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CIGRE US National Committee
2022 Grid of the Future Symposium

A Resilience-Driven Microgrid Interconnected Island Distribution System

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MOTIVATION

Electricity is an essential service and its infrastructure is a critical and essential element to society [1]. Unfortunately, the electricity grid in some jurisdictions is more susceptible to frequent and extended outages due to either a state of disrepair or increased risk of major weather events, and in some cases both. The latter is becoming more frequent, as a result of climate change and associated weather patterns, which have become the single main cause of service interruption. While electric utilities traditionally have constructed their systems to operate under normal weather [2], [3], the emerging need for accounting for high impact events and resilience has started to drive electric utility design standards, guidelines and best practices [4].

It is well known the electric infrastructure is very expensive and upgrading it entirely from generation to end-use services is not economical [5]. Targeted and strategic investment is necessary, where alternative solutions that fall under the umbrella of non-wires alternatives (e.g., distributed energy solutions, energy storage) should be evaluated against traditional solutions through comprehensive cost benefit analyses. Among alternative solutions, the infrastructure, technological advances, and control systems that are the underlying foundation of microgrids have been shown to not only be an option that can provide the necessary resilience a community needs, but in a more economical way than traditional solutions [6].

This paper presents the real case of a multi-island power system that is operated by a utility that serves about 1.5M metered premises, providing electricity to nearly 3.2M residents. The concept is focused on two of these islands. The paper presents a valuation of the societal impact of two category 5 hurricanes on the islands' residents, reinforcing the business case with a positive cost-benefit analysis for directing infrastructure investment to modernize the supply. A microgrid sizing exercise is presented, consisting of aggregations of DER and leading up to a nested architecture to leverage renewable generation. Renewables possibly will be integrated not only through utility-scale, utility-owned resources, but also through virtual power plants (VPPs) through renewable procurement processes that are currently open for bids. Approaching resilience from a grid perspective represents a novel way to think about the power system and its design, where power system infrastructure, along with control and communication

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architectures, are designed concurrently to integrate DERs and microgrids and ensure delivery of power to critical loads, even under extreme events [7]. From a theoretical perspective, there is a compelling argument for this approach, but legacy issues have slowed real adoption in the industry. The proposed concept represents a unique opportunity to develop a system according to these tenets.

KEYWORDS

Distribution system reliability, networked microgrids, outage restoration, resilience, smart grid

1. THE MULTI-ISLAND TRANSMISSION AND DISTRIBUTION SYSTEM

The main island, where the vast majority of the 2.5M residents are located, has a 230kV backbone ring and a meshed 115kV networked transmission system. It contains a highly dispersed subtransmission system operating at 38kV, supplying almost all industrial and commercial customers on the island. The utility operates about 1,250 distribution feeders, currently supplied at four different voltage levels: 13.2kV, 8.32kV, 7.2kV, and 4.16kV, which are about 25%, 15%, 3%, and 55% of the feeders, respectively. The two small islands, which are the subject of this paper, house about 10,000 residents combined. A submarine cable connects one of the 38kV lines from the main island to one of the two smaller islands, and in tandem the second smaller island. These small islands each have a 38/4.16kV distribution substation each, and have three and two feeders, respectively. This is illustrated in Fig. 1.

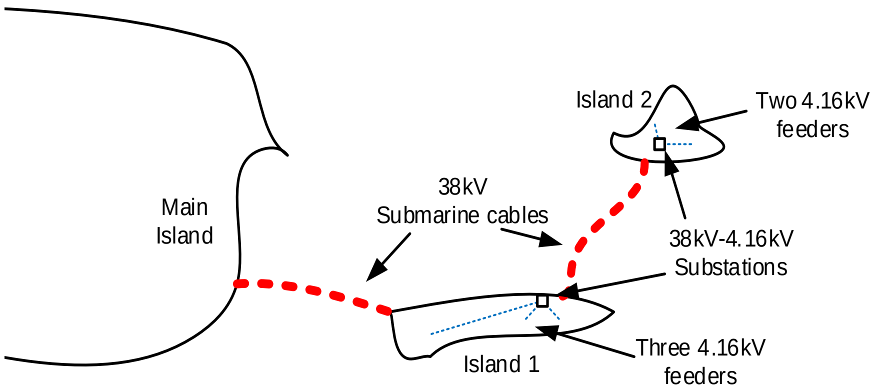


Fig. 1. A simplified representation of the island system (not to scale)

2. VALUATION APPROACH

This section quantifies the performance in the two smaller islands to past high impact events. Metric used is the rate of recovery to a loss suffered by the system during *black sky* days, i.e. following a major outage. This can be obtained by the difference between the outage rate $O(t)$ and the recovery rate $R(t)$ at time t. These instantaneous quantities can be defined as

$$O(t) = OOS_{component}(t), \quad (1)$$

$$R(t) = R_{component}(t), \quad (2)$$

where *OOS* stands for a component that is out of service. These can be assigned to the number of outages, the number of unserved customers, or another pertinent parameter. As an example, cumulatively, these can be defined as:

$$O(t_i) = \sum_{ti=t0}^{t1} OOS_{customers}(t_i), \quad (3)$$

$$R(t_i) = \sum_{ti=t0}^{t1} R_{customers}(t_i), \tag{4}$$

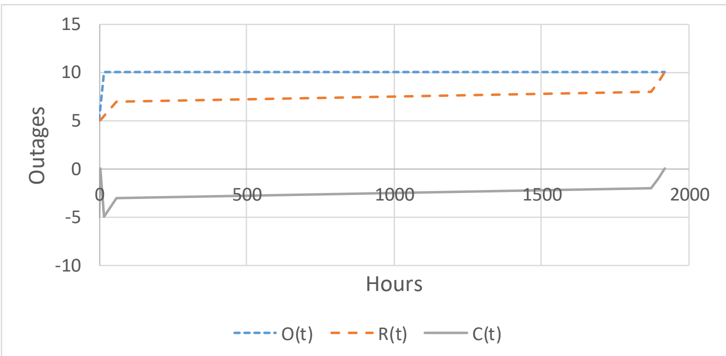
where these equations represent the customer outages following an event and those recovered, both at time t_i. The difference of these two is the remaining customers not served.

The metric we use to quantify the resilience of the system is the resilience curve, which can be calculated as [8]

$$C(t_i) = R(t_i) - O(t_i). \tag{5}$$

2.1 Resilience Curve for Two Category 5 Hurricanes

The outage and restoration rates, as well the resilience curves were populated for the two smaller islands. The calculation was carried out for a period when the islands suffered a major impact and the performance of the system under two category 5 hurricanes is analyzed. Both events took place in the summer of 2017. The first hurricane only grazed the northeast corner of the main island, but its wind activity had a significant impact. The second hurricane, on the other hand, was devastating, as its path was directly through the center of the main island and over the two small islands, entering the southeast corner and leaving through the northwest. Both islands have emergency backup diesel plants to serve the community following these events. In Island 1, the plant was inoperable and the Federal Emergency Management Administration (FEMA) had to haul in mobile diesel units, as reflected in the outage duration shown in Fig. 2, which depicts the outage, restoration, and resilience curves for the timeframe of the two hurricanes and for the two islands combined.



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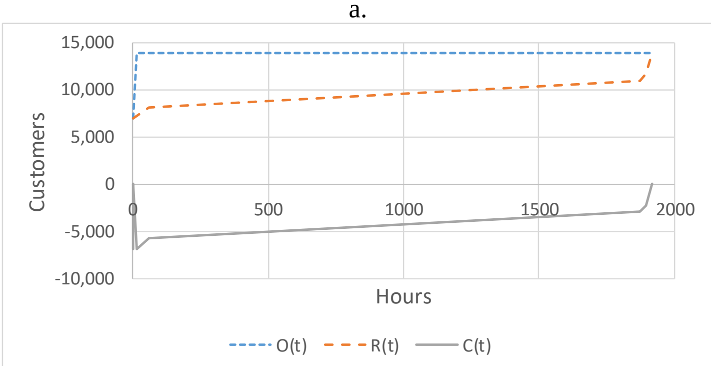

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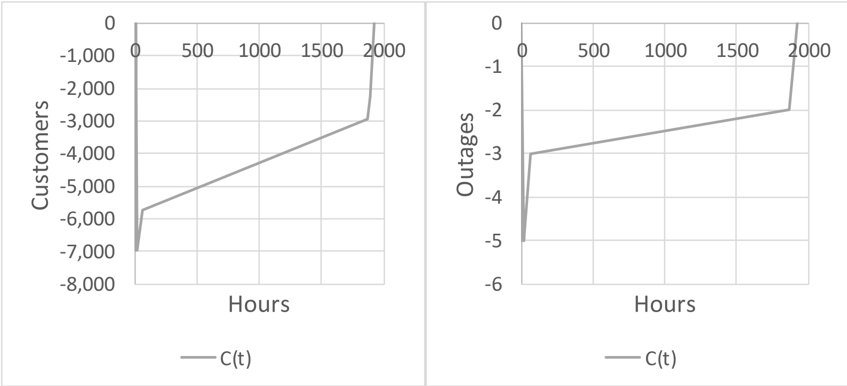

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Fig. 2. Component outage, restoration, and resilience curves for the hurricanes, (a) outage count, (b) unserved customers, and (c) resilence curves.

2.2 Assigning a Cost to Energy Not Served (ENS)

The financial impact on a customer goes well beyond the cost of electricity that was not billed to customers. In fact, there are different approaches to quantify the value of lost load (VOLL). The first approach calculates the cost of unserved MWh, whereas the second assigns financial impact on a per-person basis. This section introduces each philosophy and its results from the calculations but omits the mathematics due to space limitations. Within the first approach there are two methods [9]:

1. The first method uses a jurisdictional comparison to obtain a blended cost per lost MWh, which is used directly as $31,895 USD per MWh, as a blended class rate for the islands [9].
2. The second method, which uses the Interruption Cost Estimate (ICE) calculator [10], yields $57,940 USD per MWh as a blended class rate, for the islands.

The second approach, employed by FEMA, assigns $174 per person (not customer) per day [11]. These numbers result in the cost presented in Table 1. These results illustrate the societal impact of these hurricanes.

Table 1. VOLL Calculations

VOLL ($M USD)	Survey	ICE Calculator	FEMA
Island 1	$218.18	$396.31	$215.17
Island 2	$8.00	$14.54	$1.49
Combined	$226.18	$410.85	$216.66

3. Microgrid Sizing and Sensitivity Analysis

Different objectives were considered when deciding on the sizes of the PV generation and energy storage to be installed in both small islands. The microgrid optimization tool HOMER was used to size the DERs.

The analysis considered two objectives:

O1: Reduction in existing diesel consumption when either island is separated from the main island grid.

O2: Reduction in excess energy when Island 1 and/or Island 2 are separated from the main island grid.

These objectives are considered under four scenarios:

S1: Island 1 is isolated.

S2: Island 2 is isolated.

S3: Islands 1 and 2 are separated from the main island grid but interconnected to one another.

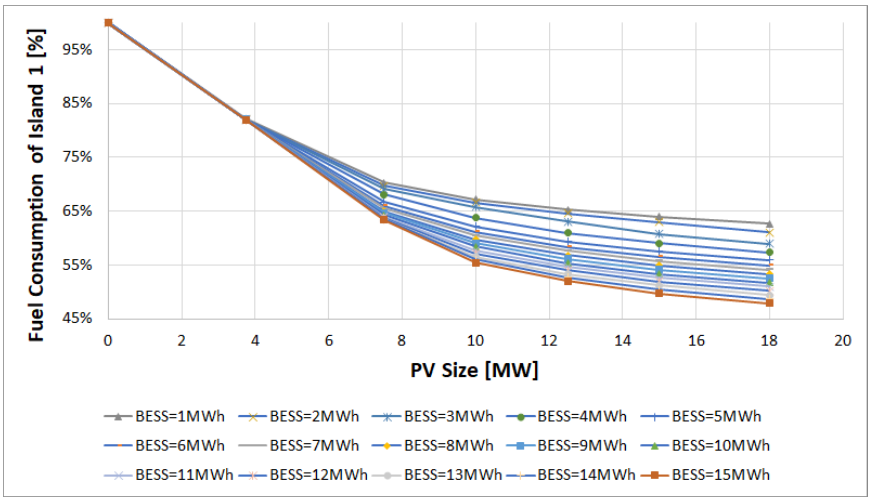
S4: Blue sky operation, i.e., both islands are connected to one another and to the main island grid.

To reach a recommendation, an exhaustive search containing various microgrid scenarios was conducted. The loading for both islands for one year, using a one-hour resolution, was used. The sizing results are shown in Table 2. These results demonstrate that renewable energy curtailment is unavoidable under practical DER sizes, but scenarios can be optimized to reduce both objectives.

Table 2. Suggested sizes and their impact on diesel consumption and energy production

Scenario	BESS	PV	O1	O2	Energy offset
S1	7 MWh	12 MW	41%	13%	41%
S2	3 MWh	3 MW	35%	5%	35%
S3	10 MWh	15 MW	42%	14%	42%
S4	10 MWh	15 MW	N/A	0%	56%

The exhaustive search conducted to reach these results also serves as a sensitivity exercise, as it displays the impact of changing the configuration on the diesel consumption. This is shown Fig. 3. This simulation considers any excess energy that may result from each case. It suggests both BESS and PV systems must be increased in size simultaneously to provide significant benefit; otherwise, we observe diminishing returns. This analysis reveals that for the allotted project budget (not discussed in detail in this paper for confidentiality), the proposed size meets the project requirements.



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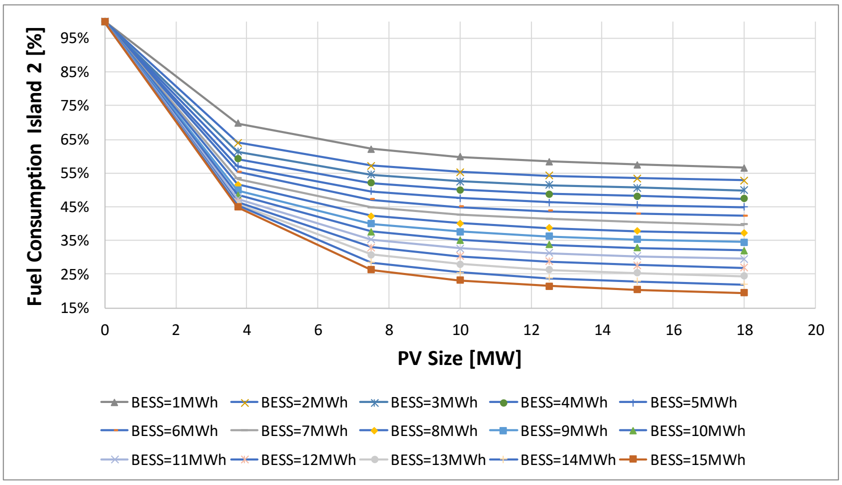

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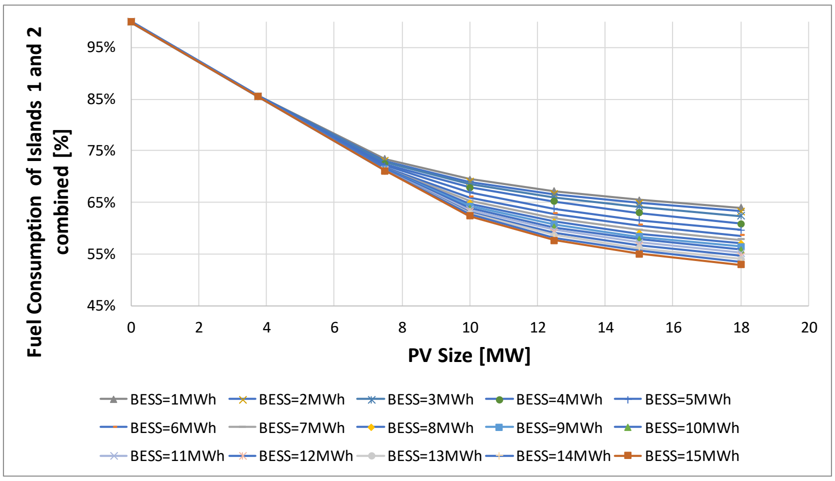

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Fig. 3. Sensitivity analysis results for diesel consumption reduction of different scenarios, (a) Island 1 microgrid, (b) Island 2 microgrid, and (c) combined Islands 1 + Island 2 integrated microgrids.

These simulations above were conducted assuming total loss of subtransmission 38kV supply (black sky event); this configuration results in major PV generation curtailment, as suggested by Fig. 4. However, the curtailed PV energy could be used under blue sky operation to further offset the total energy consumption of both islands when the subtransmission supply is available. For *blue sky* days, this microgrid will result in a substantial positive flow of renewable energy into the main island.

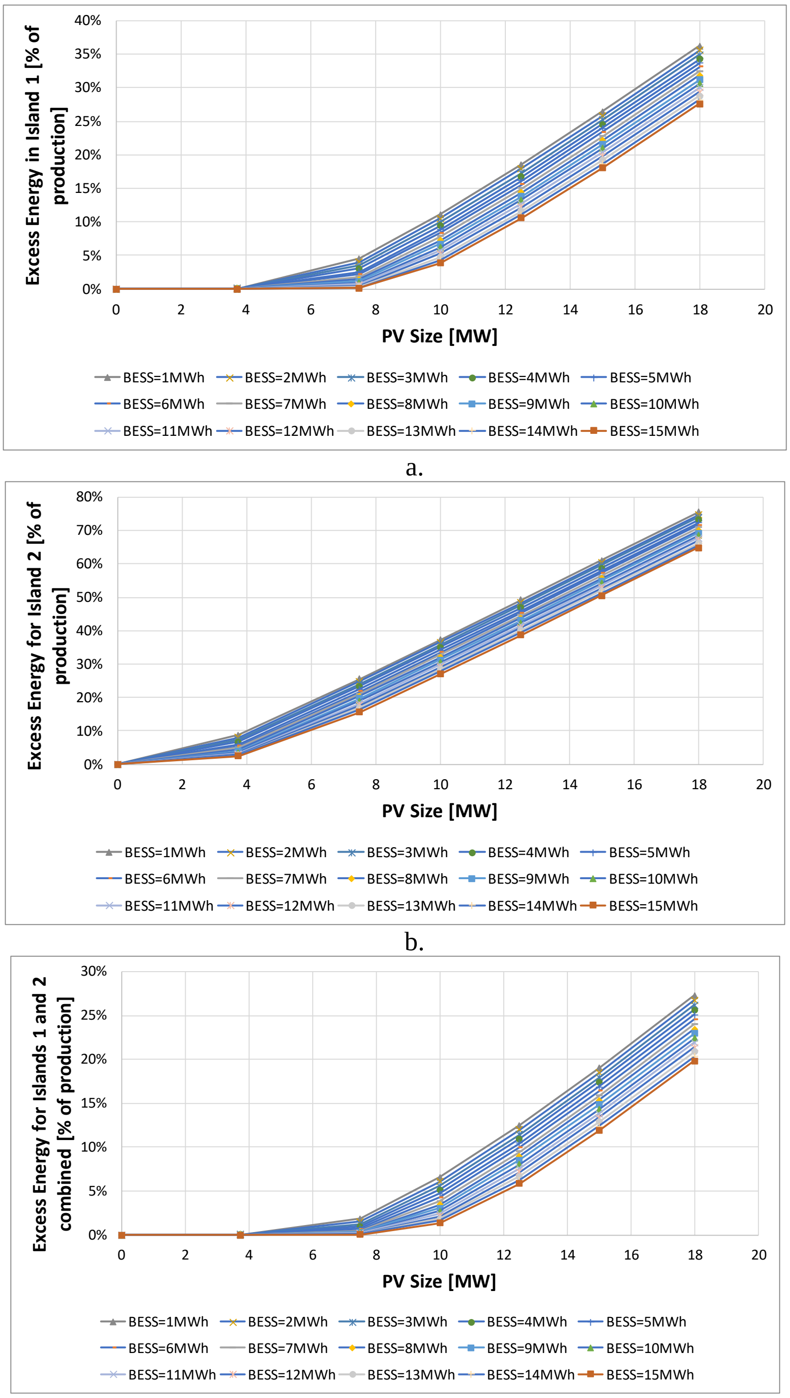

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Fig. 4. Initial feasibility analysis results showing excess energy of different islanded scenarios, (a) Island 1 microgrid, (b) Island 2 microgrid, and (c) combined Islands 1-2 integrated microgrids.

4. The Proposed Nested Microgrids Concept

The proposed project will be split into three phases. The first phase will focus on delivering resilience benefits quickly by upgrading existing assets and their controls and protections, along with the integration of a microgrid controller to enable island-wide microgrids to provide autonomy to each of the two islands in the event of power outage. The system will be planned and studied with Phases 2 and 3 in mind, that is, considering how the microgrid controller, protection scheme, communication requirements, and distributed controls will evolve under each of the phases. This includes energy efficiency measures, placement of automated switches and sensors, and development of an evolving operations concept.

Phase 2 will then integrate new renewables into the control architecture, developing resilient layers within each microgrid. Finally, Phase 3 will endeavor to operate the two island microgrids in parallel, maximizing benefits under both *blue sky* and *black sky* days.

Community engagement will initiate in Phase 1 but with a strategy that underpins successful implementation of Phases 2 and 3 as well. Phases 2 and 3 will enlarge the scope of the microgrids by incorporating a layered community microgrid concept, that considers the behind-the-meter (BTM) microgrid – residential or commercial/facility level – as the fundamental building block of a resilient grid architecture, shown conceptually in Fig. 5. Each BTM microgrid is then added to form community microgrids at the level of the service transformer and extended further to the feeder and substation level as part of the substation microgrid commissioned in Phase 1. This system of systems architecture breaks down the complexity of the problem and can be dynamically managed to scale to hundreds of DER assets, including BTM and front-of-the-meter (FTM), utility-owned or third party owned assets. These DERs can even include mobile assets such as existing mobile diesel generators or mobile energy storage systems (MBESS) to quickly optimize the system following a major event. All systems are integrated to microgrid controllers by implementing monitoring and controls over a field message bus, with automated discovery and standard data models to favor interoperability and rapid reconfiguration of the system, as illustrated in Fig. 6. The island microgrid controller will also provide integration to the SCADA system and can coordinate with back-office applications, such as energy management system (EMS).

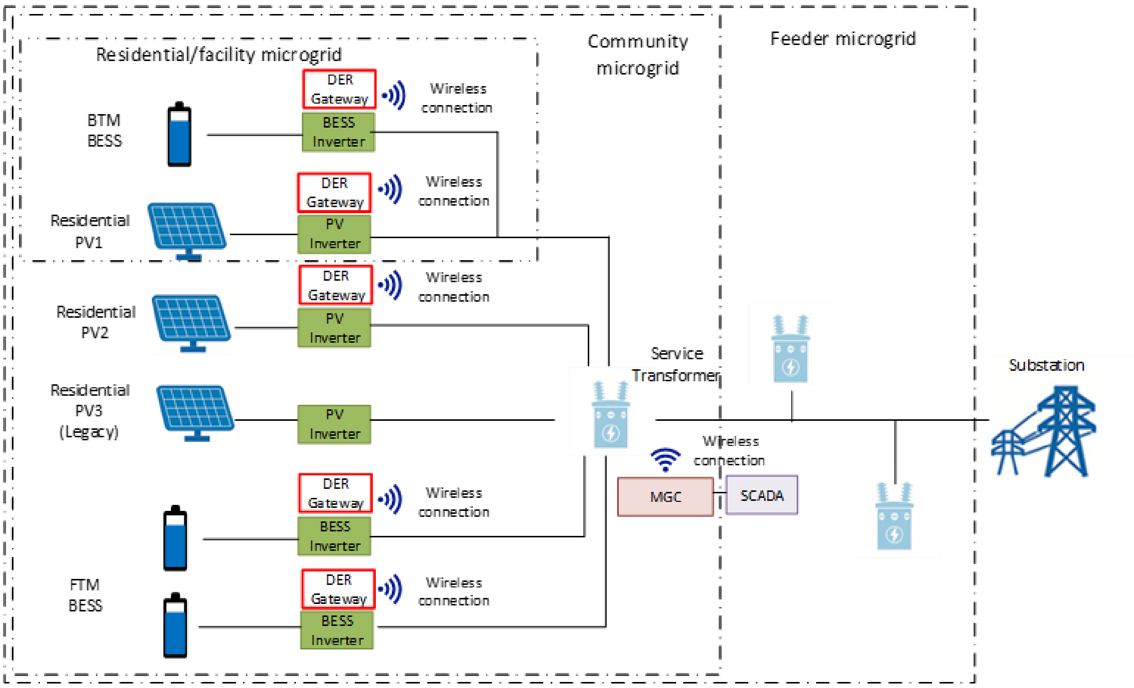

Fig. 5. Resilient community microgrid layered approach using BTM and FTM DER assets as sublayer of diesel microgrid

Based on similar architectures published in [12]-[13], this project is expected to:

- Improve the resilience of the two islands against extended outages during extreme events
- Eventually reduce the overall diesel consumption, should the islands experience another extended outage, by more than 45%.
- Reliably operate each of the community microgrid layers (BTM, service transformer, and feeder) in islanded operation, respecting industry standards [14], [15], [16].
- Connect and integrate a mobile DER or new DER to the community microgrid within two hours.
- Demonstrate through nesting of community microgrids, the technology can achieve scalability of more than 500 DER assets, through real-time simulation testing and field validation at the demonstration project.

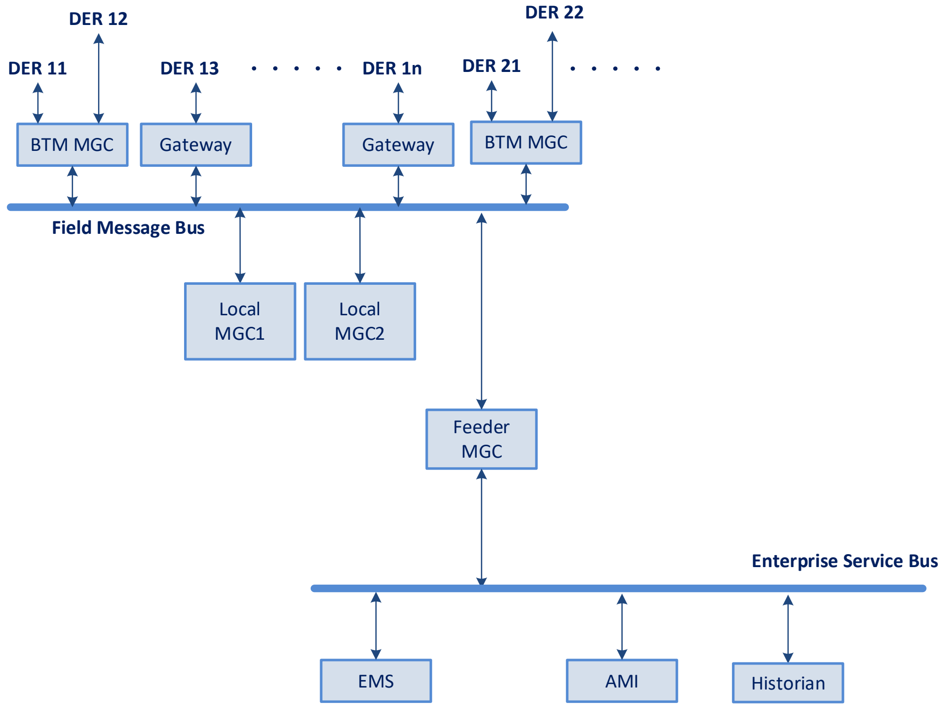

Fig. 6. Resilient architecture for monitoring and control for the microgrids on both islands

5. Conclusions

This paper presented the performance of a multi-island electric utility during two category 5 hurricanes, calculated for two small islands, quantified through resilience curves. The resilience curves suggest it took more almost three months to completely restore Island 1. When using IEEE suggested resilience metrics [4], this would result in a storm event *X* near 100%, which is a total failure. Given how devastating the second hurricane was, it is difficult to assert the fragility of the system pre-disaster.

To enhance resilience, a microgrid solution is proposed, the cost of which was measured against the societal impact of the two hurricanes. The proposed microgrids will rely on 10MWh BESS and 15 MW PV generation and will provide:

- 41% reduction of the overall diesel consumption in Island 1 for total loss of subtransmission supply.
- 35% reduction of the overall diesel consumption in Island 2, for a total loss of subtransmission supply.
- 42% of reduction of the overall diesel consumption in the minigrid containing Islands 1 and 2, assuming both are still connected to one another, should there be total loss of subtransmission supply from the main island.
- 54% reduction of the overall energy consumption in Island 1 during blue sky operation.
- 40% reduction of the overall energy consumption in Island 2 for blue sky operation.
- 56% reduction of the overall energy consumption in the minigrid of Islands 1 and 2, for blue sky operation.

The economic analysis suggests the proposed microgrid projects can add tremendous value in improving resilience of the discussed locations, by supporting the community in future major weather events. The scalable layered architecture under consideration allows scaling to larger systems, or as in the case of the proposed approach, build out resilient sublayers of diesel microgrid as renewables are integrated through VPP or other energy procurement exercises. As the team plans implementation of the proposed microgrid, it is expected the proposed innovations will benefit underrepresented and vulnerable communities and the industry at large.

BIBLIOGRAPHY

[1] "Economic benefits of increasing electric grid resilience to weather outages," U.S. Dept. Energy, Executive Office President, Washington, DC, USA, Tech Rep., Aug. 2013.

[2] Economics and Statistics Administration, "Economic impact of Hurricane Sandy: Potential economic activity lost and gained in New Jersey and New York," Office Chief Econ., U.S. Dept. Commerce, Washington, DC, USA, Tech. Rep., Sep. 2013.

[3] IEEE Guide for Electric Power Distribution Reliability Indices, IEEE Standard 1366-1998, 1999, pp. 1–21.

[4] IEEE PES-TR83, Resilience Framework, Methods, and Metrics for the Electricity Sector.

[5] M. McGranaghan, M. Olearczykm, and C. Gellings, "Enhancing distribution resiliency: Opportunities for applying innovative technologies," Elect. Power Res. Inst., Palo Alto, CA, USA, Tech. Rep. 1026889, Jan. 2013.

[6] Jeffers, Robert Fredric, Staid, Andrea, Baca, Michael J., Currie, Frank M, Fogleman, William Ernest, DeRosa, Sean, Wachtel, Amanda, and Outkin, Alexander V. Analysis of Microgrid Locations Benefitting Community Resilience for Puerto Rico.. United States: N. p., 2018. Web. doi:10.2172/1481633.

[7] Taft, J., "Electric grid resilience and reliability for grid architecture," PNNL technical report PNNL-26623, Nov. 2017.

[8] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides and N. D. Hatziargyriou, "Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems," in IEEE

Transactions on Power Systems, vol. 32, no. 6, pp. 4732-4742, Nov. 2017, doi: 10.1109/TPWRS.2017.2664141.
[9] Puerto Rico Integrated Resource Plan 2018-2019, available at https://aeepr.com/es-pr/QuienesSomos/Ley57/Plan%20Integrado%20de%20Recursos/PREPA%20Ex.%201.0%20IRP%202019%20PREPA%20IRP%20Report.pdf
[10] Interruption Cost Estimate calculator, available at Icecalculator.com
[11] FEMA Benefit-Cost Analysis (BCA) Tookit 6.0 Release Notes, available at https://www.fema.gov/sites/default/files/2020-08/fema_bca_toolkit_release-notes-july-2020.pdf
[12] K. P. Schneider et al., "A Distributed Power System Control Architecture for Improved Distribution System Resiliency," in IEEE Access, vol. 7, pp. 9957-9970, 2019.
[13] W. Du et al., "Modeling of Grid-Forming Inverters for Transient Stability Simulations of an all Inverter-based Distribution System," 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2019, pp. 1-5.
[14] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), 6 April 2018, doi: 10.1109/IEEESTD.2018.8332112.
[15] "IEEE Standard for the Specification of Microgrid Controllers," in IEEE Std 2030.7-2017, 23 April 2018, doi: 10.1109/IEEESTD.2018.8340204.
[16] "IEEE Standard for the Testing of Microgrid Controllers," in IEEE Std 2030.8-2018, 24 Aug. 2018, doi: 10.1109/IEEESTD.2018.8444947.