US72031	72031	Carolina Municipio, Puerto Rico
0500000US72139	72139	Trujillo Alto Municipio, Puerto Rico

We assumed the economic activity in these counties will be initially disrupted at 100% and will recover according to a restoration schedule by day 15. This restoration schedule is the same for all counties involved and is represented in the Table 10.

Table 10. Recovery over time. 0 - all activity disrupted, 1 - full recovery.

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
% Recovered	0	0	0	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.0

This example only serves to illustrate the approach to resilience quantification using notional data and intentionally does not yet constitute a practical study.
We consider the following scenario:

- Disruption duration: 14 days.
- Employees affected: based on the employment in affected municipalities.
- Value Added per Employee: based on specific industries.

The top-level economic losses over time when no microgrids are installed are represented in the Figure 38.

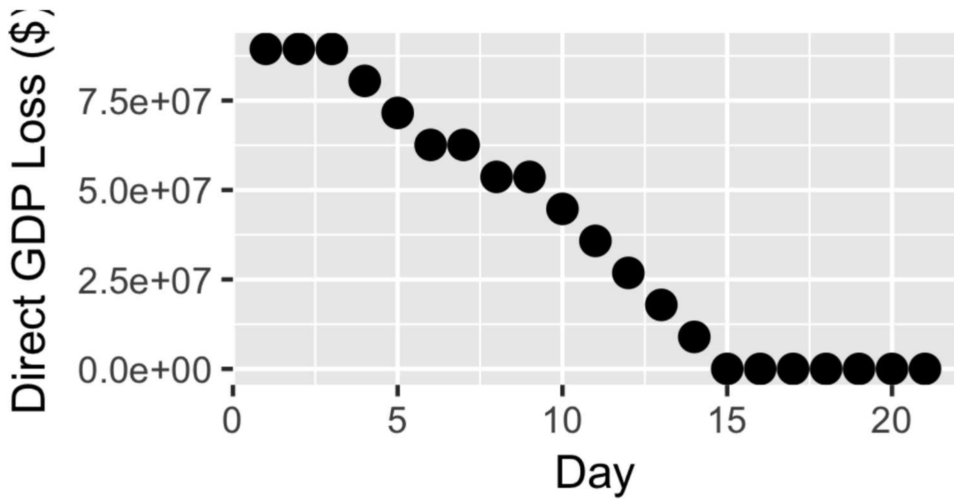

Figure 38. Direct scenario loss by day.

We have also investigated placement of a single microgrid into one of the affected municipalities. This microgrid is assumed to provide a sufficient amount of power to provide power to ensure the ability to conduct normal operations for 7000 employees, thus avoiding the corresponding losses. Depending on the specific municipality where the microgrid is placed, the avoided losses vary substantially, as represented in the Figure 39.

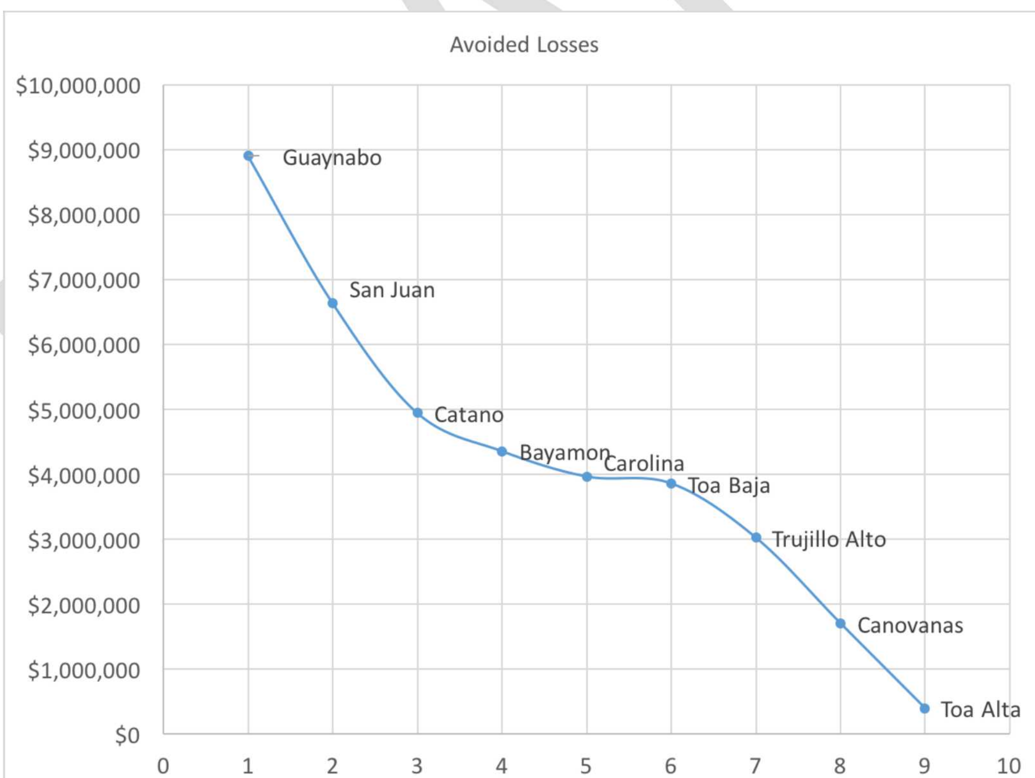

Figure 39. Ranking of avoided loss by municipality where microgrid is located.

Conclusions and Next Steps

This report described a methodology and a software framework for evaluating the economic impacts of different disruption and normal operation scenarios. It allows quantifying possible investments on the basis of avoided GDP losses. At present, the results are notional. However, even in this form they are suggestive that the framework provided a quantitative basis for differentiating across different scenarios.

Our primary objective for the next stage of this project is to create a fully calibrated model of a disruption and normal operations scenarios to recommend actual microgrid locations.
These steps specifically include:

- Associate a microgrid with an industry in a specific area, rather than with municipality-level data as at present.
- Define a set of resilience investments (R_i, C_i) $i \in \{1, K\}$ as described above
- Conduct analysis for all possible resilience investments (R_i, C_i) $i \in \{1, K\}$ as described above
- Evaluate the tradeoffs associated with different resilience options
- Estimate the Pareto efficient frontier of possible investments

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