White Paper

Creating a Resilient Grid in Puerto Rico

Hypotheses and Recommendations

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Shareables

- The main causes of Puerto Rico's lack of resiliency after Maria may lie in inflexible and poorly sited generation.
- Lessons learned from other areas in the US on updating infrastructure, creating flexibility, and introducing new resources may support a more resilient Puerto Rican grid.
- An existing cost-benefit framework should be applied to analyze upgrades to Puerto Rico's system.

Executive Summary

Following on the heels of Hurricane Irma, Hurricane Maria devastated the island of Puerto Rico and knocked out the entire power grid, demonstrating the island's extreme lack of energy infrastructure resiliency. The island's electric infrastructure will have to be rebuilt, and it will take months to restore power to customers. The current focus should be on restoring power to customers as soon as possible, but it is important to learn from what others have done to improve resiliency in order to minimize the impact of future events. By reviewing some potential reasons why the situation in Puerto Rico became so severe we can identify recommendations for improvements, and the framework around which decisions regarding resiliency should be made.

Hardening and Resiliency Mean?

Hardening means making assets less susceptible to damage. Hardened assets can withstand severe events without major damage. Resiliency refers to the ability to recover quickly from damage. Resilient systems can continue to operate despite damage or return to normal operation quickly.

Past Experiences

Over the past few years, best practices for grid resilience planning have emerged in the aftermath of other events such as Superstorm Sandy. These practices need to be applied based on site-specific conditions. The decision regarding what hardening and resiliency measures to implement vary by system and situation. ICF has participated in some notable exercises including the New York Planning Process in the aftermath of Sandy and hurricane planning efforts in Island settings like Guam and the Cayman Islands.

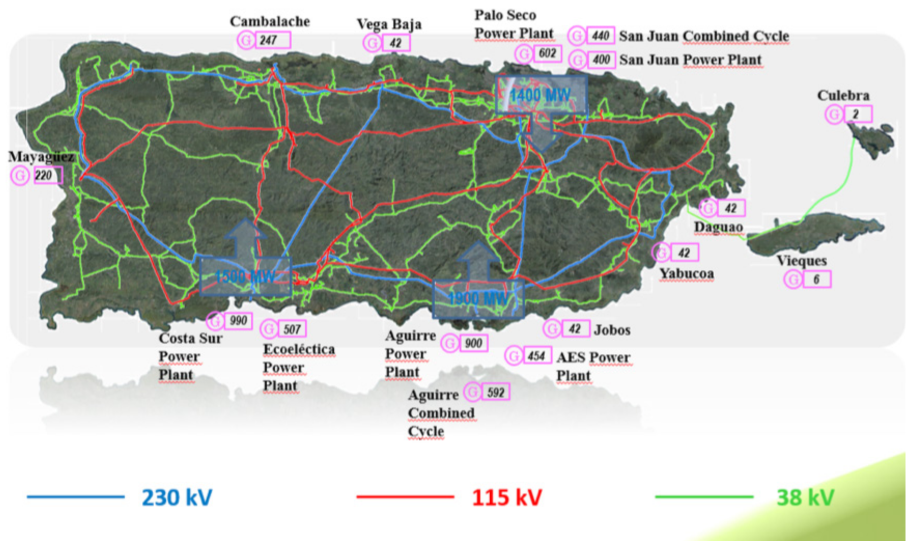
It is in the interest of customers to ensure electric infrastructure is not overly susceptible to these catastrophic events, but it is not practical to build a system that will never fail. Proper resiliency preparation allows planners and operators to minimize the duration of outages and return the system to service within minimal time. Given that the costs of hardening a grid rise exponentially as one tries to eliminate all outages, proper resiliency preparation requires that planners and operators balance the costs of resiliency with the anticipated costs of outages.

Puerto Rico's Vulnerabilities

Based on limited information on Maria, and other recent hurricanes, we present two tentative hypotheses for why the situation in Puerto Rico is extreme:

- **Current Generation** – Preliminary indications are that the generation fleet, while old, inefficient, and dependent upon high-cost fuel, survived the storm. However, inefficient plants need more fuel, and fuel delivery assurance may have been an issue. Relying upon fuel being shipped to the island, and then transported it across the island with ruined infrastructure may mean surviving generation may face fuel constraints.
- **Power Plant Siting** – Puerto Rico is an example of poor power plant siting from the perspective of resiliency. While most generators may have survived the storm, the transmission and distribution elements of the grid were devastated. Two-thirds of the power generation capacity is on the south side of the island whereas most of the load is on the north side (See Exhibit 1). Therefore, transmission lines need to cross the mountainous interior which has especially challenging terrain. This compounds the time needed to rebuild. A more resilient system would have a more balanced power plant siting with more capacity closer to the load.

EXHIBIT 1. PUERTO RICO'S ELECTRICAL SYSTEM



Source: Puerto Rico Electric Power Authority

Recommendations to Improve Resiliency

There are several resiliency measures taken by other US states and territories that could be implemented to improve the resiliency of the Puerto Rico's grid. The following is not intended as a comprehensive list but provides several examples of real-world measures that have been successful elsewhere.

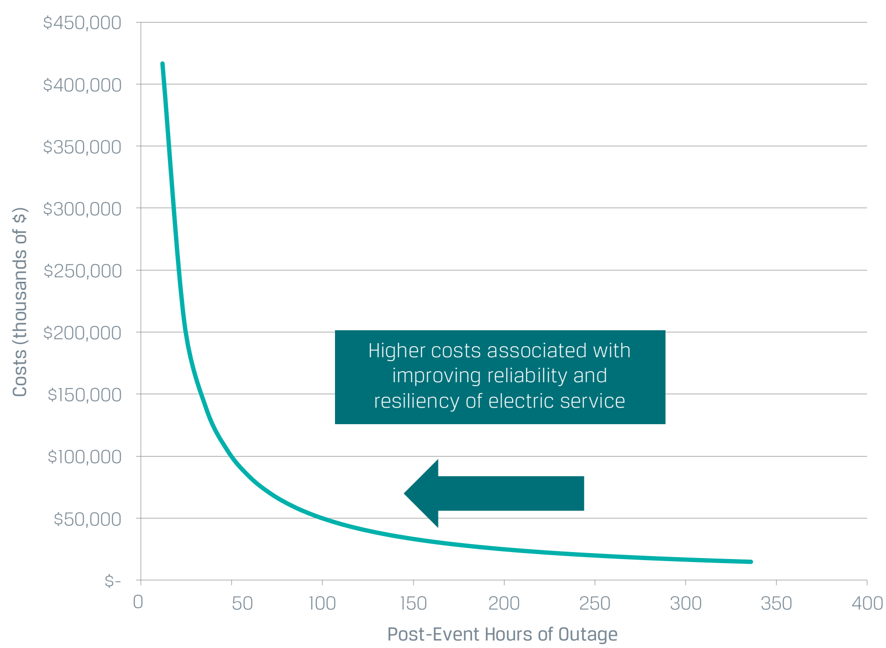
- **Improved Distribution Poles** – In Florida, the use of concrete or composite poles appears to have greatly decreased the number of poles destroyed or knocked down. This accelerates recovery by allowing crews to focus on rewiring. While the data is still being collected, these new poles appear to be more resilient. Improved distribution poles can be implemented where they will be effective in strengthening the Puerto Rico system and enhancing its resiliency.
- **Substation Monitoring and Remote Control** – Substation monitoring and remote control would allow them to be turned off in flooding situations and reduce damage due to flooding of energized equipment. Once the flooding has subsided, equipment can be returned to operation quickly. If not already implemented, this measure could provide more flexible control of the infrastructure on Puerto Rico and prevent equipment from being ruined while operating during a flooding situation.
- **Anti-Flooding Measures** – Some facilities could be moved to higher ground or otherwise protected against flooding.
- **Securing Fuel Supply** – The Puerto Rico system relies on oil and to a lesser extent natural gas and coal imports. A review is warranted regarding fuel delivery, the amount of onsite fuel and other factors. Potentially securing more fuel to be stored at any one time, and ensuring storage of fuel is secure against extreme events, could provide greater resiliency.

- **Undergrounding Transmission Infrastructure** – Selective undergrounding can improve resiliency but can be expensive. Placing electric infrastructure underground can protect it from hurricane-force winds and reduce damage compared to overhead equipment. However, underground cables are also more susceptible to damage from storm surge flooding and have higher repair times when they do fail. Therefore, undergrounding has to be done only in areas where it will be effective.
- **Ability to Finance** – Puerto Rico Electric Power Authority was in a form of bankruptcy going into the storm, and Puerto Rico was the largest example of default in public finance in the US. Most of the resiliency measures must be financed quickly to be included with the efforts to provide energy back to the population in a timely manner. A different approach in finance could be considered to avoid the current fiscal situation, and to ensure the financing of the endeavor is secured quickly.
- **Use of Renewable Resources** – Puerto Rico has an abundant supply of solar energy. Solar generation could diversify the fuel mix and reduce dependence on fossil fuel. It could also reduce the need for long transmission and distribution lines. Solutions sited at hospitals, schools, police stations and throughout Puerto Rican neighborhoods could lessen the impact on the lives of citizens during a grid failure like the one being experienced today. A review of the grid code and regulations around introducing distributed generation on the island's grid may be needed to ensure that this option is available to the public and critical sites. Adjustments to rate and incentives can be applied to encourage the adoption of renewable resources across the island or at specific locations to aid in this effort.
- **Modernize the Grid** – Puerto Rico should ensure that as it rebuilds, it takes into account major changes in the energy industry happening today. Enhanced monitoring and control systems will improve the flexibility of the power system and aid in fault detection, system reconfiguration, and disaster recovery. Increased adoption of distributed resources such as combined heat and power, storage, microgrids and electric vehicles will mean major changes for the system in the years to come. Developing a system that can accommodate these new elements in a way that boosts resiliency can be accomplished with incentives and regulations that drive their development where they are necessary.

What is the Right Level Of Resiliency?

Improving system resiliency comes at a cost. Benefits to customers should be weighed against the cost of proposed improvements. Consider Exhibit 2[1], the horizontal axis is a measure of the reliability of service to customers. This could be the number of hours of outage experienced after a major disruption, such as a hurricane event. The vertical axis shows the cost to hold the post-event outage to a defined level. The cost of system improvements is inversely proportional to the restoration time. The cost increases as the target duration of outages are lowered. Further, the curve is asymptotic, which shows that we can probably never attain 100 percent reliability at any cost.

EXHIBIT 2. COST-BENEFIT SCENARIO FOR RESILIENCY IMPROVEMENTS



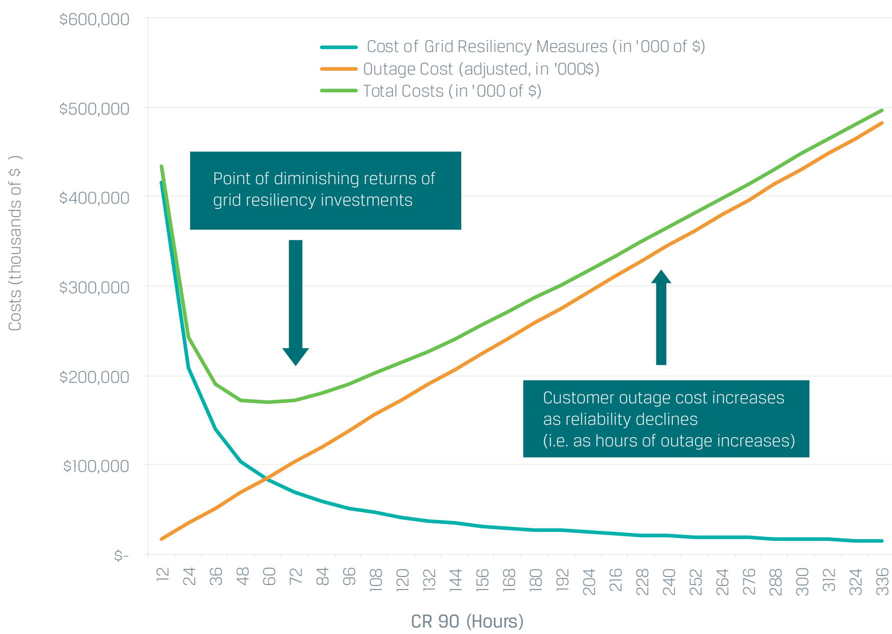
Source: ICF

[1] Cost estimates are for illustration only.

Exhibit 3 shows an approach to factor the cost of outages into the decision-making for resiliency investments.[2] It introduces the concept of "Customer Restoration-90" or CR-90 as a measure of reliability. CR-90 refers to the number of hours it takes from the start of an outage event to restore power to 90 percent of the customers of a given utility.[3] The utility can determine its own CR target or another measure of reliability, but it establishes a regulatory construct that allows for an objective assessment of proposed investments by all stakeholders. The cost to reduce the CR-90 target is also inversely proportional to the duration.

The cost of the loss of service to customers is also shown as roughly proportional to the duration of the outage. The optimal cost to achieve a given reliability target can be determined by combining the cost of improvements with the cost of outages. As illustrated in Exhibit 3, the utility would invest approximately $169 million a year in order to restore service to 90 percent of its customers within 65 hours of the start of the outage event.

EXHIBIT 3. COST OF OUTAGES SCENARIO



Source: ICF

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[2] Cost estimates are for illustration only

[3] The CR-90 is intended for high impact, low frequency events such as severe weather events, and it is not a substitute for standard utility reliability indices (e.g. CAIDI, SAIFI).

Cost Benefit Analysis of Resiliency

Assessment of resilience investments can also be based on standard cost-benefit analyses, although the conclusions will depend on the elements that are factored into the costs and benefits. In a 2005 study for FEMA, ICF analyzed and compared the costs and benefits of putting power lines underground as a means of enhancing reliability. Guam had recently been struck by a major typhoon, and FEMA wished to determine whether it would be cost-effective to upgrade the transmission system while repairing the network. The analysis took into account the frequency of storms, the severity and damage they caused, the number of customers likely to be affected, and the length of likely outages. The study found that putting lines underground was often economic if FEMA's traditional analysis was expanded to include the impact of storms and power outages on the economy of the island. Such a study would be instructive when determining what measures to implement to improve the resiliency in Puerto Rico and coastal areas in the mainland US.

Role of Regulators

Resiliency measures are extensive and expensive. Because they go beyond the utilities' mandate to ensure the reliability of the grid under limited contingency conditions (e.g. loss of two lines), regulators play a critical role in helping justify these measures. Regulators can facilitate a thorough and transparent review of available options, approve suitable options and allow for cost recovery for the utilities. This will be important in Puerto Rico given the financial situation of the utility prior to the devastation. New York regulators applied one of most comprehensive processes to assess resiliency following Superstorm Sandy in 2012. To ensure future storms will not have similarly devastating consequences Governor Cuomo established three commissions to improve the state's emergency preparedness and response capabilities, and the strength and resilience of the state's infrastructure. The commissions examined virtually every sector that was affected, including energy, fuel, transportation, water, health, and education. The recommendations are contained in the report released by the NYS 2100 Commission in February 2013, Recommendations to Improve the Strength and Resilience of the Empire State's Infrastructure.

Recommendations for the Energy Sector NYS2100 Commission Feb. 2013	
Strengthen substations against flood damage	Install remotely operated natural gas control valves
Reconfigure network boundaries to separate flood areas from non-flood areas	Protect natural gas regulators from floods
Elevate critical distribution transformer installations	Strengthen electric and steam production facilities
Install excess flow control valves on the natural gas system	Strengthen steam tunnels
Replace critical distribution wood poles with steel poles or upgrade and harden existing poles	

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Preparing for the Future

Puerto Rico has experienced one of the most devastating events in recent history. Restoration will take months, but lessons from other events can help establish the process to develop an energy sector infrastructure that will not be as susceptible to damage from future events. By incorporating a thorough and timely analysis of the different options available, alongside the costs of power system failure, Puerto Rico has a reasonable chance to come out on the other side of the storm with a more resilient power system for its citizens.

About the Authors

Ken Collison, who joined ICF in 2002, has expertise in transmission studies, power system reliability studies, critical infrastructure protection, transmission and ancillary services valuation, generation analysis, utility restructuring, and strategic studies. Mr. Collison was the overall project lead for a large ICF team engaged to support the New York State agency tasked with coordinating the efforts of the NYS 2100, Respond and Ready Commissions, formed after Superstorm Sandy, in developing recommendations to mitigate the impact of natural disasters on infrastructure in the state. He also led a study to assess the vulnerability of high voltage substation equipment in several regions in the U.S. to catastrophic events and determine optimal sparing inventory levels to improve resiliency to high impact low frequency events.

Judah Rose joined ICF in 1982 and has 30 years of experience in the energy industry with clients such as electric utilities, financial institutions, law firms, government agencies, fuel companies, and independent power producers (IPPs). He is an ICF Distinguished Consultant, an honorary title given to three of ICF's 5,000+ employees. He has served on the ICF Board of Directors as the management shareholder representative. Mr. Rose has supported the financing of tens of billions of dollars of new and existing power plants and is a frequent counselor to the financial community. He provides expert testimony and litigation support, addressed approximately 100 major energy conferences, and authored numerous articles.

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