Energy Resilient Recovery in Puerto Rico: Hurricane Maria Recovery Support

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National Renewable Energy Laboratory

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List of Acronyms

BTM	behind the meter
CPUC	California Public Utilities Commission
DER	distributed energy resource
DOE	U.S. Department of Energy
EPS	electric power system
FEMA	Federal Emergency Management Agency
FTM	front of the meter
GMLC	Grid Modernization Laboratory Consortium
HELICS	Hierarchical Engine for Large-Scale Infrastructure Co-Simulation
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronics Engineers
IRP	integrated resource plan
NREL	National Renewable Energy Laboratory
PREB	Puerto Rico Energy Bureau
PREPA	Puerto Rico Electric Power Authority
PV	photovoltaic
SCADA	supervisory control and data acquisition
VAR	volt ampere reactive

Executive Summary

This report covers microgrids as a special application of distributed energy resources (DERs). This is one of a series of reports describing the U.S. Department of Energy (DOE) multi-laboratory efforts undertaken.

To ensure the sustainable, long-term recovery of Puerto Rico's electric power grid from hurricanes Maria and Irma and to build capacity to manage future potential natural disasters in the most secure and resilient way, the DOE convened experts from multiple national laboratories to develop a comprehensive set of data, models, analytic tools, and studies, considering inputs from a wide variety of stakeholder groups, to support technically sound recommendations for Puerto Rico's energy investment decisions. In Phase 1 of the multi-laboratory effort to support Puerto Rico's recovery, the National Renewable Energy Laboratory (NREL) provided the utility company Puerto Rico Electric Power Authority (PREPA) recommendations for a new framework of interconnection standards to accelerate the integration of utility-scale, transmission-connected, renewable electrical generation and energy storage that ensure cross-technology compatibility and enable high deployment levels without compromising grid reliability, safety, or security.[1]

In Phase 2, NREL published a report[2] focused on the interconnection of DERs to the electric distribution system in Puerto Rico. This report familiarized the reader with Puerto Rico's distribution infrastructure and operational practices and procedures that are relevant to DER interconnection. The report also provided considerations for streamlining the interconnection process given the expected increase in deployments resulting from Puerto Rico's renewable portfolio standard goal of 100% renewables by 2050. Accordingly, the report identifies considerations and concerns associated with the increase in intermittent generation, strategies for DER interconnection best practices, and the potential use of the latest technological solutions identified in the latest revision of the Institute of Electrical and Electronics Engineers 1547-2018 interconnection standard. Additionally, the report identified ways to improve the physical resiliency of installed DERs.

As part of work done in Phase 3, this report presents an analysis of the Puerto Rico grid to illustrate the possible different microgrid and minigrid scenarios. The capability to form sustained microgrids and minigrids could potentially provide a high level of resiliency during disturbances on the grid. DERs, on the other hand, have the capability to aid in the microgrid operation by providing grid support as well as grid-forming functionality. Other tasks in Phase 3 include voltage regulation in distribution networks using DERs and transmission-and-distribution co-simulation.

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[1] See "Interconnection Requirements for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example" by Vahan Gevorgian, Murali Baggu, and Dan Ton, presented at the 4th International Hybrid Power Systems Workshop, Crete, Greece, May 22–23, 2019, https://www.nrel.gov/docs/fy19osti/73848.pdf.

[2] See *Considerations for Distributed Energy Resource Integration in Puerto Rico* by David Narang et al., https://www.nrel.gov/docs/fy21osti/77127.pdf.

The current effort is funded under the Federal Emergency Management Agency (FEMA) interagency agreement HSFE02-20-IRWA-0011 with DOE for Puerto Rico recovery support following Hurricane Maria. DOE's Puerto Rico recovery support is being managed by the DOE Office of Electricity. DOE is supporting FEMA under the National Disaster Response Framework Infrastructure Systems Recovery Support Function. In support of DOE's efforts to develop technical capacity to ensure that funded recovery actions (FEMA Public Assistance/Hazard Mitigation Grant Program and U.S. Department of Housing and Urban Development Community Development Block Grant–Disaster Recovery/Mitigation) adhere to industry best practices, are coordinated with long-term capital improvement projects as well as future organizational and Commonwealth of Puerto Rico goals, and support the development of the next-generation energy sector workforce in Puerto Rico, NREL worked with DOE/ Office of Technology Transitions (DOE/TT) on all aspects of these tasks and approach. The overall work effort is intended to span a three-year period starting in October 2020. The execution of the work plan is segmented under several subtasks with annual deliverables. This document reports on results of Year 1, Quarter 1–Quarter 3 (October 2020–June 2021).

Intentional islands, also known as microgrids, have been applied in Puerto Rico first in response to hurricane recovery and are also being considered in broader applications at multiple scales to improve local and regional electric system resiliency. Larger intentional islands, termed "minigrids," are proposed at a regional level in the latest integrated resources plan as a means to improve resiliency and disaster recovery. Implementing microgrids across Puerto Rico to provide reliability and resiliency against natural and man-made disasters is not trivial. It becomes more challenging because there are many technologies and models in the market to adopt. Some are mature, and the industry has substantial experience with them; examples include grid-following inverters, such as those in rooftop photovoltaic systems. On the other hand, some technologies, such as grid-forming inverters, have huge potential in the electric energy network, but the industry needs more experience to understand them better.

Puerto Rico is among the first locales in the United States to develop regulations and technical requirements for integrating intentional islands. The first set of regulations, Regulation 9028, was established by the Puerto Rico Energy Bureau (PREB) in May 2018 with the aim to "promote and encourage the development of microgrid systems in Puerto Rico" at the local level. These regulations encouraged the deployment of microgrids to be used for individual customer sites, groups of several customer sites, or microgrids developed to sell energy or services back to the microgrid's customers or PREPA (classified as a "personal microgrid," "cooperative microgrid," and "third-party microgrid," respectively, in Regulation 9028).

Chapter 1 of this report introduces the scope and background of this work. It also highlights intended audiences who might find this report useful. Chapter 2 describes policies, legislations, and regulations pertaining to microgrid and DER deployment. The relevant regulations discussed are Regulation 8915, Regulation 8916, Regulation 9028, and Act 17. This chapter also highlights some ongoing efforts on regulations combining interconnection requirements. Different microgrid scenarios, from the small scale to the very large scale, in the context of Puerto Rico are discussed in Chapter 3 using appropriate mapping information. This chapter also explores microgrid concepts in general and the main technical aspect of microgrid deployment, especially microgrid controllers. Available tools and simulation platforms to analyze microgrids are explored in Chapter 4. The last chapter, Chapter 5, starts with a gap analysis as it relates to implementing microgrids identified in the previous effort. The main gaps that were identified are:

(1) the unclear value from DERs (intentional islands are a subset value proposition of DERs);

(2) the need for additional engineering studies and analysis on microgrid integration and operation;

(3) the lack of guidance and requirements for DER grid support;

(4) the need for additional study for peer-to-peer energy exchange and microgrids;

(5) the lack of firsthand knowledge and experience with inverter-based DER capabilities;

(6) the need for additional guidance on testing, verification, and commissioning; and

(7) the commercial control and coordination solutions for nested multi-customer microgrids.

Additionally, Chapter 5 recommends some analyses and future work for the successful deployment of microgrids, especially in Puerto Rico. The main engineering analyses recommended in Chapter 5 are on

(1) stability,

(2) performance under abnormal conditions,

(3) power balance,

(4) protection and grounding, and

(5) power quality.

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1 Introduction

In response to hurricanes Irma and Maria and the subsequent need to ensure the long-term recovery of Puerto Rico's electric power grid in the most secure and resilient way, the U.S. Department of Energy (DOE) convened experts from many national laboratories to develop a cohesive set of recommendations based on the expert opinion of the varied stakeholders to ensure a strong technical rationale for Puerto Rico's energy investment decisions. A resilient electric grid is vital to Puerto Rico's security, economy, and way of life, and it will provide the foundation for essential services that people and businesses on the island rely on every day. This report shows progress for part of a grid modeling task under the DOE-sponsored project that is a collaboration among the National Renewable Energy Laboratory (NREL) and other national laboratories.

This effort was funded under the Federal Emergency Management Agency (FEMA) interagency agreement HSFE02-20-IRWA-0011 with DOE for Puerto Rico recovery support following Hurricane Maria. DOE's Puerto Rico recovery support is being managed by the DOE Office of Electricity. DOE is supporting FEMA under the National Disaster Response Framework Infrastructure Systems Recovery Support Function.

In support of DOE's efforts to develop technical capacity to ensure that funded recovery actions (FEMA Public Assistance/Hazard Mitigation Grant Program and U.S. Department of Housing and Urban Development Community Development Block Grant–Disaster Recovery/Mitigation) adhere to industry best practices, are coordinated with long-term capital improvement projects as well as future organizational and Commonwealth of Puerto Rico goals, and support the development of the next-generation energy sector workforce in Puerto Rico, NREL worked with DOE/TT on all aspects of these tasks and approach.

The overall work effort is intended to span a three-year period starting in October 2020. The execution of the work plan is segmented under several subtasks with annual deliverables. This document reports on results of Year 1, Quarter 1–Quarter 3 (October 2020–June 2021).

This task describes how distributed energy systems might participate in and contribute to improving the resiliency of Puerto Rico's energy infrastructure in the future.

1.1 Intended Audience

The intended audience for this report includes LUMA Energy; the Puerto Rico Electric Power Authority (PREPA); the Puerto Rico Energy Bureau (PREB); other regulating and certification bodies, such as the Department of Economic Development and Commerce and the Puerto Rico Department of Housing; other stakeholders in the Commonwealth of Puerto Rico that might benefit from the material and analysis presented, including distributed energy resource (DER) developers, owners, vendors, installers, and universities; as well as stakeholders on the mainland, including the DOE project management team overseeing this effort and other team members either at NREL or at other national laboratories, nonprofits, and university researchers who might find the material complementary to their analyses.

1.2 Scope and Objectives

This report focuses on microgrids in the distribution system. There is increased interest in Puerto Rico to determine how microgrids in distributed energy systems can benefit the electric power system (EPS), and in April 2019, Puerto Rico revised its renewable portfolio standard to a goal of 40% renewables by 2025 and 100% renewables by 2050 (P.R. Law 17). Based on this goal, Puerto Rico's share of renewable generation, especially photovoltaic (PV) generation, at both the transmission and distribution levels is expected to increase.[3]

This document aims to (1) summarize specific technical topics on microgrids and minigrids as concisely as possible and (2) provide the reader with introductory knowledge and information to support implementation of microgrids in the field.

1.3 Background

PREPA, created in 1941 as the Puerto Rico Water Resources Authority and renamed the Puerto Rico Electric Power Authority in 1979, was, until recently, one of the largest utilities in the United States (O'Neill-Carrillo et al. 2018). The operation-and-maintenance responsibilities of the 18,000-mile PREPA-owned transmission-and-distribution system was transferred from PREPA to LUMA Energy, owned by ATCO and Quanta Services, in 2021, following years of preparation, with the aim to develop a more reliable, resilient, and cleaner energy system through a public-private partnership (*Newsroom Weekly Journal* 2021; Robert 2021). Before this transition, PREPA was a vertically integrated company that owned and operated the transmission-and-distribution system. Because the policies and infrastructure of Puerto Rico's power system have been developed for a long time considering a centralized and hierarchical utility, there is a significant challenge to get a robust infrastructure for microgrids in Puerto Rico. This is reflected in Puerto Rico's generation mix, where in Fiscal Year 2019, 2.3% of power was generated from renewable energy, and the rest was generated from petroleum, gas, and coal (EIA 2021). Despite hurdles in implementing renewable energy-centric policies, however, several steps have been taken to increase the share of renewable energy in Puerto Rico, such as Act No. 82 in July 19, 2010, and Act 17-2019 (Narang et al. 2021).

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[3] This report includes information available at the time of writing; recent developments might change the outlook.

2 Summary of Policy, Legislation, and Regulations Affecting Deployment

2.1 Act No. 82: Public Policy on Energy Diversification by Means of Sustainable and Alternative Renewable Energy in Puerto Rico

Act 82 (Act82 2010), passed July 19, 2010, as amended, defined specific requirements to promote energy diversification by creating a renewable portfolio standard. This rule required load-serving entities to supply increasing shares of retail sales with qualified renewable and alternative sources starting at 12% in 2015 and increasing to 20% in 2022, 40% in 2025, 60% in 2040, and 100% in 2050.

2.2 Regulation 8915: Interconnection of Resources to the Distribution System (2017)

In 2017, PREB passed Regulation 8915, "Reglamento para interconectar generadores con el sistema de distribución eléctrica de la autoridad de energía eléctrica y participar en los programas de medición neta" (PREB 2017). This regulation provides a good technical overview of some interconnection requirements, including protection and control schemes, power quality operational thresholds, and equipment certification requirements.

2.3 Regulation 8916: Interconnection of Resources to the Transmission and Subtransmission System (2017)

Regulation 8916 provides technical requirements for generators connecting to Puerto Rico's bulk power system (Puerto Rico Energy Commission 2018).

2.4 Regulation 9028: Microgrid Development (2018)

Regulation 9028, on microgrid development, was developed by PREB and implemented in May 2018 (PREB 2018). This provides general commercial terms and provisions and high-level technical requirements to encourage microgrid deployment.

2.5 Act 17: Puerto Rico Energy Public Policy Law (2019)

Act 17: Puerto Rico Energy Public Policy Law,[4] approved in April 2019, cemented the adoption of microgrids and distributed generation interconnection requirements (Leyes de Puerto Rico 2019). This law established a renewable portfolio standard of 40% on or before 2025, 60% on or before 2040, and 100% on or before 2050. The law also allows microgrid connections of:

- Up to one (1) MW to connect to the distribution system
- Up to five (5) MW to connect to the subtransmission or transmission voltages (38 kV or 115 kV).

Connections greater than five (5) MW must be approved by PREB and will include citizen's participation (Leyes de Puerto Rico 2019).

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[4] Also referred to as S. B. 1121.

2.6 Proposed Regulation Combining Interconnection Requirements (2021)

In 2021, PREB proposed draft regulation that combines interconnection requirements for all generators connecting at either the distribution or transmission level. This is under public review.[5]

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[5] See https://energia.pr.gov/wp-content/uploads/sites/7/2019/06/Resolution-and-Order-NEPR-MI-2019-0009.pdf.

3 Technical Aspects of Microgrid Deployment

Achieving 100% renewables will likely require not only very high penetrations of distributed generation but also the adoption of controllable loads as well as energy storage systems in the electric grid. Because microgrids have local control capability to more efficiently manage the local generation and load, they the potential to help utilities increase their DER hosting capacity, and grid resiliency (Asmus and Labastida 2020). Microgrids sponsored by utilities to support the distribution network, defined as a utility microgrid, constitute 14% (ranked third) of the total world-wide microgrid market segment (Asmus and Labastida 2020). The full potential of utility microgrids, however, could be achieved in cases where the microgrid serves as a foundation of the electric grid.

In the context of Puerto Rico, the adoption of microgrids paves the way for the adoption of DERs because they increase the value proposition by increasing resiliency and reliability. Utility microgrids can set the stage for the adoption of DER management systems on a wider scale that is applicable to both isolated utility microgrids or a whole area that is serviced by the utility. The operation of the utility with thousands, sometimes millions, of controllable assets is not an insignificant problem. Special attention must be paid to the communications and control layers for the proper operation of the electric grid or microgrid with very high levels of controllable assets (Rojas and Rousan 2017).

The capability to form a microgrid within the different physical boundaries of the traditional grid could potentially offer a high degree of flexibility in terms of the diversification of energy resources and the optimized energy delivery from local generation as well as resiliency under both normal and extreme operating conditions, e.g., extreme weather conditions. The physical boundary of microgrids can vary widely, ranging from the very small, serving only a few loads to the very large, serving a large community or a geographic area. For example, the 2018 integrated resources plan (IRP) filed by PREPA considers islanding entire regions of the Puerto Rico transmission system under a set of “minigrids” to aid in future disaster recovery. PREPA’s administrative regions have been conceptually reorganized in the 2019 IRP to form regional minigrids (PREPA 2019).

The minigrid concept could be used to provide a high degree of resiliency to natural disasters by delivering crucial energy needs to customers even when the main grid is unavailable. Further, it is technically feasible but has not yet been demonstrated in the field to realize nested microgrids by adding the capability to form smaller microgrids within the minigrids.

To facilitate the increase in renewable energy in Puerto Rico and the realization of regional minigrids as envisioned PREPA’s 2019 IRP, adequate policy and market regulations need to be adopted. The relevant policies play a vital role in the proliferation of DERs as well as their impact on system resiliency. For example, behind-the-meter (BTM) DER integration could provide enhanced reliability and resiliency given that appropriate settings and technical requirements are met. It the most common approach to serve specific customers, e.g., university campuses and hospitals. Note, however, that although DER adoption on the customers’ premises generally provides many benefits to the customers, there are some effects of DER integration that are not very beneficial. Examples include voltage rise due to the high penetration of DERs and reduced short-circuit current, among others (Seguin et al. 2016). To mitigate these effects, there needs be careful planning, design, and operational strategies. On the other hand, in theory, DERs have the capability to provide many grid services, such as (GMLC 2020):

- Peak capacity management
- Autonomous frequency response
- Capacity market dispatch
- Traditional frequency regulation
- Spinning reserve
- Dynamic frequency regulation
- Autonomous distribution voltage response.

Although the wide-scale application of DERs to provide grid services has not been fully implemented by the industry, researchers have demonstrated the potential of such capabilities in the laboratory setup (Gevorgian et al. 2020) and in a field demonstration (Loutan et al. 2017). The policy regulations must consider the current technologies available for microgrids and leave room to take advantage of future applicable technologies. The following subsections discuss overviews of the key technical aspects for microgrids that can be leveraged to full implementation.

3.1 Islanding Scenarios

With the availability of commercially mature technologies that allow grid-forming inverters and with the proliferation of DERs, it is now possible to ensure the sustained, long-duration operation of a section of the grid or even a microgrid with no support from the main grid. Depending on the size and complexities of the microgrids, different scenarios can be conceptualized:

1. Islanding one or two residential customers on the same feeder (~2 kW–25 kW)
2. Islanding one commercial/industrial site (facility island) (~250 kW–1 MW)
3. Islanding several facilities on the same feeder (~250 kW–1 MW)
4. Islanding a feeder or an entire substation (area EPS island) (~1 MW–~100 MW)
5. Islanding a minigrid, e.g., San Juan-Bayamon minigrid (proposed minigrid region in Puerto Rice by PREPA 2019 IRP) (~100 MW–1,000 MW).

Scenarios 3 and 4 will most likely be utility microgrids. All these islanding scenarios are expected in the future in Puerto Rico.

3.2 Proposed Minigrid Regions

In PREPA’s 2018 IRP, minigrids “are regions of the system that are interconnected with the rest of the EPS via transmission lines that could take more than a month to recover after a major event, and should be able to operate largely independently, with minimum disruption for the extended period of time that would take to recover full interconnection” (PREPA 2019). PREPA’s 2019 IRP proposed intentional islands formed by minigrids and microgrids for Puerto Rico, as shown in Table 1. Figure 1 shows an alternate view of the proposed minigrids with minigrid backbone formations and minigrid interconnections for consolidation. Siemens (2019) conducted analysis to determine potential locations for microgrids and stressed the need for additional study, including the following (PREPA 2019):

- Exact boundaries of the microgrids within the zones
- Load analysis
- Generation selection
- Available sites to install generation
- Transmission-and-distribution system analysis
- Engineering design
- Environmental/permitting.

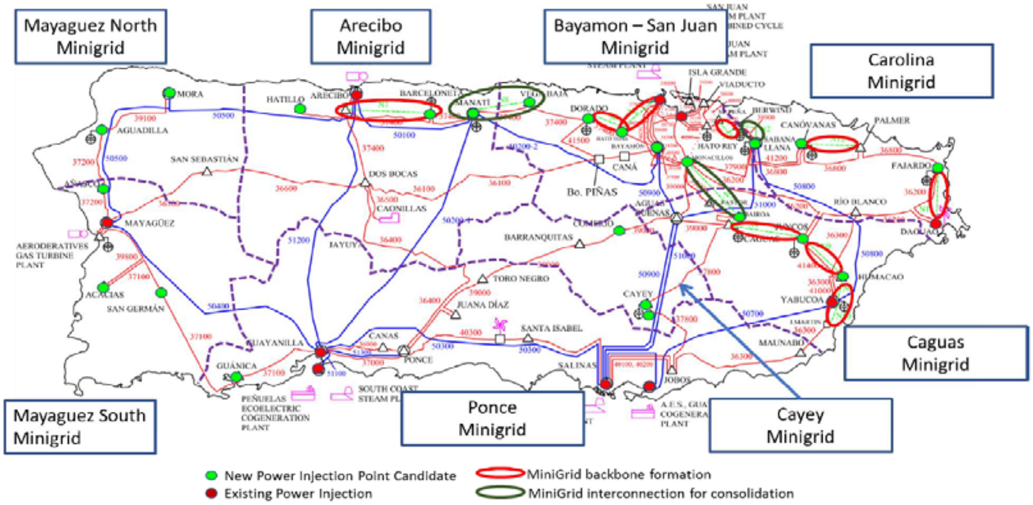
Table 1. Summary of Proposed Intentional Islands in PREPA's 2019 IRP

Minigrid Region	No. of Proposed Micro-Grids	Total Night Peak Load (MW)[a]	Minigrid Connected Load (MW)	Microgrid Connected Load (MW)	Proposed Microgrid Synchronous Generation (MW)	Planned and Proposed Microgrid PV+ Battery Energy Storage System (MW)
Arecibo	12	234.2	168.7	63.4	56	21.6
Caguas	6	306.7	271.7	40.7	36	8.1
Carolina	2	310.8	296.6	8.6	(Under request for proposal)	(Under request for proposal)
Cayey	5	101.1	59.9	41.2	41	20
Mayaguez North	2	163.5	139.2	32.8	23	10.2
Mayaguez South	9	161.7	140.2	22.2	18	6.9
Ponce	5	332.3	285.7	40.1	25	25.5
San Juan-Bayamon	7	1050.5	961.6	89.2	28	97.1
Totals[b]	48	2660.8	2322.6	338.2	235.6	189.4[c]

[a] Total load includes "critical," "priority," and "balance of the loads," as specified in (PREPA 2019). The IRP uses 2019 for loading conditions; however, the IRP notes that this level is appropriate to plan for future years also.

[b] Note that differences in totals might exist in this table from source tables. The referenced document itself differs between tables and text.

[c] This total includes 124.8 MW of planned PV-plus-battery energy storage system and 64.6 MW of additional needed to balance the load" (Siemens 2019).



Source: PREPA 2019

Figure 1. Minigrid concept proposed in PREPA 2019 IRP with minigrid backbone formations and minigrid interconnections for consolidation

As noted, in addition to the regional-scale intentional islands, PREPA proposed more than 48 smaller intentional islands around distribution substations. These are described as “microgrid zones” in the IRP. These area EPS islands are illustrated in Figure 2.

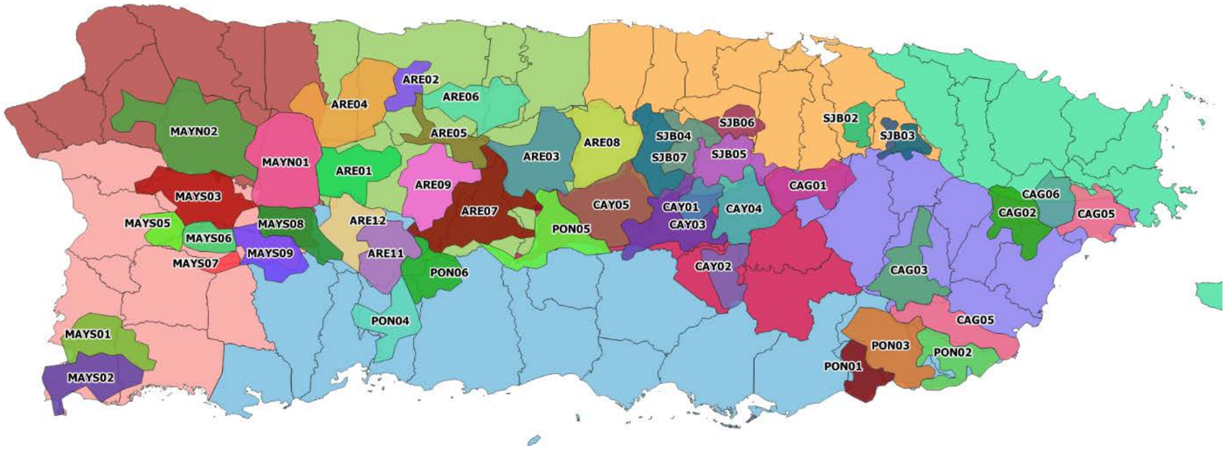
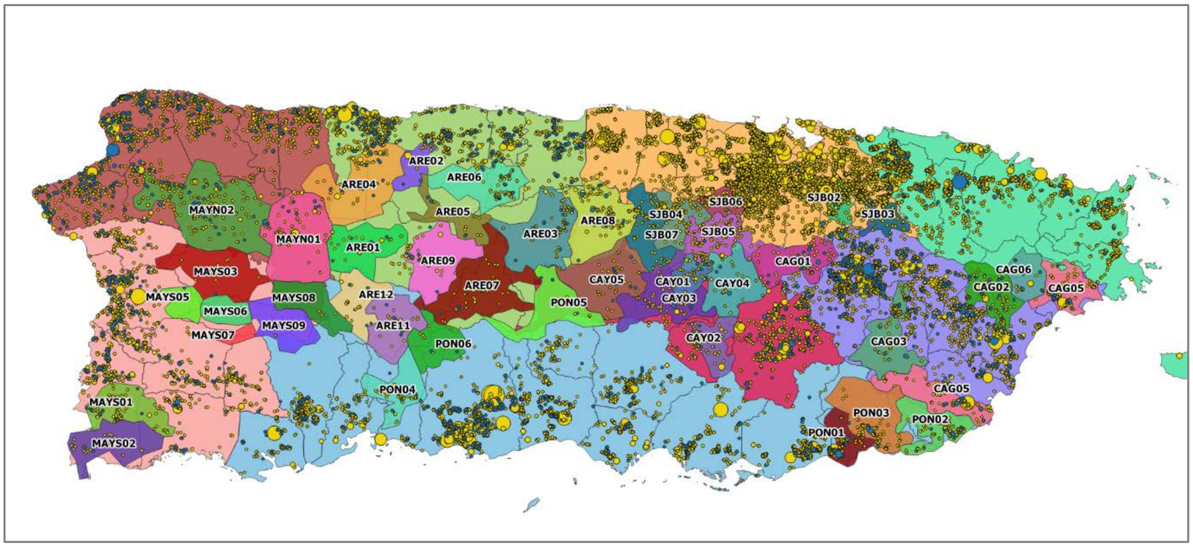


Figure 2. Area EPS islands within regional islands

3.2.1 Distributed Energy Resource Capacity in Minigrid Regions

PREPA’s 2019 IRP noted more than 172 MW of DER (mostly inverter-based residential solar) installations across all operating regions. A certain portion of the installed DER systems are capable of intentional islanding. Figure 3 illustrates the distribution of these systems across Puerto Rico. The yellow and blue circles represent grid-tied solar or solar-plus-battery DER systems. The yellow circles are “typical” grid-tied/grid-following systems, and the blue circles represent “bimodal” systems that have the capability to intentionally island. The size of the circle represents the system capacity, with the largest system being 2 MW. Note that the illustration includes interconnected systems in operation as well as systems under construction and systems under study.



Source: Based on PREPA’s 2019 IRP and data from PREPA

Figure 3. Distribution of DERs and intentional island-capable DERs by minigrid region

The vast majority of installed DERs are PV systems. The capacity of installed PV[6] and intentional island-capable systems[7] by minigrid region is illustrated in Figure 4. The illustration is intended to show the deployment of these types of technologies in the minigrid regions. It is currently unclear whether these systems can be called upon to support the broader minigrids. It is also unclear is whether these systems need to be considered in system planning or modeling to understand the interaction of minigrid control systems at the various levels. Note that Figure 4 illustrates the current installation of DERs, which is still not very high. Because a very high penetration of DERs is expected in the next 20 years, any system planning or modeling to understand the interaction of minigrid control systems at the various levels should also consider future DER scenarios.

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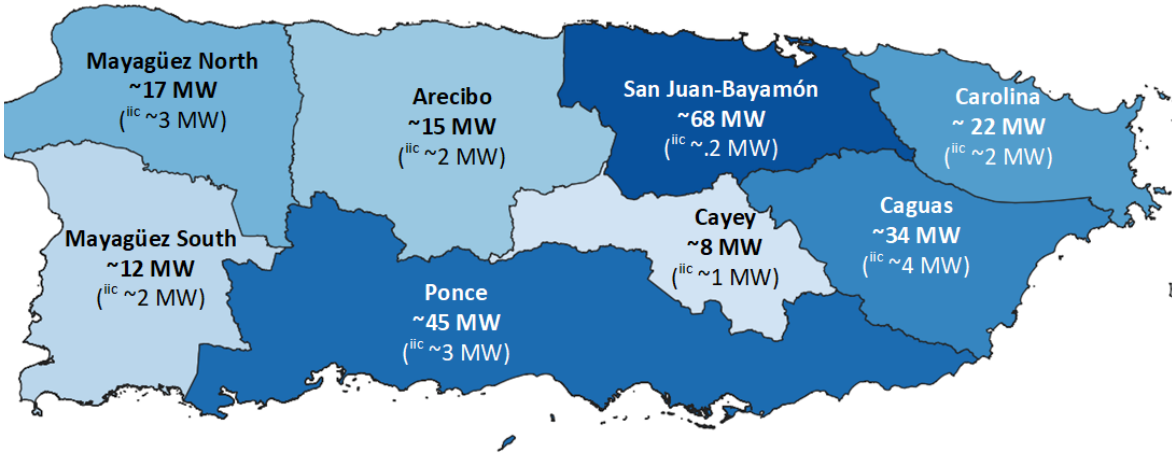
[6] Note that many conventional grid-following PV systems can operate as part of a microgrid as long as the microgrid contains enough other sources that are grid forming.

[7] To have the capability of the intentional island-capable systems to synchronize with other sources when in island mode, additional capabilities—e.g., communications, controllers—might be required.



Source: Based on 2018 data courtesy of PREPA

Figure 4. Installed PV capacity and intentional island-capable systems by minigrid region

Minigrid regions, associated area EPS islands, customer-owned intentional islands, and customer-owned grid-tied PV are described in greater detail in the following subsections.

3.2.2 Mayaguez North Minigrid

As proposed in the 2019 IRP , the Mayaguez North minigrid region would contain two area EPS islands, which are shown as the smaller colored irregular shapes in Figure 5. This minigrid region has approximately 3 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 12 MW of standard grid-tied PV that are not capable of intentional islanding.

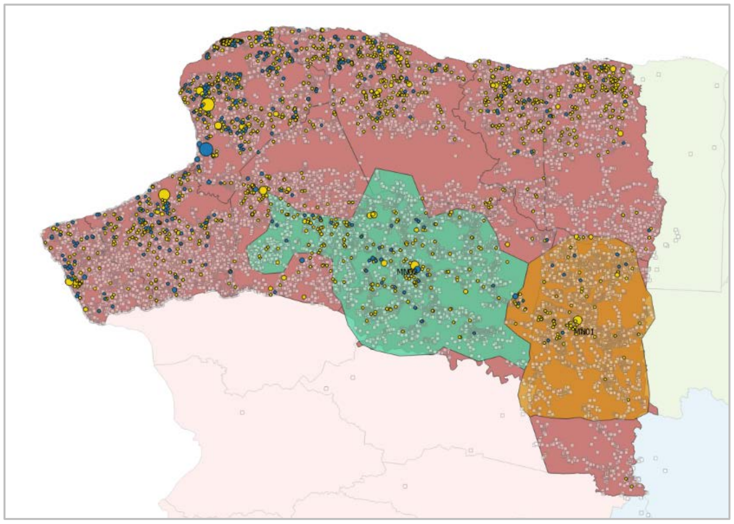


Figure 5. Mayaguez North regional minigrid

3.2.3 Mayaguez South Minigrid

The Mayaguez South minigrid region contains nine area EPS islands, which are shown as the smaller colored irregular shapes in Figure 6. This minigrid region has approximately 1.5 MW of

DERs classified as bimodal DERs that are capable of intentional islanding and approximately 11 MW of standard grid-tied PV that are not capable of intentional islanding.

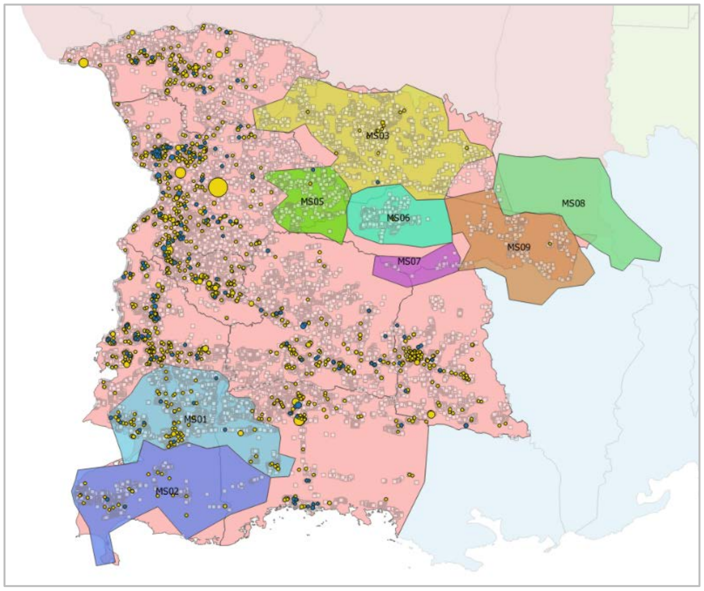


Figure 6. Mayaguez South regional minigrid

3.2.4 Arecibo Minigrid

The Arecibo minigrid region contains 11 area EPS islands, which are shown as smaller colored irregular shapes in Figure 7. This minigrid region has approximately 2 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 15 MW of standard grid-tied PV that are not capable of intentional islanding.

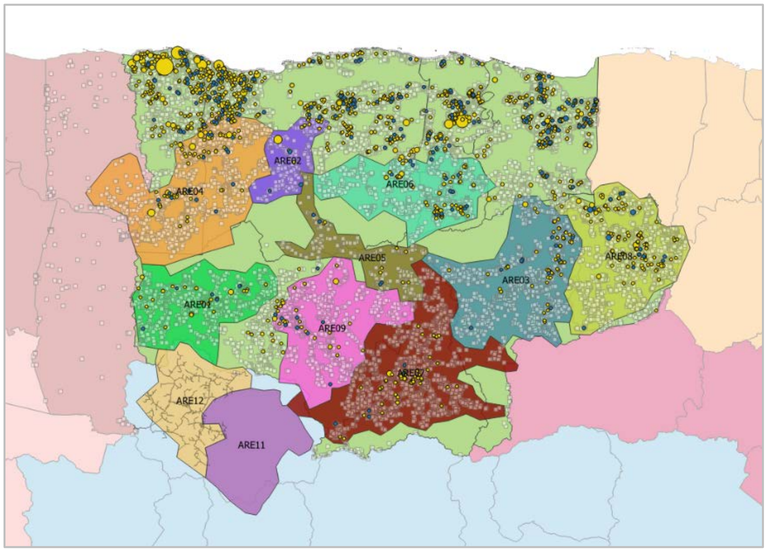


Figure 7. Arecibo regional minigrid

3.2.5 Caguas Minigrid

The Caguas minigrid region contains six area EPS islands, which are shown as the smaller colored irregular shapes in Figure 7. This minigrid region has approximately 3.7 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 30 MW of standard grid-tied PV that are not capable of intentional islanding.

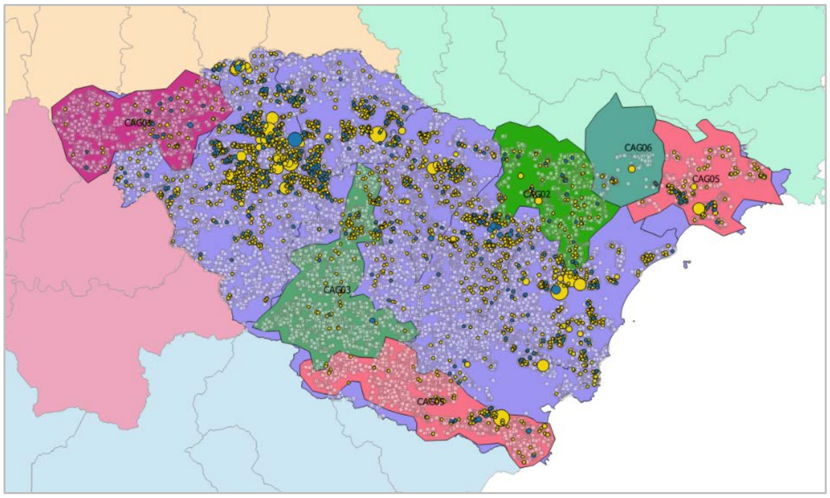


Figure 8. Caguas regional minigrid

3.2.6 Carolina Minigrid

The Carolina minigrid region, illustrated in Figure 9, contains the islands of Vieques and Culebra, considered stand-alone microgrids. This minigrid region has approximately 1.5 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 20 MW of standard grid-tied PV that are not capable of intentional islanding.

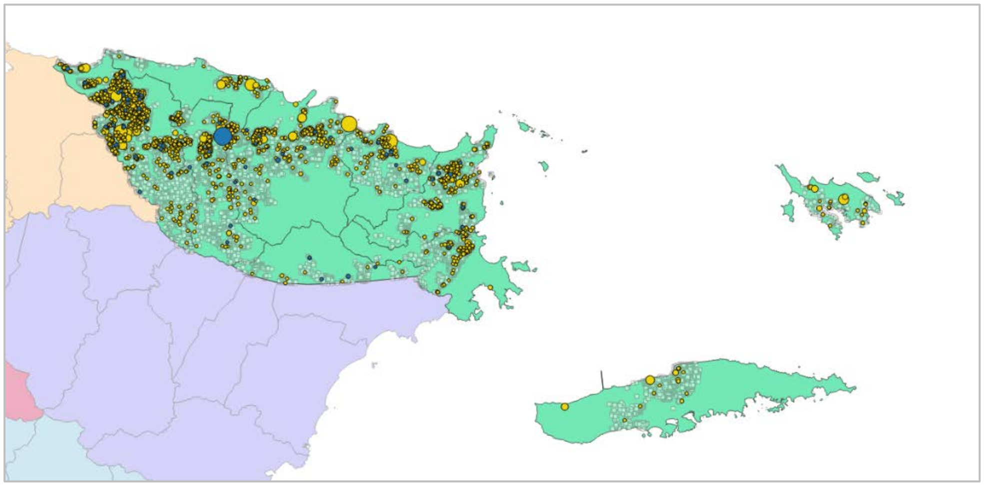


Figure 9. Carolina regional minigrid

3.2.7 Cayey Minigrid

The Cayey minigrid region contains five area EPS islands, which are shown as the smaller colored irregular shapes in Figure 10. This minigrid region has approximately 1 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 7 MW of standard grid-tied PV that are not capable of intentional islanding.

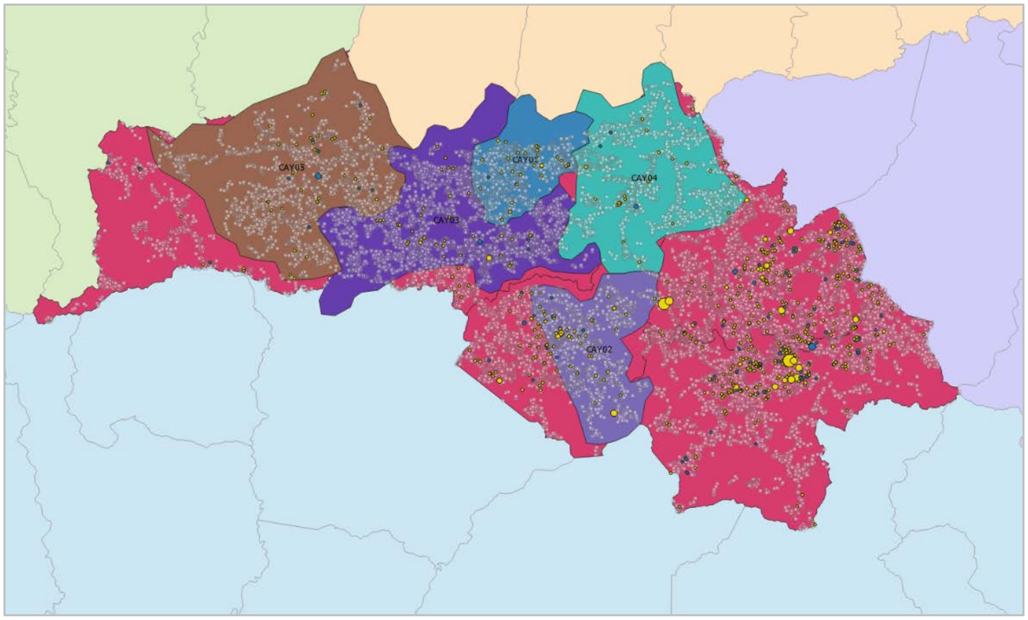


Figure 10. Cayey regional minigrid

3.2.8 San Juan-Bayamon Minigrid

The San Juan-Bayamon minigrid region contains seven area EPS islands, which are shown as the smaller colored irregular shapes in Figure 11. This minigrid region has approximately 68 MW of DERs, but it is currently unknown how much of this capacity is islandable.

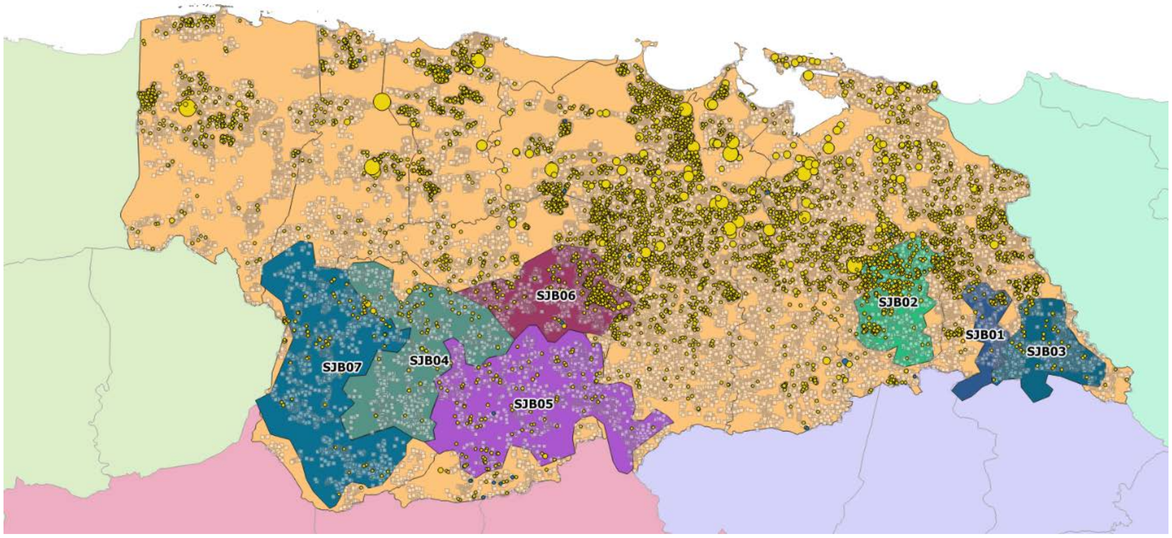


Figure 11. San Juan-Bayamon regional minigrid

3.2.9 Ponce Minigrid

The Ponce minigrid region contains six area EPS islands, which are shown as the smaller colored irregular shapes in Figure 12. This minigrid region has approximately 2.5 MW of DERs classified as bimodal DERs that are capable of intentional islanding and approximately 42 MW of standard grid-tied PV that are not capable of intentional islanding.

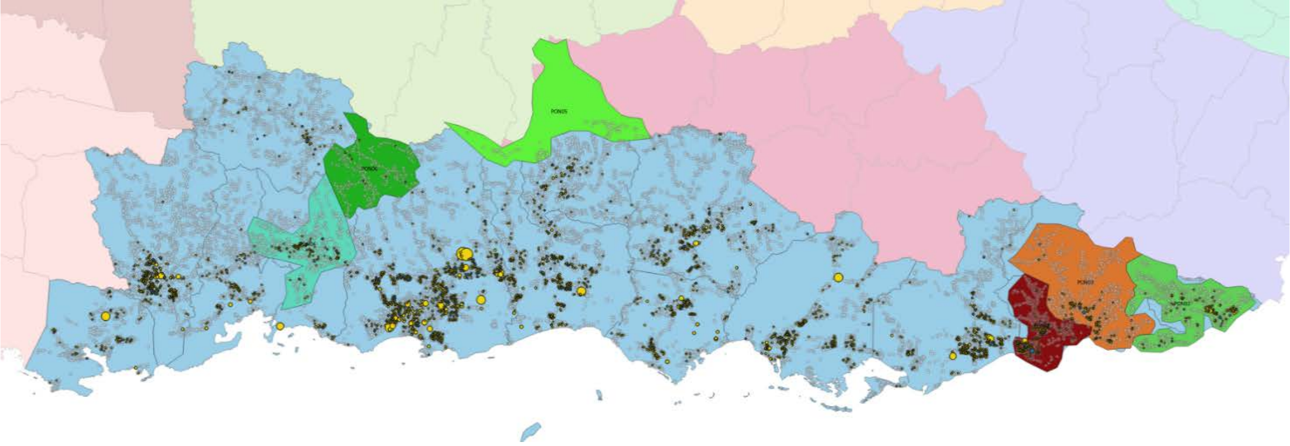


Figure 12. Ponce regional minigrid

As shown, each minigrid region contains multiple types of intentional islands at a variety of scales. Analysis of these in greater detail is expected.

3.3 Microgrid Control

The study by Siemens (2019) emphasized the need for microgrid controllers that have applications to at least two levels: (1) The controller must coordinate with the upper-level supervisory control and data acquisition (SCADA) system, and (2) the controller must support islanded mode operation as well as grid-connected mode (optional) operation. Microgrid control is an active research area, with controller architectures ranging from a centralized controller to a distributed controller. For almost all control architectures, however, the control layers can be divided into three groups based on the temporal requirements (Rojas and Rousan 2017):

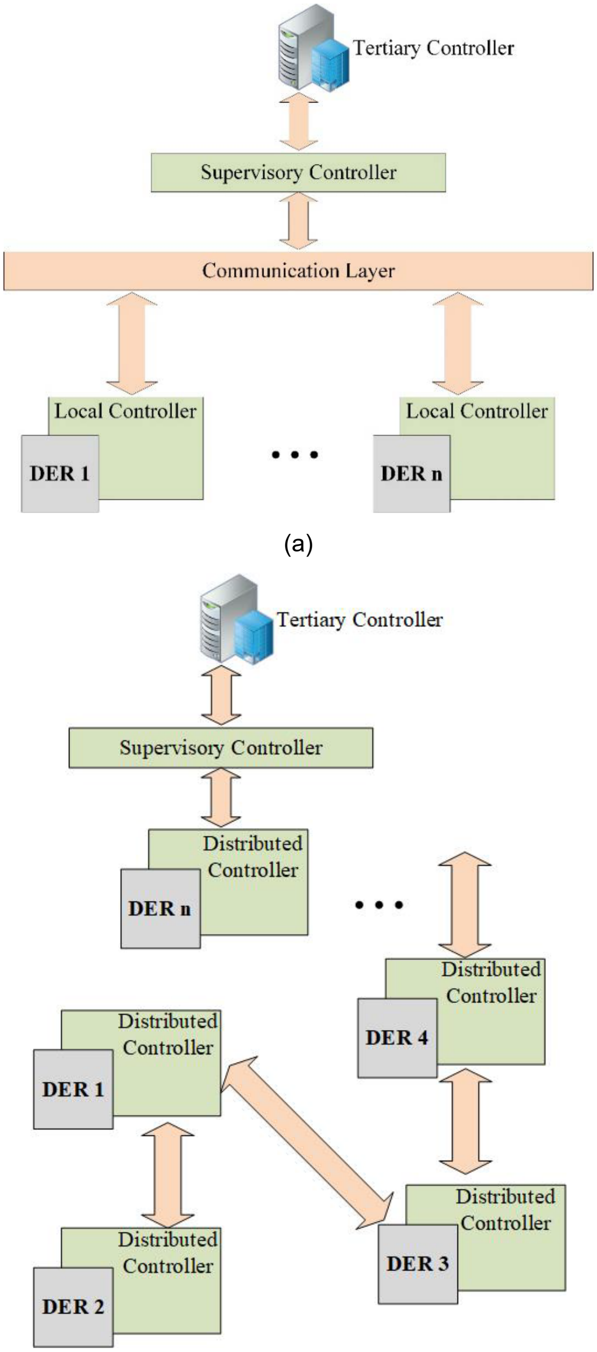
1. Local or primary layer: This is the device-level autonomous controller, and it is also the fastest control. Examples include maximum power point tracking and droop control. Many voltage regulation functions, such as vol-volt ampere reactive (VAR) as specified in the Institute for Electrical and Electronics Engineers (IEEE) Std 1547-2018, can be implemented in this layer. The local controller can use different sensors—e.g., voltage, current, temperature—to perform the control function. Most of these functions do not require communicated signals from a higher-level controller or other assets in the network.
2. Secondary or supervisory layer: This layer uses measurements from sensors positioned within a wider area to coordinate many DERs located within a wide area. The key function of this layer is to provide frequency and/or voltage frequency regulation and SCADA functionality.
3. Tertiary layer: This is the slowest layer. It covers slower functions, such as economic and environmental optimization and network reconfiguration.

Table 2 provides an overview of the control layers of microgrids and the types of studies where the layers are needed for modeling.

Table 2. Control Layers of Microgrids

Control Layer	Temporal Resolution	Key Functions	In the Context of Microgrid Simulation	Needed for Modeling	Relevant Standards
Primary (autonomous)	µs to ms	Pulse-width modulation, droop control, volt-VAR, specific power factor, inverter protection, island detection	Transient or dynamic simulation	Stability analysis, power quality	IEEE 1547-2018, IEC 61727
Secondary (coordination required)	Seconds to hours	Frequency regulation, coordinated voltage regulation, SCADA, synchronization/ transition	Dynamic simulation, steady-state simulation	Stability analysis, power quality	IEEE P2030.7, IEC TS 62898-3, IEEE P2030.10, IEEE P2030.7
Tertiary (coordination required)	Minutes to Days	energy management system, network reconfiguration	Steady-state simulation	Hosting capacity, inter-connection, parallel operation	IEC TS 62898-2, IEEE P2030.9

Because very large numbers of devices (DERs, loads, etc.) need to be controlled for the reliable and efficient operation of microgrids and minigrids, many control architectures for microgrid operation have been proposed, as shown in Figure 13.



(a)

(b)

Figure 13. Conceptual diagrams of microgrid control architectures: (a) centralized and (b) distributed

3.4 Microgrid Controllers and Commercial Solutions for Microgrids

Microgrid controllers are one of the most important components of microgrids for efficient, reliable operation by optimally managing energy sources, loads, and the microgrid network. With increasing numbers of microgrids deployed around the world, many vendors of microgrid controllers are active in the market. Without any standardization of microgrid controllers, solutions from different vendors vary in terms of functionalities and capabilities. The main functions of microgrid controllers, however, are shown in Table 3 (Liu, Starke, and Herron 2016).

Table 3. Key Functions of Microgrid Controllers

Function	Mode of Operation	
	Grid Connected Mode	Islanded Mode
Frequency control	No	Yes
Voltage control	Yes	Yes
Mode transition—grid connected to islanded	Yes	
Mode transition—islanded to grid connected		Yes
Energy management	Yes	Yes
Ancillary services for grid	Yes	
Black start		Yes
User interface, monitoring, and data management	Yes	Yes
Cybersecurity	Yes	Yes
Resiliency against abnormal operating conditions	Yes	Yes

A comprehensive list of microgrid controller functions can be found in Liu, Starke, and Herron (2016). The overall microgrid controller market size in 2019 was U.S. $6.1 billion, and it is expected to grow to U.S. $12.6 billion in 2024. The market for grid-connected microgrid controllers is forecasted to have higher growth than controllers for islanded microgrids. The major vendors in microgrid controllers are Schneider Electric, GE Power, ABB, Siemens, and Schweitzer Engineering Laboratories (Marketsandmarkets 2019).

3.5 Capabilities Needed for Islanded Operation

The islanded operation of minigrids and microgrids requires that there must be at least a source that can maintain the voltage and frequency in islanded mode and sustain the islanded operation until grid connection is available. In a traditional grid, this function is covered by large synchronous generators. The synchronous generators also provide inertia, which is helpful to maintain the stability of the grid. A minigrid formed by a regional transmission network, however, might not have adequate synchronous generators to provide frequency regulation and high enough inertia to maintain system stability. Under such scenarios, the grid-forming inverters connected in the distribution and transmission networks could be installed to enhance the minigrid's voltage and frequency regulation. This is also applicable for smaller microgrids within the minigrids. The absence of large synchronous generators and high penetrations of renewable DERs also presents a problem of power imbalance arising from the intermittent nature of renewable generation sources. Energy storage systems could be used to mitigate this problem.

4 Modeling and Simulation

Several simulation and modeling platforms are available for the analysis and modeling of microgrids (Hossain-McKenzie et al. 2019). Brief summaries of these tools and their capabilities are listed in Table 4. Note, however, that this list is not complete; it is presented to provide a background on the available simulation platforms.

Table 4. Modeling and Simulation Tools for Microgrids

Software	Time Resolution	DER Modeling Capability	Main Application
HOMER (HOMER n.d.)	1 minute to 1 hour	Limited	Techno-economic simulation
MDT (Eddy et al. 2020)	1 minute to hours	Limited	Microgrid decision support
GridLAB-D (GridLAB-D n.d.)	Subseconds to many years	Limited	Distribution automation and retail markets interaction
DER-CAM (Berkeley Lab n.d.)	1 minute to hours	Limited	Microgrid decision support
Opal-RT (OPAL-RT n.d.)	µs to seconds	Yes	Real-time simulation
REopt® (Mishra et al. 2021)	1 minute to hours	Limited	Energy systems optimization
PSCAD	µs to seconds	Robust	Electromagnetic transient simulation
MATLAB/Simulink	µs to seconds	Yes	Microgrid control
RTDS	µs to seconds	Yes	Real-time simulation
SynerGi	Seconds to minutes	Limited	Power distribution system planning, reliability
OpenDSS	Seconds to minutes	Limited	Power distribution system planning, reliability
CYME	Subseconds to longer time resolution	Yes	Power network planning and operation
ASPEN	Subseconds to longer time resolution	Limited	Short-circuit and relay coordination

Many factors determine which simulation platform will be most useful to achieve the simulation objective. One key factor in determining the appropriate simulation platform is the time steps needed to capture of the dynamics of interest. For example, if only steady-state voltage regulation of the microgrid is needed for the analysis, phasor domain simulation could be of great use in terms of faster simulation time and the accommodation of a large network model; however, a fault analysis might be needed to capture the dynamics that happen in milliseconds.

In that case, an electromagnetic transient domain simulation might be of interest. With increasing levels of adoption of solar and wind power, there could be many cases where it is beneficial to capture the dynamics of power electronics-based converters used in the DERs. In such cases, if power electronics switching-level dynamics are of interest, the simulation platform should have the capability to simulate systems with very small time steps (e.g., μs). Table 5 presents examples of how different tools and simulation platforms are used in a hypothetical analysis of system restoration and recovery using microgrids.

Table 5. Analysis Needed for System Restoration and Recovery Using Microgrids

Objective	Description	Tools
Contingency analysis	Analysis to determine system resiliency if any system component (e.g., an important line) fails	PSCAD CYME OpenDSS RTDS Opal-RT
Fault contribution and protection studies	Response of DERs to fault and analysis of the protection system in the microgrid	ASPEN RTDS Opal-RT
Cyber threat	Analysis of the control and communications reliance against a cyber threat	Mixed (Mishra et al. 2021)
Training and scenario analysis	Real-time simulation for operator training, tuning of machine learning-based algorithms, and scenario analysis	RTDS Opal-RT
Black-start capability	Analysis on the capability of the microgrid and associated generators as well as grid-forming inverters to initiate power delivery without the presence of bulk grid support	PSCAD MATLAB/Simulink

There are several obstacles to performing analysis on utility microgrids, such as the uncertainty of applicable technologies and relevant modeling data. These shortcomings can be summarized as follows:

1. The presence of only power electronics-based energy sources (i.e., the presence of no synchronous generators) in the microgrid might create some modeling issues with some of the most popular simulation tools used for dynamic simulations of microgrids.
2. There is no standardized microgrid control architecture
3. There is not enough information on the installed and projected DER models, including grid-following and grid-forming DERs.
4. There is not enough information related to protection and power quality studies.

5 Recommended Analysis for Future Effort

Implementing microgrids across Puerto Rico to provide reliability and resiliency against future potential disasters is not trivial. It becomes more challenging because there are many technologies and models in the market to adopt. Some are mature, and the industry has substantial experience with them; examples include grid-following inverters, such as those in rooftop PV systems. On the other hand, some technologies, such as grid-forming inverters, have huge potential in the electric energy network, but the industry needs more experience with them. To meet the energy requirements of Puerto Rico, comprehensive analyses are needed to implement robust microgrids considering both technologies and regulations that are currently available as well as potential future technologies and resources. This section summarizes previous findings on microgrid implementation in Puerto Rico and proposes needed analyses.

5.1 Gaps as They Relate to Implementing Microgrids

This team's previous recommendations were published in a report (Narang, et al. 2021). These are summarized in Table 6.

Table 6. Gaps as They Relate to Implementing Microgrids Identified in Previous Effort

Gaps/Issues	Opportunities/Solutions
Unclear value from DERs (intentional islands are a subset value proposition of DERs)	Puerto Rico stakeholders should consider developing a framework for estimating the optimal mix of renewable energy that should be provided by DERs (connected to microgrids) and how much should be connected to the bulk grid (connected to minigrids).
Need for additional engineering studies and analysis on microgrid integration and operation	Puerto Rico stakeholders should consider planning, coordination, communications, and control strategies for the numerous islanded systems potentially expected.
Lack of guidance and requirements for DER grid support	Requirements should be reviewed to determine whether new guidance is appropriate or required for DER operations under grid normal and abnormal conditions, including islanded mode.
Lack of guidance and requirements for improved interoperability	Requirements should be reviewed to determine whether new interoperability guidance is appropriate or required. Special note should be given to long-term energy policy and market goals. Determine communications, monitoring, and control strategy for DERs in the context of grid services, customer participation, aggregation, community solar, and various stakeholders.
Need for additional study for peer-to-peer energy exchange and microgrids	To enable broader participation from individuals and to spur market engagement, Puerto Rico stakeholders should consider exploring a regulatory and technical framework for peer-to-peer energy exchanges. This could be of benefit under many grid conditions: normal, emergency, and recovery.
Lack of firsthand knowledge and experience with inverter-based DER capabilities	Conduct studies and pilots designed to improve DER integration.
Need for additional guidance on testing, verification, and commissioning	Guidance for testing, verification of performance requirements, and commissioning should be determined and seems to be lacking in existing publications.
Need for commercial control and coordination solutions for nested multi-customer microgrids	Though several companies in the market offer solutions for microgrid control, the industry has very limited experience with commercial solutions for nested multi-customer microgrids. Puerto Rico stakeholders should consider exploring available commercial solutions for nested microgrid controls if the proposed concept of microgrids within minigrids is found to be feasible.

Given the types of intentional islands expected (as shown Table 7) the approach and analysis for minigrid and microgrid deployments should be formalized. Considerations for these activities are summarized in the following subsections.

Table 7. Types of Intentional Islands Expected

Voltage Level	Intentional Island Type	Expected Duration of Sustained Operation of Intentional Islands
Transmission: 230 kV, 115 kV **Subtransmission:** 38 kV	Minigrid/microgrid	<10 days
		<30 days
		>1 month
		Approx. several months
Distribution:	Personal microgrid	Approx. several days to several months?
	Cooperative microgrid	
	Third-party microgrid	

5.2 Additional Engineering Studies and Analysis

An overview of additional engineering studies and analysis as indicated in Table 5 on microgrid integration and operation is presented as follows:

1. **Stability**: This is crucial for a system with low inertia, e.g., a minigrid. Power electronics-based DERs do not have Newtonian/mechanical inertia to stabilize the system; however, power electronics-based DERs are very robust and fast. The careful selection of the smart features of DERs might help stabilize the microgrid under disturbances (Hoke et al. 2021).
   Study method: Stability analyses need a detailed model of the network and the network components. These studies also need to consider grid-forming inverters and energy storage systems (Reilly et al. 2021). The relevant simulation software that can be used, e.g., PSCAD, MATLAB, should be capable of capturing the dynamic interactions of the important network components.

2. **Performance under abnormal conditions**: Studies are needed on the required fault ride-through and tripping behavior of DERs under abnormal grid conditions. Additionally, technical evaluations are required to answer the question: What are the needed capabilities and resources to provide a black start in case of an extreme disturbance? Interconnection requirements for individual DERs as well as microgrids to other microgrids (parallel operation) or minigrids (to provide better resiliency).
   Study method: Various research organizations, including NREL, have done much research on this topic (Hanif et al. 2021; Giraldez et al. 2017; Prabakar et al. 2018; Wang, Cissee, and Brown 2017). The efficient process to perform analysis regarding the fault ride-through and tripping behavior of DERs under abnormal grid conditions will depend on many factors, including the complexity of the network and the modeling requirement of the DERs. To provide a high-level overview of the necessary tools and relevant analyses, however, the following might be needed: Voltage regulation performance and power balance analysis can be done with OpenDSS; black-start transient capability can be evaluated with MATLAB/Simulink or PSCAD; and transmission-and-distribution co-simulation using the Hierarchical Engine for Large-Scale Infrastructure Co-Simulation

(HELICS) can provide a better understanding for minigrid scenarios considering both the transmission and distribution networks.

3. **Power balance**: With high penetrations of renewable DERs, instantaneous power might see significant imbalances between renewable generation and demand. Energy storage systems or other assets are needed to address this. The parallel operation of microgrids might be useful to mitigate some power imbalances (Denholm et al. 2021).
   Study method: Evaluations of different solutions using optimization for load and generation are needed. Steady-state power flow solutions can provide an idea about the power balance under different loading and generation profiles. Faster simulations, e.g., transient simulation, might be needed to characterize the performance that can support the grid during instantaneous power imbalances.

4. **Protection and grounding**: The fault response of power electronics-based DERs is different than that of traditional synchronous machines (Mahmud, Hoke, and Narang 2020; Mahmud, Narang, and Hoke 2021). The presence of an energy source in the distribution network also changes the network response expectations from the point of view of traditional protection systems.
   Study method: DER fault response and the presence of DERs need to be considered for protection systems planning and design.

5. **Power quality**: When tested in isolation, most commercial power electronics-based DERs, including grid-forming and grid-following inverters, exhibit excellent performance in terms of power quality. Relevant standards, e.g., IEEE Std 1547-2018, recommend containing the harmonic contamination below a certain threshold. When integrated with many DERs with a diverse range of control mechanisms and operation objectives, however, the DERs and network might interact with each other, resulting in power quality issues.
   Study method: Key components of power quality analysis are the measurement and monitoring of the power quality issues in the network, the identification of the root cause of the problem, and the provision of corrective/preventive measures to mitigate the problem.

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Appendix A: Definition of Important Terms

Microgrid: A microgrid is “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode” (Ton and Smith 2012).

Utility microgrid: A utility microgrid can be any microgrid for which the utility (e.g., distribution system operator) has the access and capability to use the generation assets in that microgrid.

Behind the meter: Behind the meter “(BTM) refers to electrical equipment and technologies that are interconnected on the customer’s side of the electric meter. Customer-sited distributed energy resources (DERs) such as rooftop solar PV arrays are one of the most common examples of BTM resources” (CPUC 2021).

Energy management system: An energy management system is “an automated system that collects measurement data, monitors the performance of the transmission system and in some cases primary distribution substations, and controls and optimizes system operation through optimizations and contingency analysis” (Ding et al. 2022).

Distributed energy resources: Distributed energy resources “(DERs) include distributed renewable generation resources, energy efficiency, energy storage, electric vehicles, time variant and dynamic rates, flexible load management, and demand response technologies. Most DERs are connected to the distribution grid behind the customer’s meter (BTM), and some are connected in front of the customer’s meter (FTM)” (CPUC 2021).

Interoperability: Interoperability is “the capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information securely and effectively” (CPUC 2021).

Resiliency: Resiliency is “the ability of the grid to resist failure, reduce the magnitude and/or duration of disruptive events to the grid, and recover from disruptive events” (CPUC 2021).