INTEGRACIÓN EFICIENTE DE
ENERGÍAS RENOVABLES VARIABLES
AL SISTEMA COLOMBIANO

PROVIDENCIA ISLAND WHITE PAPERS: POTENTIAL FOR INCREASING THE PHYSICAL RESILIENCE OF DISTRIBUTED ENERGY RESOURCES

Michael Ingram

USAID
FROM THE AMERICAN PEOPLE

NREL
Transforming ENERGY

INTEGRACIÓN EFICIENTE DE ENERGÍAS RENOVABLES VARIABLES AL SISTEMA COLOMBIANO

Author
Michael Ingram
National Renewable Energy Laboratory

December 2022

Prepared by

NREL

NOTICE
This work was authored, in part, by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the United States Agency for International Development (USAID) under Contract No. IAG-17-2050. The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof, including USAID.

NREL/TP-5D00-83563 | December 2022

Front cover images, left to right:
Shutterstock 11027570a,
Dennis Shroeder, NREL 58003

INTEGRACIÓN EFICIENTE DE ENERGÍAS RENOVABLES VARIABLES AL SISTEMA COLOMBIANO

On November 16, 2020, Hurricane Iota struck Providencia Island. Home to fewer than 7,000 residents, the Category 5 hurricane damaged over 95 percent of Providencia Island's energy and road infrastructure, property, and motor vehicles, causing its electricity grid to collapse overnight. The Colombian government took immediate action to address this catastrophe, and within 100 days, almost all electricity was restored. However, a realization emerged: while Providencia previously relied entirely on fossil fuels, Hurricane Iota created an opportunity for the island to rebuild a more sustainable and resilient energy infrastructure that could better withstand the ever-growing effects of climate change.

Together with USAID, ECOPETROL, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), the Scaling Up Renewable Energy (SURE) program, the United States Energy Association (USEA), and Colombia Inteligente, (then) President Iván Duque Márquez announced a working group in Colombia's Ministry of Mines and Energy. The working group conducted high-level technical analyses and workshops which led to the development of these four White Papers. The Providencia Island White Papers are a set of 4 papers designed to guide Providencia Island's sustainable energy transition. However, each paper also serves as a valuable resource for any islanded power system looking to transition to renewable energy sources.

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Disclaimer

Disclaimer: The following information is adapted from a technical report developed under a U.S. Department of Energy project supporting the long-term recovery of Puerto Rico's electric power grid after hurricanes Irma and Maria devastated the island in 2017. The content is a pared-down version of the full report highlighting sections most relevant to the Providencia Island context and augmenting with specific references to Colombia. The full original document is available online:

Narang, David, Michael Ingram, Xiangkun Li, Sherry Stout, Eliza Hotchkiss, Akanksha Bhat, Samanvitha Murthy, Jeremy Keen, Chinmay Shah, Murali Baggu, and Aadil Latif. 2021. *Considerations for Distributed Energy Resource Integration in Puerto Rico: DOE Multi-Lab Grid Modeling Support for Puerto Rico; Analytical Support for Interconnection and IEEE Std 1547-2018 National Renewable Energy Laboratory (Task 3.0)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-77127. https://www.nrel.gov/docs/fy21osti/77127.pdf.

Acknowledgments

The authors would like to thank Alison Holm from NREL and Ricardo Ramirez from Tetra Tech Scaling Up Renewable Energy (SURE) Program for their review and support of this work. The authors would additionally like to acknowledge the support from Thomas Black from USAID, Lina Marcela Vega, Luis Julián Zuluaga, and Alejandro Cardona Vélez, from the Colombian Ministry of Mines and Energy, Jairo Hernán Duarte from Ecopetrol, and Juan David Molina from Colombia Inteligente This report is available through the USAID Colombia Mission Buy-In under the USAID-NREL Partnership.

List of Acronyms

NEMA	National Electrical Manufacturers Association
PV	photovoltaic

Table of Contents

List of Figures

List of Tables

1 Introduction

This section corresponds to Section 5 of the *Considerations for Distributed Energy Resource Integration in Puerto Rico* report, beginning on page 52. Primary section authors: Sherry Stout, Eliza Hotchkiss, and Michael Ingram.

On-site energy generation can be a resilience strategy for vulnerable power systems if designed appropriately. Using technologies such as solar photovoltaics (PV) to provide power to a site during a large-scale grid outage can be an effective solution for enhancing resilience. Resilience in this context is typically measured by the ability of a system or organization to reduce the impacts of threats and vulnerabilities.

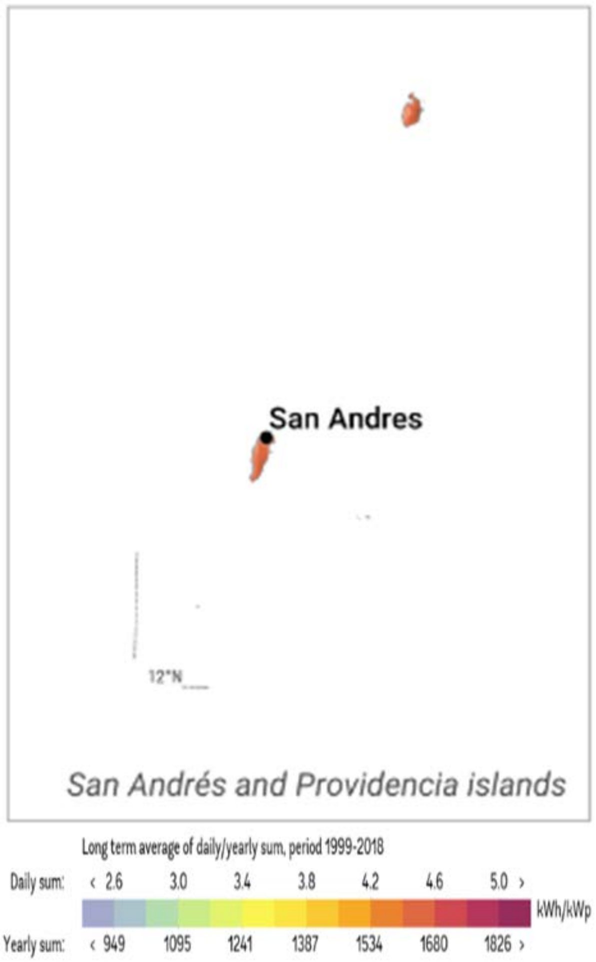

Figure 1. PV power potential

Source: 2019 The World Bank; Global Solar Atlas 2.0

Providencia Island has a valuable solar resource, making PV a viable renewable energy technology for on-site energy generation (**Figure 1**). More resilient systems should include well-designed PV panels (e.g., consider wind-loading standards) with secure racking systems, backup energy storage (e.g., battery systems), and islanding controls—including related policy—to disconnect from the grid and operate in a safe and independent mode.

Solar water heating systems can also be used to supply hot water to building occupants when the grid system is down. Both technologies can reduce operational costs during typical conditions while providing on-site generation (or offset, in the case of solar water heating) during disruptive events.

2 Experience in Puerto Rico After Hurricane Maria

The U.S. Federal Emergency Management Agency *Mitigation Assessment Team Report* found that in Puerto Rico, most PV systems installed prior to Hurricane María were permitted—a requirement for interconnection with the grid system; however, codes only required systems costing more than $6,000 to have permits and therefore the majority did not require inspection upon installation. This lack of inspections and permits created a network of installations of unknown quality and construction, thus increasing overall system risk during a major weather or geologic event (FEMA 2018). The *Mitigation Assessment Team Report* also found that there was a lack of guidance for designing and siting solar technologies, apart from the interconnection of PV. As noted, "this lack of guidance is especially noteworthy given that local permitting does not review or inspect PV panels or solar heating system installations" (FEMA 2018). Two major challenges with PV during Hurricane María included panels being struck by wind-borne debris (e.g., an antennae or tower falling over and damaging PV panels); and racking and through-bolting not being installed properly, which caused the panels to loosen under dynamic wind loads and separate from the racking system, thus becoming wind-borne debris (see Figure 2). Note that in post-storm conditions, the ability to generate power from on-site generation is tied to both the robustness of the technology and the policy that allows or disallows operation in intentional-islanded mode.

Figure 2. Broken solar panels in Humacao

Photo by Erika P. Rodriguez (Gallucci 2018)

3 Resilient Physical Design and Safety Codes

There are many benefits to incorporating safe on-site generation systems. During future storms, resilient on-site solar and storage would allow occupants to shelter in place. If rooftop systems are designed and installed safely and securely, and if they are paired with energy storage systems and inverters that can island from the larger grid, the impacts related to widespread power outages can be minimized. On-site energy generation and storage, along with strategically placed microgrids, have the potential to reduce the impact on Providencia Island residents and reduce economic losses as well.

Appropriate siting and design must be included if PV systems are to provide power in post-storm scenarios. FEMA noted that "the performance of PV power systems varied depending on the type of anchoring system and the type of clamping system connecting the PV panels to the aluminum frame" (FEMA 2018).

A potential benchmark for Providencia Island, the 2018 Puerto Rico building codes mandate that "wind loads on every building or structure shall be determined in accordance with Chapters 26 to 31 of American Society of Civil Engineers (ASCE) 7" (Puerto Rico Permits Management Office 2018). This document incorporates many standards for building codes in the United States, and the ASCE publication on "*Minimum Design Loads and Associated Criteria for Buildings and Other Structures*" (ASCE 2016) describes the means for determining dead, live, soil, flood, tsunami, snow, rain, atmospheric ice, earthquake, and wind loads and their combinations for general structural design (ASCE 2016). The inclusion of ASCE 7-16 is a significant step forward in enhancing the safe siting of rooftop PV and thermal systems because it includes guidance for wind loading on building-mounted arrays (ASCE 2016). There is no current ASCE design standard for ground-mounted PV; however, there are standards in other countries (e.g., Japan and Taiwan) that might be useful examples for resilience.[1]

To maximize the survivability of systems under disaster conditions, roof-mounted and ground-mounted solar technologies can be designed to static wind-loading conditions as well as dynamic wind-loading conditions. The ASCE codes could be reviewed, to determine whether these standards are suitable and to provide the tools for designers and installers to verify that installation techniques are adequate, and the workforce should be trained on safe installation practices and verification during commissioning of the system.

Studies were conducted following Hurricane María to determine the points of failure in PV systems. In reviews conducted by the National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, and the Rocky Mountain Institute, there were six technological categories of failure:

1. PV module frame and laminate
2. Module connection hardware
3. Structural racking member
4. Structural racking connections
5. Racking foundations

---

[1] Testing in Taiwan's research institute, ITRI, uses dynamic wind-loading test criteria of 5,000 Pa for 200 cycles to simulate the strongest possible typhoon, which is more than Level 17 on the Beaufort scale. With less than 0.29% power degradation, a Japanese test module has been shown to survive in wind speeds faster than 220 km/h (130m/h) when mounted on an equally secure mounting system.

6. Electrical balance of systems.[2]

Each category is summarized in the following subsections as lessons learned for resilient siting considerations.

3.1 PV Module Frame and Laminate

PV frame and laminate failures following Hurricane María were all related to the panel itself tearing out of the frame or to impact damage from flying debris (Figure 3). To limit the failure of the frame and panels, project developers should ensure that the system design meets wind-loading and pressure specifications. Underwriters Laboratories 1703 (UL 2002) is the standard for flat-plate PV modules and panels and includes information on static loads. System designers should ensure that modules and panels meet static load requirements specific to each deployment site—that is, each location for the possible deployment of PV should be assessed for local topography and wind conditions before choosing the equipment type. Because the standard accounts for only static loading, it might be useful to incorporate topography and dynamic wind loading into a model of a planned solar array. However, this option might not be viable in all cases because of financial or timing constraints.

Figure 3. PV module torn from racking, lying face down, shows laminate failure

Photo by Eliza Hotchkiss, NREL

Minimizing debris can increase system survivability. This includes regular maintenance of vegetation at or near the site, as well as removal of any small equipment that is not firmly secured. Additionally, pre-hurricane preparations could include the removal of any objects of concern that might become airborne during storm conditions. Siting PV systems outside of areas of impact can also be useful. In hurricane-prone areas, additional siting considerations related to flying debris can be integrated into initial planning at system introduction.

---

[2] For the full report on failure modes and solutions for ground-mounted PV, see *Solar Under Storm: Select Best Practices for Resilient Ground-Mount PV systems with Solar Exposure* (Burgess and Goodman 2018), https://rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf.

3.2 PV Module Connection Hardware

Another mode of failure observed after Hurricane María involves the hardware that attaches the PV modules to the racking. Hardware failure occurs through loosening of bolts, rotation of clamps, and a subsequent cascading failure of hardware. Loosening of bolts can occur in any location with rapid pressure or temperature swings or because of vibrations in the system. Specifying bolt-locking hardware could be included in specifications for installations. Additionally, pre-hurricane preparation could include torque checks; however, this is labor-intensive and will require diligent maintenance and verification processes.

In Puerto Rico, hardware failure in Hurricane María was noted to be caused by undersized racking systems compared to load (Robinson, Walker, and Fu 2018). Similar to PV model frames, hardware should be specified based on the local conditions expected at each PV array site. Note that large ground-mounted arrays might have varying conditions across the site based on topography. Hardware should be sized based on maximum expected load on the array.

Failure of one hardware connection can, in some cases, cause cascading failures that result in the loss of multiple panels (see Figure 4 for an example of hardware failure).

Figure 4. Examples of failure of clamp (top left of photo) causing attached modules to overturn

Source: Robinson, Walker, and Fu 2018

In Puerto Rico, this was particularly true of T-clamps that rotated with the loss of one clamp and subsequently allowed the loss of multiple modules. The studies following the hurricane recommended that modules be through-bolted, rather than T-clamped, to mitigate this vulnerability (Robinson, Walker, and Fu 2018; Burgess and Goodman 2018). Alternatively, clamps that do not rotate, and allow the freeing of modules subsequent to a single failure, could be employed.

3.3 Structural Racking Member

Structural racking members were another common point of failure of PV arrays during Hurricane María. These failures largely resulted from inadequate materials and design for appropriate wind loads. ASCE 7-16 details wind loads for structural design. This code was designed for buildings, but could also be employed for any ground structure such as a utility-scale PV array. Additionally, PV arrays should be analyzed for their interference with airflow. It was noted that some solar power plants experienced dynamic (mechanical) excitation when natural frequencies matched vortex-shedding frequencies.

Modeling these mechanical frequencies for each solar power plant should reduce racking failures associated with dynamic amplification.[3]

Finally, solar arrays built on tracking systems had a high rate of failure because of torsion on the torque tubes. Dynamic wind modeling of each tracking array in hurricane zones could be considered—if tracking must be employed at all at the latitude. The high failure rates of tracking arrays might necessitate the use of fixed-tilt solar arrays in areas that have a high likelihood of Category 4 and 5 hurricanes. An analysis could also be conducted to determine whether tracking systems are cost-effective in hurricane-prone regions. Typically, tracking systems are used to track the sun's progress across the sky from dawn to dusk to allow panels to absorb as much solar energy as possible. In locations such as the Caribbean, which are close to the equator, the tilt angle of the panels is less severe than in northern locations, such as Alaska. This means that the tilt angle in Puerto Rico could be close to 0°, minimizing the need for tracking and maximizing efficiency.

3.4 Structural Racking Connections

Like the module mounting bolts, structural racking bolts loosened during Hurricane María. Connections should include specifications for bolt-locking mechanisms to prevent this from occurring. Other modes of failure included shearing of bolts and self-tapping screws. In both cases, hardware specifications should be updated based on the (1) expected wind-loading conditions, (2) 25–30-year life span of the array (or replaced at specified intervals), and (3) expected vibration during storm events. Preventing shear of the connections will aid in survivability of the entire solar power plant by also reducing airborne debris during a major storm.

Figure 5. Examples of hardware failure

SOURCE: Robinson, Walker, and Fu (2018)

3.5 Racking Foundations

Racking foundations of solar arrays failed during Hurricane María for several reasons, including foundational structure failure, overturning of foundation posts, erosion, and corrosion. Instances of foundation structural failure might be reduced only through site-specific geotechnical studies and mitigation. Geotechnical studies should be performed on foundations for utility-scale arrays located in hurricane zones to reduce the risk of failure. Researching the geologic conditions prior to system design will be useful to ensure more stable system design. The overturning of foundation posts might be mitigated through reducing the angle of panels, thus reducing the momentum on the system. Erosion at or

---

[3] More information is available from the Solar Energy Industries Association: www.seia.org/sites/default/files/Cain%20and%20Banks%20Utility%20Scale%20Wind%20Presentation%202015%20SEAOC%20Convention.pdf.

near foundations should be reduced through standard hydrologic/runoff modeling and subsequent drainage planning. Site-specific drainage plans should be created based on local topography and site conditions. Finally, corrosion could be addressed through additional galvanization of components. This might be cost-prohibitive, so galvanization could be limited to the most critical components.

3.6 Electrical Balance of Systems

Finally, additional failures were caused through losses of the electrical balance of systems, including wiring, inverters, and combiner boxes. Wire pullout could be mitigated by specifying torque at points of coupling. Additionally, pre-hurricane preparation should include checks for appropriate torque on connections. Wires should also be regularly checked for sheathing condition and sagging. In both cases, these conditions caused failure during Hurricane María. Finally, combiner boxes and inverters should be fully weather sealed according to the National Electrical Manufacturers Association (NEMA) 4 standards against significant rain events and should be properly secured (NEMA 2019).[4] Pre-hurricane preparation should include checks of weather seals and locking mechanisms to prevent water intrusion.

---

[4] NEMA enclosure rating minimally 4, 4X or equivalent, recommended; 6 or 6P might be specified for certain facilities. NEMA 4/4X enclosures are “watertight”; NEMA 6/6P are capable of withstanding submergence.

4 Distributed Energy Resource Design Recommendations and Best Practices

4.1 Roof-Mount

Roof-mounted distributed energy resources must consider the loads on both the PV array and the rooftop. As the *New York Solar Guidebook for Local Government* notes, "Solar electric contractors are responsible for ensuring that their installations do not jeopardize the structural integrity of the buildings upon which they are mounted. Due to their large surface areas, PV arrays can catch updrafts and create significant amounts of uplift during windy conditions" (NY-Sun 2019). As such, rooftop systems should be assessed for location-specific wind loads. In the case of Puerto Rico, Category 5 hurricane winds should be assumed possible. Wind loading on rooftop systems depend on the topography of the roof as well as the array design. Modules located high above the roof surface, at the ridge of the roof, or overhanging the roof tend to be subject to greater wind forces. The prevailing direction of wind could also be considered in siting roof-mounted arrays to minimize loads. The permitting process might require review of these loads under the authority having jurisdiction inspection.[5], [6], [7]

The number and dispersed nature of roof-mounted systems makes pre-storm system preparation by qualified personnel particularly challenging. As such, constructing roof-mounted systems with more robust racking, bolting, and modules could aid in survivability without increasing maintenance checks. For example, systems installed with wedge-lock hardware, rather than split washers and nylon nuts, tend to perform better under vibration conditions associated with hurricanes (DOE 2018). Systems might also be powered down to ensure that damage from possible water infiltration is kept to a minimum. Systems should be allowed time to dry after major storms. Optimally, system components would be cleaned and tested by a qualified installer in a post-storm environment; however, the nature of small DERs might make this infeasible.

4.2 Ground-Mount

Similar to roof-mounted systems, ground-mounted PV arrays should be designed for maximum expected wind conditions. The ground topography has greater influence on ground-mounted systems and should be evaluated on a site-by-site basis. Modules in hurricane-prone areas should replace clamping with through-bolting to minimize module loss. These fasteners should be approved for use in coastal areas where corrosion is expected. Other site considerations include design of appropriate water drainage and avoidance of low-lying or flood-prone areas. It has been noted that perimeter fences can be designed to calm winds and reduce damage to solar arrays. These fences might also aid in reducing debris impacts to the array during a storm.

Ground-mounted arrays might have dedicated operation-and-maintenance staff that make pre-storm preparations more feasible. Pre-storm checks should include balance-of-system checks to ensure that

---

[5] An example checklist, from the New York State Energy Research and Development Authority, can be found at https://www.nyserda.ny.gov/All-Programs/Programs/NY-Sun/Communities-and-Local-Governments/Solar-Guidebook-for-Local-Governments.

[6] An example of solar array checks, including wind uplift, from the Los Angeles area can be found at http://dpw.lacounty.gov/bsd/lib/fp/Small%20Residential%20Rooftop%20Solar%20Energy%20Systems/BCM%206807%20Article%201%20-%20Expedited%20Permitting%20Process%20for%20Small%20Residential%20Rooftop%20Solar%20Energy%20Systems%20COMPLETE%20POLICY%2004-04-16.pdf.

[7] California expedites solar permitting that meets structural criteria; see page 70 of the California Solar Permitting Guidebook: https://energycenter.org/sites/default/files/docs/nav/policy/research-and-reports/California_Solar_Permitting_Guidebook_2015.pdf.

connections are appropriately torqued, confirming the site is cleaned of potential debris that could damage the system, and guaranteeing the system is powered down to minimize damage. Post-storm maintenance should include drying components, testing for faults, and replacing damaged equipment (DOE 2018).

Table 1. Summary of Storm-Hardening Recommendations

CATEGORY	GAP OR ISSUE	OPPORTUNITY OR SOLUTION
On-site energy generation	Incorporate codes for resilient siting of solar arrays, including wind-loading requirements, racking specifications, and site modeling (for large arrays only)	Review solar installation requirements to ensure that roof-mounted and ground-mounted solar technologies are designed to static wind-loading conditions, as well as dynamic wind-loading conditions.
	Verify bolting torque, appropriately protect balance of systems, and limit potential debris	Field verification could be conducted on large systems to ensure safe installation practices.
	Review site characteristics that might increase vulnerabilities during storm events—particularly after significant rainfall or flooding	Consider conducting geotechnical studies on utility-scale array foundations located in hurricane zones.
Outreach	Develop workforce engagement accompanying updated or revised site requirements, potential codes, and best practices	Workforce development strategies could enhance implementation and build knowledge of secure PV installation and building code designs and enforcement.
Emergency preparedness	Extend traditional storm preparation to include generation resource	Checklists for pre-hurricane preparation could be developed to secure and prepare solar arrays for coming storms. These checklists would include items such as removal of potential debris, checks to ensure adequate weather sealing on combiner boxes and inverters, and torque checks for all connections and bolts.

5 Next Steps

Roof-mounted, small ground-mounted, and utility-scale solar technologies could be designed for static wind-loading conditions, as well as dynamic wind-loading conditions. A review of the codes could determine whether these standards are currently being required and provide the tools for designers and installers to verify that installation techniques are adequate, and the workforce should be trained on safe installation practices and verification during commissioning of the system. Field verification could be conducted on every large ground-mounted system to ensure safe installation practices.

Geotechnical studies could be performed on foundations for utility-scale arrays located in hurricane zones. Minimally, researching the geologic conditions prior to system design will help ensure more stable system design. Further, site-specific drainage plans should be created based on local topography and site conditions. Soil stability should be studied under a variety of conditions. In Puerto Rico, multiple workshop participants noted that Hurricane Irma left soils saturated prior to Hurricane María landfall, contributing to overall instability in foundations.

Engagement with Colombian agencies on the strategies for resilience might prove useful. Ultimately, implementing new resilience codes will rely on support from numerous stakeholders. The public must be made aware of the new codes—and the need for them. The public should also be consulted on customer fees related to enforcing codes. Codes should be made easily accessible to the public in both Spanish and English, and summary codes might also be made available for general consumption.

Workforce development and training is likely needed. Agencies having authority will likely need to be trained on resilience standards and how to ensure that structures are compliant.

References

American Society of Civil Engineers (ASCE). 2016. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7-16). Reston, VA. https://www.asce.org/asce-7/.

Burgess, Christopher, and Joseph Goodman. 2018. *Solar Under Storm: Select Best Practices for Resilient Ground-Mount PV Systems with Hurricane Exposure*. Boulder, CO: Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf.

Federal Emergency Management Agency (FEMA). 2018. Mitigation Assessment Team Report Hurricanes Irma and Maria in Puerto Rico—Building Performance Observations, Recommendations, and Technical Guidance (FEMA P-2020). Washington, D.C. https://www.fema.gov/media-library/assets/documents/173789.

Gallucci, Maria (2018). “Rebuilding Puerto Rico’s Power Grid: The Inside Story.” IEEE SPECTRUM. https://spectrum.ieee.org/energy/policy/rebuilding-puerto-ricos-power-grid-the-inside-story

National Electrical Manufacturers Association (NEMA). 2019. *Evaluating Water-Damaged Electrical Equipment* (Document ID: 100547; NEMA GD 1-2019). Rosslyn, VA. https://www.nema.org/Standards/SecureDocuments/NEMA%20GD%201-2019%20Evaluating-Water%20Damaged-Electrical-Equipment-Guide.pdf.

New York State of Opportunity (NY-Sun). 2019. *New York Solar Guidebook for Local Governments*. New York, NY. https://www.nyserda.ny.gov/All%20Programs/Programs/Clean%20Energy%20Siting/Solar%20Guidebook.

Puerto Rico Permits Management Office. 2018. “Puerto Rico Codes 2018.” Department of Economic Development and Commerce, November 15, 2018.

Robinson, Gerald, Andy Walker, and Ran Fu. 2018. Solar Array Inspection, Failure Analysis, Specifications, and Repair Scopes of Work Caribbean Region Post 2017 Hurricane Season: Hurricanes Irma and Maria. Golden, CO.

Underwriters Laboratory (UL). 2002. Standard for Flat-Plate Photovoltaic Modules and Panels, (UL 1703).

INTEGRACIÓN EFICIENTE DE ENERGÍAS RENOVABLES VARIABLES AL SISTEMA COLOMBIANO

This work was authored, in part, by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the United States Agency for International Development (USAID) under Contract No. IAG-17-2050. The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof, including USAID.

NREL/TP-5D00-83563 | December 2022
NREL prints on paper that contains recycled content.

USAID
FROM THE AMERICAN PEOPLE

NREL
Transforming ENERGY