INL/CON-24-77648-Revision-0

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June 2025

Changing the World's Energy Future

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517, DE-AC07-05ID14517

Hierarchical Resilience Planning for Networked Microgrids: A Case Study of Puerto Rico

Jitendra Thapa[1], Bikash Poudel[2], Michael Stadler[3], Muhammad Mansoor[3], Timothy R. McJunkin[2], C. P. Smith[4], Mohammed Benidris[1]
[1]Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, 48824
[2]Power and Energy Systems, Idaho National Laboratory, Idaho Falls, Idaho, U.S.A.
[3]Xendee Corporation, 7855 Fay Avenue, Suite 100, La Jolla, CA 92037, USA
[4]Cooperativa Hidroeléctrica de la Montaña, Puerto Rico
Email: thapajit@msu.edu, bikash.poudel@inl.gov, mstadler@xendee.com, mmansoor@xendee.com, timothy.mcjunkin@inl.gov, cpsmith@cooperativahidroelectrica.coop, and benidris@msu.edu

***Abstract*—Microgrids can be designed to enhance the energy resilience of communities and critical infrastructures, such as hospitals, data centers, and communication networks, which are vulnerable to frequent weather-related disruption. Coordinating multiple microgrids in a network can leverage the geographical diversity of load and generation resources while enabling resilient and cost-effective planning of the distribution system. Designing a networked microgrid is complex, involving intricate technical assessment, cost-benefit analysis, site-specific requirements, and the evaluation of existing resources. Therefore, this paper proposes a hierarchical resilience planning framework and performs an extensive techno-economic analysis for the design of a networked microgrid. Hierarchical resilience planning involves technology sizing at an individual community level to meet the critical load and satisfy resilience criteria, and resource optimization at networked microgrid level to provide a higher level of resilience and energy adequacy. A real-world case of Puerto Rico's cooperative microgrid "Microrred de la Montaña" is investigated considering localized electricity tariffs, site-specific demand profiles, solar generation, and existing hydro resources. Multiple optimization scenarios are developed based on the resiliency requirement to estimate the capacity of solar photovoltaic and battery energy storage (BES) to be installed at each substation. The results provide the optimal sizing for individual community and networked microgrid to withstand 1-day and 3-day outages along with the criteria for critical load.**

***Keywords*—Battery energy storage, microgrid, hierarchical resilience planning, optimization, resilience, solar, techno-economic analysis**

I. Introduction

The increment and severity of weather disasters can have significant impacts on power grids causing long-duration outages and economic losses [1], [2]. It was reported an economic loss of 92.9 billion in the United States due to weather disaster in the year of 2023 [3]. Puerto Rico is one of the highly impacted areas due to the occurrence of frequent disasters with severity levels ranging from category-1 to category-5, causing territory-wide outages, health emergencies, and economic losses impacting millions of customers [4]. These massive destruction and power outages have led Puerto Rico Electric Power Authority (PREPA) to plan actions for enhancing the resilience of their system by building a self-sustaining microgrid in the event of a disaster, incorporating distributed generation and renewable energy resources [5]. This calls for techno-economic analysis and resource planning for a resilient microgrid taking into consideration site-specifics such as local geography, climate, and existing infrastructure.

Several strategies have been proposed to enhance the resilience of power grid against high-impact low probability weather disasters, which includes formulation of microgrids, application of distributed and renewable energy resources, infrastructure hardening and many more. The selection of resilience enhancement strategies is primarily based on the scenario of local environments and the past events that occurred [6]–[8]. Among the aforementioned strategies, microgrids play a major role in enhancing the resilience of the power grid as it offers decentralized energy generation, support local and critical loads, and can run in islanded conditions during grid disturbances or emergencies such as natural disasters. In [9], the application of different types of microgrid including networked and dynamic microgrid for outage management and defensive islanding are explored. Moreover, the concept of community microgrid, primarily dedicated to community consumers or connected neighborhoods, is growing as a viable solution to enhance the resilience at the community level as well as the entire power system as a whole [10]. Microgrids can supply local critical loads and utilize the excess capacity from their resources to supply critical loads even outside the microgrid during the event of grid disconnection [11]. Microgrids can also be utilized as black start resources to start the plants that are disrupted during natural disasters [12]. Furthermore, a plethora of studies [13]–[15] have been conducted to enhance the resilience of distribution systems exploring the application of microgrid.

Motivated by the potential of microgrids in resilience enhancement, this paper proposes a hierarchical resilience planning strategy and techno-economic analysis for building com-

This work is supported by the National Science Foundation (NSF) under Award No. ECCE-1847578, and funding from the Energy Transitions Initiative Partnership Program (ETIPP) of Department of Energy (DOE) Office of Energy Efficiency & Renewable Energy (EERE) under Contract No. DE-AC07-05ID14517.

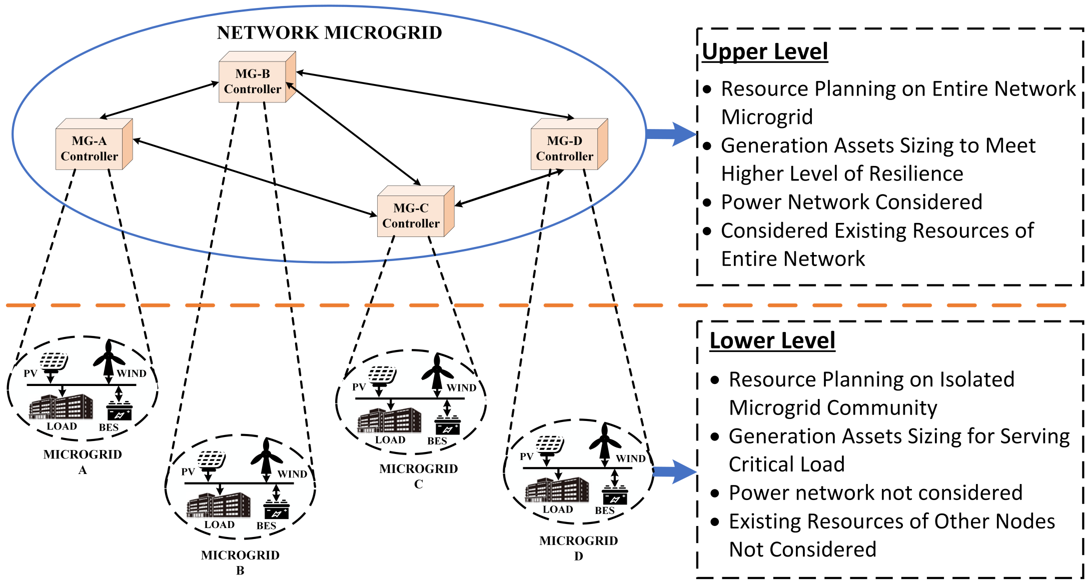

Fig. 1. Proposed Hierarchical Resilience Planning Framework

munity microgrids and as a whole a networked microgrid. The initial planning stage involves the estimation of resources considering multiple scenarios of outage duration in a networked microgrid and finding out whether the estimated capacity at the community level is technically feasible or not considering the site-specifics such as power budget, financial resources, and environmental conditions. After the initial planning stage, a proposed hierarchical resilience planning strategy involves resilience planning at the level of community microgrids to meet the specific critical load requirement considering the site-specific factors such as power budged, available space for solar installation, and so on. The final level of resilience planning estimates the extra amount of generation required to achieve higher level of resilience at the level of networked microgrid. These resource planning at different levels is based on the optimization conducted in a techno-economic analysis software Xendee [16] and a comparative study among several scenarios.

The remainder of the paper is organized as follows. Section II presents the methodology with the description of the proposed resilience planning framework, data collection process, and the formulation of an optimization problem. Section III provides a case study and results for multiple scenarios based on optimization. Finally, section IV summarizes the paper and provides concluding remarks.

II. Methodology

A. Proposed Resilience Planning Framework

In this paper, a hierarchical resilience planning framework is proposed for building a resilient community microgrid and as a whole a networked microgrid. Fig. 1 illustrates the proposed resilience planning framework. The resilience planning framework minimizes the overall total annual system costs (including annualized capital costs and electricity sales) along with the technology sizing for serving critical loads and satisfying resilience criteria.

In the lower level, an optimization is performed to determine the optimal sizing of generation assets in an individual community microgrid. The optimization is formulated in such a way that the estimated sizing of generation asset will serve the critical load all the time and even during the grid outage for 1-day. The site-specific yearly load profile, tariff structure, parameters associated with solar generation such as solar insolation and tilt angle are considered. One of the main constraints associated with the resilience planning at the individual community level is the consideration of power budget which refers to the maximum amount of solar that can be installed at a particular place considering the available open areas and rooftops. The significance of individual community resilience planning is to ensure and enhance resilience at the level of a community before conducting resilience planning for the entire networked microgrid.

In the upper level, the entire networked microgrid is considered for optimization. The resilience planning framework in this stage involves the determination of extra generation required to meet the higher level of resilience and serve the larger percentage of critical load. In contrast to the lower-level planning, resilience planning in this stage considers other existing resources within the network including all the generation assets determined in the lower level. The optimization reduces the total annual cost of the entire networked microgrid in addition to the estimation of technology size for higher level of resilience.

B. Data Collection

The data for the community microgrid application and hydro component were conveniently provided by the Cooperative Hidroelectrica de la Montaña. The PV performance data are

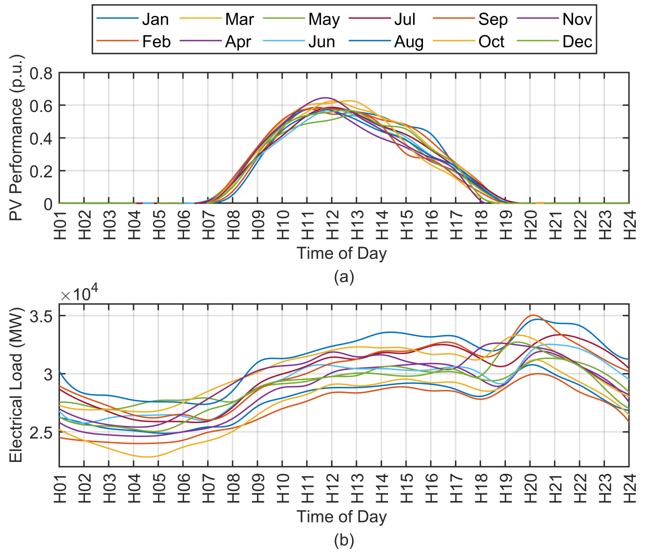

Fig. 2. Time Series Profile of (a) Solar Performance and (b) Peak Aggregated Load

modeled using NREL's PVWatts Calculator and retrieved through the Xendee API. The features of solar such as array and PV type, panel efficiency, inverter efficiency, tilt and azimuth, DC to AC ratio along with the solar insolation data typical for the Puerto Rico location has been utilized to compute the solar PV performance data. Fig 2(a) illustrates the PV performance time series profile.

Furthermore, the electrical demand for each community was obtained from LUMA Energy for fiscal year 2021 and these data represent the aggregated demand of each community. The aggregated annual energy and annual peak demand of all the communities are approximately 232 GWh and 35 MW respectively. The provided data are processed and analyzed to develop full-year time-series load profiles in hourly granularity suitable for Xendee load input. Fig 2(b) illustrates the hourly peak of an aggregated load of all six communities.

The Caonillas-Dos Bocas hydroelectric generation plant Dos Bocas and Caonillas-1 is taken into consideration for the analysis. Caonillas-2 has not been taken into consideration as the generation unit is not in operation since it was flooded during Hurricane Georges in 1998. The missing data of the considered hydropower are collected using the National Inventory of Dams [17], an authorized database of all the dams in the United States and its territories.

C. Optimization Problem Formulation

The objective of the formulated optimization problem is to reduce the total annual cost of meeting system energy demand and resilience requirements. The total annual cost includes all investment and operational costs, such as: utility purchase (C^{ut}), annualized technology investment cost (C^{tec}), technology operation and maintenance ($C^{O\&M}$) cost. The objective function is as follows:

$$Cost = \min \sum_t C_t^{ut} + \sum_t C_t^{tec} + \sum_t C_t^{O\&M} \tag{1}$$

subject to

$$L_t + E_t^{ex} = E_t^{im} + \sum_{j \in X^J} g_t^j \tag{2}$$

where, (L_t, E_t^{ex}, E_t^{im}) represents the demand, electricity export, and import at time t respectively. g_t^j represents the power generated by generation asset j at time t and X^J represents the set of generation assets. Equation (2) represents the energy balance constraint. Xendee [16] utilizes mixed integer linear programming in its back end and considers all the appropriate constraints for resilience requirement based on model outages, critical and non-critical loads, and curtailment percentages.

III. Case Study and Results

A. System Description

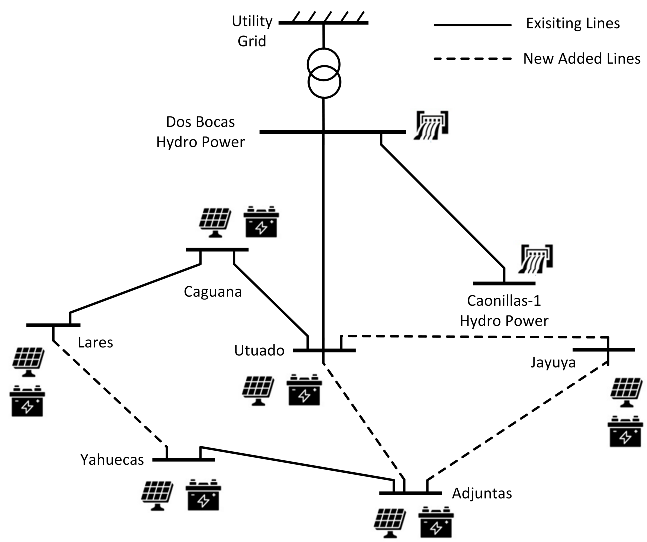

Fig. 3. Microrred de la Montaña - Network Diagram

In this study, the municipalities located at central Puerto Rico which are prone to frequent weather events and long-duration outages are selected for the case study to build a resilient networked microgrid. The Microrred de la Montaña (Mountain Microgrid) operates under the authority of the Co-operativa Hidroeléctrica de la Montaña (Cooperativa), which is recognized as a cooperative and power provider according to Puerto Rico's law [18]. The members are the municipalities of Adjuntas, Jayuya, Lares, Utuado,Yaheucas, and Caguanna. Puerto Rico Energy Power Authority (PREPA) owns central generation and delivers power to the people of Puerto Rico through the use of power networks managed by LUMA Energy. A recent study conducted as a part of the technical assistance provided through the Energy Transitions Initiative Partnership Program (ETIPP) recommended the use of existing lines along with new transmission upgrades between the municipalities to improve reliability and resilience and prepare

TABLE I
SUMMARY OF TECHNO-ECONOMIC PARAMETERS OF CONSIDERED GENERATION ASSETS

Generation Asset	techno-economic Parameters
Solar	Solar PV Per Unit Install Cost = 1863/kWDc, Lifetime = 25 years; Monthly fixed Maintenance = 0.84/kWDC/Month; Panel Efficiency = 19 %; Inverter Efficiency = 96%; Array Type = Fixed Roof-Mounted Array; Array Tilt Angle = 19°S;
BES	Inverter Cost = 250 \$/kW; Battery System Per Unit Install Cost = 563 \$/kWh; Lifetime = 15 years; Charging/Discharging Efficiency = 0.9; Charging/Discharging Rate = 0.25; Min$\sim$Max SOC = 5$\sim$100%
Hydro	**Dos Bocas**: Nominal Capacity = 5 MW; No. of Units = 3; Lifetime = 25 years; NID Storage =$50,000$ acre-ft, Surface Area = 634 acres; Head Range = $135 \sim 153$ ft; Min $\sim$ Max Flow = $193 \sim 1650$ cfs; Coefficient of Discharge = 0.61; Pipe Head loss = 0.1; Total Efficiency = 0.7229 **Caonillas-**1: Nominal Capacity = 10 MW; No. of Units = 2; Lifetime = 25 years; NID Storage =$54,970$ acre-ft, Surface Area = 700 acres; Head Range = $498 \sim 538$ ft; Min $\sim$ Max Flow = $0 \sim 540$ cfs; Coefficient of Discharge = 0.61; Pipe Head loss = 0.1; Total Efficiency = 0.82875

the Cooperativa for optimal utilization of resources during extreme outages [19]. Based on this study, four new 38 kV transmission represented by dotted lines in Fig. 3 is added to the network for the analysis.

The potential distributed energy resources considered in this study to develop Microrred de la Montaña as a resilient microgrid include solar, battery energy storage (BES), and hydroelectricity. Solar PV and BES are hosted in each substation to provide power for critical load offering a certain level of resilience at the local community level. The summary of all the parameters associated with the potential generation assets for techno-economic analysis is listed in Table I. The considered BES are allowed to export and charge from the grid. Furthermore, the solar and existing hydro power plants Dos Bocas and Caonillas-1 are allowed to export as well.

B. Base Case Scenario: Connected Communities, Only Utility Supply, No DER

The base case scenario refers to the scenario where the utility is only responsible for supplying the total demand of the networked microgrid. In this scenario, there is no involvement of DERs and as a result, there are no onsite generation that can support the system load during grid outages. In other words, the system cannot satisfy any resilience criteria during grid interruption. All the community microgrids are connected as shown in Fig. 3. The total annual system costs (dollars in thousands) obtained from the base case scenario analysis is $\$73,416.5$. The total annual electricity purchase is $257,598,366$ kWh. The levelized cost of electricity is

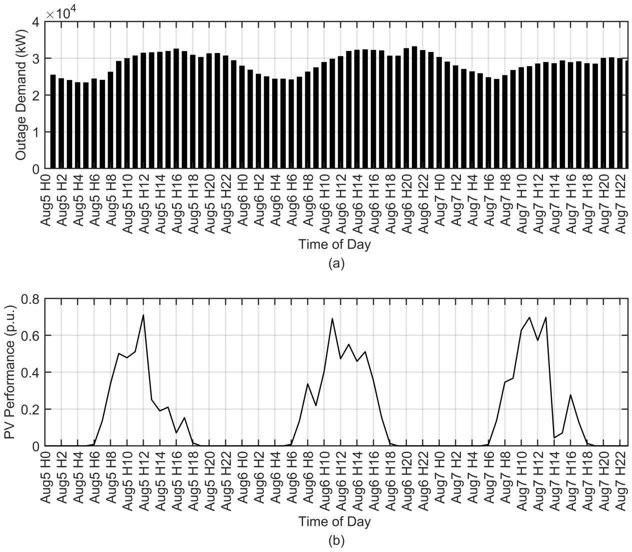

Fig. 4. Full Time-Series 3-days Outage Period (a) Outage Demand (b) PV Performance

$\$0.2850$/kWh. The base case scenario will serve as a reference for comparing total annual costs, determine extra onsite generation required for satisfying resilience criteria, analyze electricity balance and curtailment.

C. Scenario 1: Connected Communities, DER investments, Utility Supply, Full Resilience (8-hours/1-day/3-days outage)

In this scenario, the potential generation assets i.e., solar and BES are considered for the optimization to meet the full resilience criteria during the event of 8-hours, 1-day, and 3-day outages. An 8-hours outage is specified for August 13 from $4:00$ PM to $12:00$ PM. A 1-day outage is considered in August (August 13, $12:00$ AM through August 13, $12:00$ PM) whereas the period of August 05, $12:00$ AM through August 07, $12:00$ PM is considered for 3-day outage. The month of August is selected as it has the highest average hourly demand.

All the six microgrid communities are interconnected and the optimization is executed in grid-connected mode. To avoid, system economics influence on technology sizing, the electricity export is disabled such that new technologies are hosted to meet the specified resilience criterion. The summary of results listing the optimal sizing of solar plus storage in all the communities is provided in Table II. We observed that the optimized sizing for generation assets for 8-hours and 1-day grid outage criteria are the same. This is due to the optimization process which despite disabled electricity export for identifying sizes of new assets, still aims to reduce the overall cost of operation which includes electricity purchase. Notably, the most economic sizing without specific resilience criteria already fulfills the 8-hours and 1-day resilience requirements. Therefore, the sizes of assets reported for 8-hours and 1-day resilience criteria remain the same. The total annual system costs (dollars in thousands) obtained for both 8-hours and 1-day scenarios is $\$64,446.8$. The total annual electricity purchase is $89,924,085$ kWh. The levelized cost of electricity is \$0.2405/kWh. For 3-days outage, the total annual system cost, levelized cost of electricity, and total annual electricity purchase obtained are \$$66,471.7$, 0.2322/kWh, and $21,671,675$ kWh.

In this analysis, there is no requirement for critical load serving for individual communities. Since the estimated sizing of assets are determined to ride through grid outage for 8-hours, 1-day, and 3-days, the estimated capacity at each community either may be underestimated or overestimated to meet the critical load requirement. For instance, the estimated capacity of generation asset shown in Table II for Adjuntas is only solar of 1.02 MW and as a result, the community is highly vulnerable to power outages when operated as an isolated microgrid in the event of disaster. In contrast, the optimal sizing determined for 3-day outage may result in excessive investment in generation assets although critical load requirements are met. Based on the result, the estimated capacity of solar and BES are large in the community with higher annual peak load. The reason behind this is to supply larger loads locally as much as possible and to avoid losses as a result of power flow.

Furthermore, considering the unfavorable terrain (mountainous) of central Puerto Rico, the amount (optimal size) of solar and BES for 1-day and 3-day outage as shown in Table II obtained from the optimization is practically infeasible to install. This infeasibility warranted the determination of practical amount of solar that can be installed in each of the communities considering the surface area available for solar installation (e.g., rooftops and open areas). Based on the geographical survey for solar installation and the financial resource constraint, the maximum amount of solar that can be installed at each community is 5 MW. The constraint of 5 MW of solar for each community does not mean the installation of exact 5 MW, rather it means the sizing of solar can vary from 0 MW to 5 MW depending upon the optimal solution.

TABLE II
SUMMARY OF ESTIMATED GENERATION ASSETS FOR FULL RESILIENCE: 1-DAY AND 3-DAY GRID OUTAGE RIDE THROUGH

Generation Asset	Total New Capacity	Installed Location	Optimal Capacity (1-Day Outage)	Optimal Capacity (3-Day Outage)
Solar	117.8*/172.5** MW	Adjuntas	1.02 MW	11.9 MW
		Caguana	26.4 MW	43.9 MW
		Jayuya	49.1 MW	53.9 MW
		Lares	-	10.7 MW
		Utuado	16.5 MW	11.3 MW
		Yahuecas	24.8 MW	40.7 MW
BES	173.9*/362.1** MWh	Adjuntas	13.4 MWh	34.1 MWh
		Caguana	24.9 MWh	81.6 MWh
		Jayuya	86.4 MWh	107.9 MWh
		Lares	15 MWh	63.2 MWh
		Utuado	-	4.86 MWh
		Yahuecas	34.3 MWh	70.4 MWh

*: Total New Capacity for 8-hours & 1-Day Outage
**: Total New Capacity for 3-Day Outage

TABLE III
SUMMARY OF ESTIMATED GENERATION ASSETS FOR ISOLATED COMMUNITIES WITH CRITICAL LOAD SERVING

Generation Asset	Total New Capacity	Installed Location	Optimal Capacity (1-Day Outage)
Solar	22.9 MW	Adjuntas	4.36 MW
		Caguana	2.39 MW
		Jayuya	5.00 MW
		Lares	5.00 MW
		Utuado	3.76 MW
		Yahuecas	2.39 MW
BES	80.3 MWh	Adjuntas	6.33 MWh
		Caguana	5.23 MWh
		Jayuya	31.8 MWh
		Lares	22.9 MWh
		Utuado	8.82 MWh
		Yahuecas	5.23 MWh

D. Scenario 2: Isolated Communities, DER investments, No Utility Supply, Resilience with Critical Load Serving

The total optimal amount of solar and BES to meet the full resilience criteria obtained from Scenario-1 is practically infeasible, which led to relaxing the full resilience requirement and determining the optimal hosting capacity of solar and BES to serve the critical loads for each community. In this scenario, the solar PV and battery energy storages are optimized first to provide a level of resilience at the community level during grid disconnection. The resilience level in this scenario is to provide power to the critical load which is considered as 20% of the individual community load. The maximum size for the BES during the analysis is not restricted, however, the maximum size for the solar at each community is constrained with the upper limit of 5 MW. Table III provides the list of the estimated capacity of generation assets at each municipality substation of Puerto Rico. The uneven distribution of resources can be attributed to the uneven distribution of load in each community, which is more optimal in comparison to the uniform sizing where solar is fixed to 5 MW.

Furthermore, the objective of this scenario is to find out the maximum percentage of critical load that the resources obtained from this scenario can handle along with the consideration of 1-day grid outage when all the community microgrid are interconnected. Therefore, the capacity of generation assets are forced with the optimal solution and the percentage of critical load is sequentially incremented until there is no curtailment. Although the sizing of resources obtained in

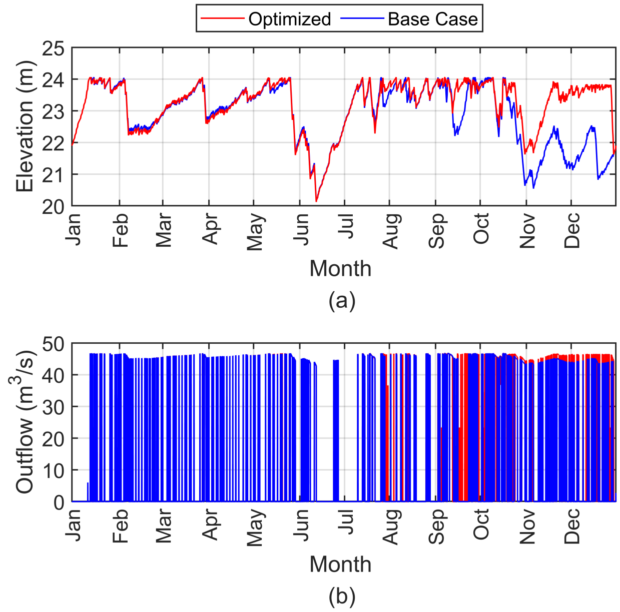

Fig. 5. Hydro Dispatch Result (a) Dos-Bocas Elevation (b) Dos-Bocas Outflow

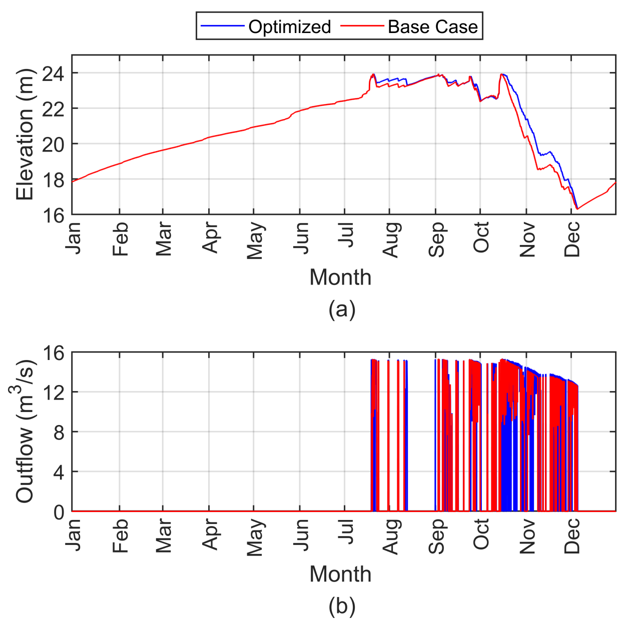

Fig. 6. Hydro Dispatch Result (a) Caonillas-1 Elevation (b) Caonillas-1 Outflow

Table III are based on 20% load as critical load, the same resources is able to meet 42% of the total load for a networked microgrid even during the condition of 1-day grid outage. This clearly depicts the benefit of interconnected microgrid which in turn improves the resilience of networked microgrid as a whole. Furthermore, the existing resources such as hydropower i.e., Dos-Bocas and Caonillas-1 hydro units in this case are considered to provide an additional amount of generation to meet the demand. When all the resources estimated on the community level resilience planning are connected to the networked microgrid, the total annual system cost, levelized cost of electricity, and total annual electricity purchase obtained are $\$79,257.4$, 0.3089/kWh, and $21,947,653$ kWh.

Fig 5 and Fig 6 depict the optimal hydro dispatch results compared with the dispatch of the base case. The base case refers to the operation of hydro units when generation assets are not considered in the optimization. Up until mid-July, the dispatch setpoints for the optimized case were nearly identical to that of the base case for both Dos Bocas and Caonillas-1 hydropower plants, as depicted by elevation and outflow profiles in Fig 5 and Fig 6. However, after mid-July, the water elevation of the Dos Bocas reservoir for the optimized case drops below and generally stays lower as compared to the base case indicating that the power production of Dos Bocas plant is maximized earlier than in the base case. The optimizer was attempting to find the right balance to dispatch hydro resources amid variability in solar generation. It is found to be economical to maximize the power production sooner even though it resulted in lower net water elevation and therefore lower efficiency of hydropower production. Conversely, the elevation level of Caonillas-1 hydropower reservoir in the optimized case occasionally exceeds that of the base case, but generally remains close.

E. Scenario 3: Connected Communities, DER investments with constraints from Scenario-2, Utility Supply, Full Resilience and with Critical Load Serving

The objective of this scenario is to determine the optimal sizing for generation assets to meet higher level of resilience i.e., 50% of load as critical load along with the consideration of 1-day and 3-day grid outage. To analyze this scenario, all the generation assets are constrained with the lower limit obtained from scenario-2 and the upper limit for BES is not bounded whereas solar are bounded to 5 MW limit. Table IV provides the optimal capacity determined to meet 50% of load as critical load all the time including 1-day and 3-day grid outages. Compared to the results of scenario-2, the additional amount of solar and BES to increase the critical load requirement from 42% to 50% of load are 7.1 MW and 26.2 MWh respectively for 1-day outage. A significant amount of BES totaling 782 MWh is required to ride through grid outages for continuous 3-days outage and meet 50% critical load all the time. Considering the maximum total amount of solar installation of 30 MW, a significant difference of 675.5 MWh of battery is required to enhance the resilience of the microgrid to ride through grid outage from 1-day to 3-days. The significance of this scenario is to provide technology sizing with a higher level of resilience requirement. The total annual system costs (dollars in thousands) obtained for 1-day scenarios are $\$79,019.5$. The total annual electricity purchase is $201,308,434$ kWh. The levelized cost of electricity is $\$0.3081$/kWh. For 3-days outage, the total annual system cost, levelized cost of electricity, and total annual electricity purchase obtained are $\$122,241.5$, 0.4787/kWh, and $200,315,814$ kWh.

TABLE IV
SUMMARY OF ESTIMATED GENERATION ASSETS TO MEET 50% CRITICAL LOAD CONSIDERING 1-DAY AND 3-DAY OUTAGES

Generation Asset	Total New Capacity	Installed Location	Optimal Capacity (1-Day Outage)	Optimal Capacity (3-Day Outage)
Solar	30*/30** MW	Adjuntas	5 MW	5 MW
		Caguana	5 MW	5 MW
		Jayuya	5 MW	5 MW
		Lares	5 MW	5 MW
		Utuado	5 MW	5 MW
		Yahuecas	5 MW	5 MW
BES	106.5*/782** MWh	Adjuntas	6.33 MWh	98.7 MWh
		Caguana	5.23 MWh	55.9 MWh
		Jayuya	52.8 MWh	263.6 MWh
		Lares	22.9 MWh	243.5 MWh
		Utuado	8.82 MWh	60.9 MWh
		Yahuecas	10.4 MWh	59.4 MWh

*: Total New Capacity for 8-hours & 1-Day Outage
**: Total New Capacity for 3-Day Outage

IV. CONCLUSION

This paper has proposed a hierarchical resilience planning strategy and performed an extensive techno-economic analysis for resilience planning of a networked microgrid. A case of Puerto Rico was taken into consideration to demonstrate the proposed resilience planning strategy along with the consideration of site-specifics such as real load profiles, solar generation, hydro power, utility tariffs and many more. This study determined the optimal technology sizing at the level of community microgrid and networked microgrid as well. Hierarchical resilience strategy optimally estimated the size of generation asset in all the isolated community and ensures the base resilience requirement of individual community are preserved when the communities are interconnected. A techno-economic analysis platform Xendee which utilizes Mixed Integer Linearized Optimization was used along with the consideration of site-specific constraints such as power budget, critical load, and predefined length of outage period for resilience planning of microgrid. As a future work, multiple resilience planning strategy will be proposed and compared to determine the superior strategy for designing the resilient networked microgrid.

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