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THESIS

**PUERTO RICO'S HOMELAND SECURITY READINESS:
REDESIGNING THE ISLAND'S POWER GRID TO
IMPROVE ITS RESILIENCY**

by

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March 2019

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REDESIGNING THE ISLAND'S POWER GRID TO IMPROVE ITS RESILIENCY**

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ABSTRACT

The damage caused by Hurricane Maria to Puerto Rico left this American territory ill-equipped to rebuild—or even maintain—its aging power grid. As reconstruction is in order, this tragedy presents an opportunity to design a more resilient and efficient power grid for Puerto Rico. A sustainable distributed power plan that includes renewable energy, distributed generation, and smart grid technology could be the answer to Puerto Rico’s energy problems. This grid could incorporate features that exploit the unique environment of Puerto Rico and include maintenance fees commensurate with the financial abilities of the island. The prospect of a new power grid is not simply a question of opportunity or need; it is part of a homeland security mandate. The exploration of alternative and sustainable power options for Puerto Rico can serve as a test bed for new technology, systems, and protocols that could affect other jurisdictions under similar economic or natural hazard circumstances.

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LIST OF ACRONYMS AND ABBREVIATIONS

DHS	Department of Homeland Security
IEEFA	Institute for Energy Economics and Financial Analysis
EV	electric vehicle
MOP	measure of performance
MW	megawatt
NSC	National Security Council
PREPA	Puerto Rico Electric Power Authority
OPEC	Organization of Petroleum Exporting Countries
<i>QHSR</i>	<i>Quadrennial Homeland Security Review</i>

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EXECUTIVE SUMMARY

Resiliency is the ability to bounce back from adversity and return to the previous norm. This term not only describes a quality in people but also the ability of objects or places to recover to their original shape or function. In the case of the Puerto Rico Electric Power Authority (PREPA), its antiquated infrastructure, its centralized power production and distribution network, and Puerto Rico's financial bankruptcy all hindered its ability to return to its original functioning state after the destruction by Hurricane Maria in 2017.

PREPA expanded rapidly in the 1970s to support an industrialization move in Puerto Rico, but when federal incentives were peeled back in 1996, factories left the island, and PREPA lost its customers.¹ The decrease in revenue forced PREPA to borrow funds from international creditors to sustain its operations, but “political patronage, corruption, and inefficiency” led PREPA to a \$9 billion deficit.² Due to PREPA's budget deficit and lack of maintenance, electrical cables deteriorated and generators failed. The company, failing to conform to environmental standards and experiencing work-related disabilities and deaths among its workforce, incurred costly fines.³ Furthermore, power outages were four times more frequent in Puerto Rico than in the continental United States.⁴

On September 20, 2017, Hurricane Maria brought 150 mph winds to Puerto Rico and dumped 25 inches of rain while following a northwesterly track and entering the island through the southeast corner—like all other previous hurricanes.⁵ Puerto Rico's power grid was categorically destroyed, with 100 percent of PREPA's customers without power. High

¹ “Be PREPA-ed: The Story of Puerto Rico's Power Grid Is the Story of Puerto Rico,” *Economist*, October 19, 2017, <https://www.economist.com/united-states/2017/10/19/the-story-of-puerto-ricos-power-grid-is-the-story-of-puerto-rico>.

² “Be PREPA-ed.”

³ “Be PREPA-ed.”

⁴ “Be PREPA-ed.”

⁵ Puerto Rico Energy Resiliency Working Group, *Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico* (New York: New York State Power Authority, 2017), 10, https://www.governor.ny.gov/sites/governor.ny.gov/files/atoms/files/PRERWG_Report_PR_Grid_Resiliency_Report.pdf.

winds massively destroyed the transmission lines and lattice towers running through the mountains of Puerto Rico because 85 percent could not survive a Category 4 hurricane, owing to decades of service neglect.⁶ Furthermore, reduced standards had been used to build the remaining 15 percent of the transmission lines in Puerto Rico; then again, almost all power lines were already “cracking, corroding and collapsing,” thus making them vulnerable to hurricane forces such as Maria.⁷ In the end, Hurricane Maria caused approximately 2,975 deaths, most of which were traced to the lack of electricity that crippled all medical, emergency services, communications, and basic utilities—such as water and sewer—on the island.⁸

To improve PREPA’s ability to recover rapidly in the future and to avoid or minimize the loss of property and lives, this thesis explores the incorporation of new measures to enhance its network communications, decentralize its power production and distribution, and insert new electricity storage capacity as part of a new operational strategy. Therefore, new technology—in the form of renewable energy production and storage, the insertion of the smart grid concept, and the establishment of independent microgrid systems—was utilized to design a system that could improve PREPA’s ability to recover after a natural or manmade disaster. Using available electricity in megawatts and time to recover as the measures of performance, a decentralized grid proves more resilient to PREPA’s centralized system because, under the proposed decentralized system, more electrical power is available in the shortest amount of time, thus making this system able to recover faster after a natural or manmade disaster.

This thesis found that the combination of ocean tidal power, a smart grid, electricity storage, microgrids, and solar energy could improve Puerto Rico’s power grid reliability, resiliency, and efficiency, thus improving its homeland security readiness. The roadmap for an improved power grid in Puerto Rico is noted in this thesis, and it is now up to

⁶ Puerto Rico Energy Resiliency Working Group, 17.

⁷ Puerto Rico Energy Resiliency Working Group, 17.

⁸ “GW Researchers: 2,975 Excess Deaths Linked to Hurricane Maria,” George Washington University, August 29, 2018, <https://gwtoday.gwu.edu/gw-researchers-2975-excess-deaths-linked-hurricane-maria>.<https://gwtoday.gwu.edu/gw-researchers-2975-excess-deaths-linked-hurricane-maria>.

policymakers to implement its findings effectively, not only for Puerto Rico but also as a test bed for new technology, systems, and protocols that may affect other jurisdictions under similar economic circumstances and natural hazards.

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First and foremost, I cannot start without expressing gratitude to the most magnificent friend anyone could have—more than a friend, a father who has always been there, even when some doubted me. I hope that this small appreciation captures the essence of my deepest gratitude, as part of my endless effort to live worthy of the gift of life. Thank you, Jesus Christ.

I also dedicate this thesis to my wife, Naomi, whose resolute support never faded; she was always a beacon of hope and strength. Thank you, Naomi, for always being the supporting column of our family. To my son, Elias, and daughter, Alondra, thank you for your patience during my long absences from home. I am blessed with your love and care.

Training ourselves to think differently is in my opinion the key element of improving our education. This statement reflects how my mindset has changed to think differently and challenge previously learned facts. I do not consider myself a great thinker or a scholar in any capacity, but the skills I acquired during my time at the Center for Homeland Defense and Security have taught me to explore new possibilities and use my cognitive reasoning to overcome obstacles and discern facts from illusion.

In 1988, from a small, unknown Spanish-speaking town in Puerto Rico, I left in search of what was an improbability for me—the American dream. Thirty-one years later, I can attest that the American dream is alive and real and have learned to embrace life as a gift of opportunity and growth. To the CHDS faculty and staff, thank you for being part of my American dream.

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I. INTRODUCTION

This thesis addresses Puerto Rico’s homeland security readiness by investigating how the island’s power grid might be re-designed to improve resiliency. But besides being the focus of this thesis, it is important to define what resiliency is to allow a more refined focus for this investigation. *Merriam-Webster Dictionary* defines the word *resiliency* as “an ability to recover from or adjust easily to misfortune or change.”¹ Generally, resiliency is not defined as the ability to be impervious to misfortune or change but as the aptitude to recuperate from such calamity. Therefore, it is implied that an adverse event must happen before one can experience or test resiliency.

When applying this term to infrastructure design, Professor Abi-Samra of the University of California in San Diego and president of Electric Power & Energy Consulting maintains that resiliency is the “characteristics of the infrastructure and operations such as strength and the ability to make a fast recovery, which help utilities minimize or altogether avoid disruptions during and after an extreme weather event.”² Samra further argues that resiliency begins, when speaking about power grids, with a new grid design, and efforts to harden the infrastructure are simply not enough.³ In essence, Samra claims that an electric power grid will fail regardless of the measures taken, but there are actions that can be taken to minimize power interruption and expedite repairs.⁴ Supporting Samra’s arguments, the National Infrastructure Advisory Council defines infrastructure resilience as “the ability to reduce the magnitude and/or duration of disruptive events.”⁵ The National Infrastructure Advisory Council further maintains that resiliency is dependent on the infrastructure’s

¹ David Wagman, “How to Build a More Resilient Power Grid,” IEEE Spectrum, December 14, 2017, <https://spectrum.ieee.org/energywise/energy/the-smarter-grid/learning-from-grid-failures-a-conversation-with-nicholas-abisamra>.

² Wagman.

³ Wagman.

⁴ Wagman.

⁵ Aaron Clark-Ginsberg, “What’s the Difference between Reliability and Resilience?,” Department of Homeland Security, March 2016, https://ics-cert.us-cert.gov/sites/default/files/ICSJWG-Archive/QNL_MAR_16/reliability%20and%20resilience%20pdf.pdf.

ability to predict, adjust, and swiftly recover from a hazardous event.⁶ There is one important aspect of resiliency not clearly defined in the literature that proved to be an obstacle during this investigation: How do we measure resiliency, and what metrics should be used?

While there are differences in definitions, Henry H. Willis and Kathleen Loa of the RAND Corporation were able to identify four elements that are common among all criteria that attempt to measure resilience:

- Establish if the service provided has been reduced.
- Quantify the amount of service reduction.
- Measure how fast service has been reestablished.
- Measure the amount of service reestablished.⁷

Accordingly, this investigation did not focus on finding new methods to make Puerto Rico's power grid invulnerable to hurricanes but concentrated on suggesting new designs and technological measures to increase its capacity to recover after a catastrophic natural event. To accomplish this, the following measures of performance (MOPs) were analyzed to compare resiliency differences between Puerto Rico's current power grid and a reconfigured grid as proposed in this thesis:

- Amount of electrical service reduced after Hurricane Maria;
- Time to restore electrical service after Hurricane Maria;
- Amount of electrical service restored after Hurricane Maria.

In the end, the goal of this thesis is to provide an alternative to Puerto Rico's electricity power grid problem and increase its resiliency, taking into account the island's fiscal situation and the vulnerability of this system to future natural hazards.

⁶ Clark-Ginsberg.

⁷ Henry H. Willis and Kathleen Loa, *Measuring the Resilience of Energy Distribution Systems*, RR-883-DOE (Santa Monica, CA: RAND Corporation, 2015), https://www.rand.org/pubs/research_reports/RR883.html. Kathleen Loa and Henry H. Willis, 2015.

A. BACKGROUND AND PROBLEM STATEMENT

In early May 2017, the territory of Puerto Rico was declared one of the biggest U.S. municipality insolvencies, with an approximate \$123 billion in obligations and retirement fund commitments, exceeding the 2013 Detroit bankruptcy of \$18 billion.⁸ While the per capita debt for each of Detroit's 690,000 people was approximately \$26,086, Puerto Rico has approximately 3.337 million people, resulting in a debt of roughly \$36,859 per person.⁹ To make matters worse, from September 19, 2017, through the evening of September 21, 2017, Hurricane Maria devastated the island of Puerto Rico, unleashing winds of 175 mph and leaving an apocalyptic path of destruction across the 3,500-square-mile island. Besides the humanitarian crisis, Maria's legacy left Puerto Rico with an additional \$30 billion in damages, representing 30 percent of the island's annual gross domestic product.¹⁰

The damage caused by Hurricane Maria, compounded by Puerto Rico's current fiscal crisis, has rendered the American territory ill-equipped not only to rebuild but even to maintain its aging power grid. However, as a near total rebuild is in order, this tragedy presents an opportunity to design and build a more resilient, damage-tolerant power grid for Puerto Rico. This new grid could incorporate design features that exploit the unique environment of Puerto Rico while also requiring low generation and maintenance fees, commensurate with the financial abilities of the island. A sustainable, distributed power plan that includes renewable energy, distributed generation, a smart grid, and electric vehicle energy storage could be the answer to Puerto Rico's energy problems.

The prospect of a new power grid is not simply a question of opportunity or need, however; it is also part of a homeland security mandate. *The Quadrennial Homeland Security Review (QHSR)* to Congress provides an analytic and strategic foundation for how

⁸ Mary Walsh, "Puerto Rico Declares a Form of Bankruptcy," *New York Times*, May 3, 2017, <https://www.nytimes.com/2017/05/03/business/dealbook/puerto-rico-debt.html>.

⁹ "Quick Facts: Puerto Rico," U.S. Census Bureau, accessed February 15, 2019, <https://www.census.gov/quickfacts/fact/table/pr/PST045218>.

¹⁰ Julia Horowitz, "Hurricane Maria Is a Nightmare for Puerto Rico's Economy," CNN, September 25, 2017, <http://money.cnn.com/2017/09/25/news/economy/hurricane-maria-economic-damage/index.html>.

the Department of Homeland Security (DHS) operates and accomplishes its mission.¹¹ The most recent *QHSR* states that one of DHS's five basic homeland security missions is to "strengthen national preparedness and resilience" with special emphasis on the nation's critical infrastructure.¹² The CNA Military Advisory Board indicates, "Electricity underpins every facet of American lives. Without it, our homes, our businesses, and our national security engine would grind to a halt—especially when so much of this power is becoming "smart" and integrated."¹³ According to the *National Electric Grid Security and Resiliency Action Plan*, "There are three strategic goals to reduce the systemic risk to the electric grid through combined and aligned organizational, technical, and policy efforts across the public and private sectors."¹⁴ The three essential goals are as follows:

- Improve readiness and safeguard the national electric power network.
- Improve reaction and recuperation undertakings and direct arising eventualities.
- Construct a power grid that can be more reliable and durable.¹⁵

As the island is located in the Caribbean, the last goal is particularly important to Puerto Rico. Located in a hurricane hazard zone, Puerto Rico is threatened by hurricanes every year. The potential impacts of this threat are exacerbated by Puerto Rico's bankrupt economy, which hinders efforts to maintain and update an aging power grid that dates back to 1941. It is evident that the Federal Emergency Management Agency is repairing Puerto Rico's power grid; however, this process does not incorporate new technologies, methods, or infrastructure to minimize the effects of future catastrophic events such as hurricanes.

¹¹ Department of Homeland Security, *The 2014 Quadrennial Homeland Security Review* (Washington, DC: Department of Homeland Security, 2014), <https://www.dhs.gov/sites/default/files/publications/2014-qhsr-final-508.pdf>.

¹² Department of Homeland Security.

¹³ CNA Military Advisory Board, *National Security and Assured U.S. Electrical Power* (Arlington, VA: Center for Naval Analyses, 2015), https://www.cna.org/CNA_files/PDF/National-Security-Assured-Electrical-Power.pdf.

¹⁴ Executive Office of the President, *National Electric Grid Security and Resilience Action Plan* (Washington, DC: White House, December 2016), https://www.whitehouse.gov/sites/whitehouse.gov/files/images/National_Electric_Grid_Action_Plan_06Dec2016.pdf.

¹⁵ Executive Office of the President.

Even if or when power is fully restored in Puerto Rico, it could be argued that its government does not have the economic ability to operate effectively and maintain an outdated power grid. Hence, there is a real and pressing need to find alternative sources of sustainable power if Puerto Rico is to maintain a strong and resilient homeland security posture.

B. PURPOSE AND SIGNIFICANCE OF THE STUDY

Based on DHS's strategic mission and PPD 21, the power grid in Puerto Rico must be studied to identify the crux of its vulnerabilities, develop solutions that can increase response and recovery efforts, and construct a more robust sustainable power grid—all within the context of Puerto Rico's financial predicament and geographical location.¹⁶ The development of these potential solutions will be framed within the reproduction of current commercial best practices, such as solar energy, micro-grid systems, smart energy storage, and integration systems. However, there is the potential for integrating current best practices with uncharted technological opportunities by combining them into a single power-production plan.¹⁷ Renewable energy sources and smart electrical grids are technologies that already exist and have been proven effective. However, these technologies have not been incorporated and some not even considered in solving the vulnerabilities of the electrical grid in Puerto Rico. Therefore, this thesis leverages these existing technologies to propose a solution that could transform Puerto Rico's power grid.

Finally, the importance of exploring alternative sustainable power options for Puerto Rico surpasses the local benefits for the island. It can serve as a test bed for new technologies, systems, and protocols that may affect other jurisdictions under similar economic circumstances and natural hazards.

¹⁶ Interagency Security Committee, *Presidential Policy Directive 21 Implementation: An Interagency Security Committee White Paper* (Washington, DC: Department of Homeland Security, February 2015), <https://www.dhs.gov/sites/default/files/publications/ISC-PPD-21-Implementation-White-Paper-2015-508.pdf>.

¹⁷ New technological opportunities to be explored in this research consist of Puerto Rico's natural resources as potential platforms for energy production. For example, Puerto Rico has abundant access to salt water and synergic wave power from the ocean. These could be converted into electricity using new technologies currently under development.

C. RESEARCH QUESTION AND HYPOTHESIS

1. Primary Question

How can Puerto Rico's power grid be restructured to improve its reliability, resiliency, and efficiency, thus improving the island's homeland security readiness?

2. Hypothesis

A decentralized, renewable energy smart grid is more efficient and resilient than a centralized conventional power grid.

D. LITERATURE REVIEW

In his monograph, Jose Bolivar Fresneda, a prominent Puerto Rican historian, provides what appears to be one of the only historical analyses of Puerto Rico's power production dating back to the mid-1930s. Fresneda argues that prior to and during World War II, the U.S. federal government initiated in Puerto Rico industrialization that included the expropriation of private utilities and bond measures to subsidize the establishment of the Puerto Rico Electric Power Authority (PREPA).¹⁸ Fresneda further maintains that PREPA originated from the government's purchase of the only three private power companies on the island: Ponce Electric Company, Porto Rico Railway Light & Power Company, and Mayagüez Light, Power & Ice Company.¹⁹ Fresneda notes that by 1946, the electric power production in Puerto Rico was 152,913 kVA; thus, PREPA was created to increase production capacity by constructing more efficient power plants.²⁰ Fresneda's analysis is important as it provides a historical baseline, which can be used to show how

¹⁸ Jose Bolivar Fresneda, "El banco de fomento de Puerto Rico y las primeras emisiones de bonos de la Autoridad de las Fuentes Fluviales 1941–1948," *Revista de Ciencias Sociales*, 19 (2008).

¹⁹ Fresneda, 100–127.

²⁰ Fresneda, "El banco de fomento de Puerto Rico"; and Juan Ruiz Toro, "Puerto Rico's Operation Bootstrap," Brown University Library, accessed March 30, 2018, <https://library.brown.edu/create/modernlatinamerica/chapters/chapter-12-strategies-for-economic-developmen/puerto-ricos-operation-bootstrap/>. Operation Bootstrap was a strategy to develop and modernize Puerto Rico's economy, which began in the mid-1940s. Therefore, many foreign companies moved to Puerto Rico, and they required electric power to run their factories. In light of this, Puerto Rico's electricity production was insufficient; hence, the need to build more efficient power plants to augment the island's electricity production arose.

Puerto Rico's electricity demands are directly linked to its dependence on imported fossil fuels.

This import dependency continued to grow between the mid-1940s and the late 1950s, as evidenced in a 1958 report to a national planning association titled *The Prospects for Nuclear Energy in Puerto Rico*.²¹ The report's author, Alvin Mayne, agrees with Fresneda, arguing that the need for electricity in Puerto Rico was a growing trend, with oil as its main source of energy. However, unlike Fresneda, Mayne explores hydroelectric plants as an alternate source of energy between 1945 and the 1950s, but he indicates this kind of electricity production declined due to lack of water storage and fluctuating rainfall on the island.²² In addition, Mayne provides one of the first energy production cost analyses for Puerto Rico.²³

Puerto Rico's energy production and transmission issues continued to be a relevant problem, as indicated by the House Committee on Interior and Insular Affairs in 1984. The committee proclaims, "Dependence of the U.S. Insular Areas on oil imports and lack of energy self-sufficiency are a burden on the Federal and insular budgets."²⁴ In addition, the committee specifically addresses the climatic, geological, cultural, and economic conditions of Puerto Rico as circumstances that have made traditional energy technology unsuitable for the island's requirements. Fresneda and the Committee on Interior and Insular Affairs agree that Puerto Rico's energy needs have not been met by traditional power sources dependent on oil. Fresneda, Mayne, and the committee agree that oil has been the main source of electricity production; however, the committee further argues that this source of power has been detrimental to Puerto Rico's economy. This appears to be the first source to note specifically the need for Puerto Rico to seek alternate sources of

²¹ Alvin Mayne, *The Prospects for Nuclear Energy in Puerto Rico* (Ann Arbor: University of Michigan Press, 1958). This report seems to be the first and only report on Puerto Rico's electrical power needs and the possibility of using nuclear energy on the island.

²² Mayne.

²³ Mayne.

²⁴ U.S. Congress, House, *Energy planning Planning and Implementation in the U.S. Insular Areas: Problems and Policy Options* (Washington, DC: Congressional Research Service, 1984). The mentioned U.S. insular areas referred specifically to Puerto Rico and the U.S. Virgin Islands.

energy due to the high costs of importing fuel and its unique climatic and geological conditions.

In their National Public Radio news article, Allen and Penaloza put forth another analysis of why the cost of electricity production in Puerto Rico is high. Essentially, Allen and Penaloza argue that PREPA has never upgraded its power plants.²⁵ As 60-plus-year-old power plants, they are obsolete and inefficient, thus making the cost of energy more than in any other U.S. state, except Hawaii.²⁶ Allen and Penaloza's report confirms the conclusions of Fresneda, Mayne, and the Committee on Interior and Insular Affairs about the inadequacy and potential issues of Puerto Rico's electric power production and its dependency on oil imports.

Further supporting the concerns of the aforementioned authors, a 2017 article in the *Economist* provides an analysis of PREPA's situation before Hurricane Maria destroyed Puerto Rico's power grid. PREPA had expanded rapidly in the 1970s to support an industrialization move in Puerto Rico, but when in 1996 federal incentives were peeled back, factories left the island, and PREPA lost its customers.²⁷ The decrease in revenue forced PREPA to borrow funds from international creditors to sustain its operations, but "political patronage, corruption, and inefficiency" led PREPA into a \$9 billion deficit.²⁸ Due to PREPA's budget deficit and lack of maintenance, electrical cables began to deteriorate, and generators began to fail. The company, failing to conform to environmental standards and experiencing work-related disabilities and deaths among its workforce, incurred costly fines.²⁹ Furthermore, power outages became four times more frequent in

²⁵ Greg Allen and Marisa Peñaloza, "Power Problems: Puerto Rico's Electric Utility Faces Crippling Debt," National Public Radio, May 7, 2015, <https://www.npr.org/2015/05/07/403291009/power-problems-puerto-ricos-electric-utility-faces-crippling-debt>.

²⁶ Allen and Peñaloza. The average residential electricity price in the United States (excluding Hawaii) is 12.3 cents per kWh. The residential cost for electricity in Puerto Rico is 22.7 cents per kWh.

²⁷ "Be PREPA-ed: The Story of Puerto Rico's Power Grid Is the Story of Puerto Rico," *Economist*, October 19, 2017, <https://www.economist.com/united-states/2017/10/19/the-story-of-puerto-ricos-power-grid-is-the-story-of-puerto-rico>.

²⁸ "Be PREPA-ed."

²⁹ "Be PREPA-ed."

Puerto Rico than in the continental United States.³⁰ This article supports the concerns of the Committee on Interior and Insular Affairs about oil imports and a lack of energy self-sufficiency becoming a burden on the federal and insular budgets.

Thus far, the literature agrees with the concerns over Puerto Rico's dependency on fossil fuel for power generation and the potential and actual problems of PREPA. Still, the Committee on Interior and Insular Affairs is the only source that indicates concern about Puerto Rico's climatic and geological characteristics and their impact on the island's capacity to produce electricity. This concern was validated when Hurricane Maria hit Puerto Rico in September 2017.

Given the recent impact of Hurricane Maria, most of the available literature is composed of news reports that provide estimates of what the total impact was on Puerto Rico's economy. One of the earliest reports after Hurricane Maria is in September 2017 by Julia Horowitz, who reports that Puerto Rico would likely face \$30 billion in damages and another \$10 billion in the loss of economic productivity.³¹ Dave Graham and Robin Respaut in an article for Reuters concur with the damages estimated by Horowitz.³² Regarding Puerto Rico's power grid, Davis Ferris notes that Hurricane Maria destroyed 80 percent of its power lines, with a loss of 1.25 billion hours of electricity.³³ Supporting the Committee on Interior and Insular Affairs' concerns about Puerto Rico's geography, Ferris indicates that power lines are "vulnerable because they traverse the entire island, from generation plants in the south to San Juan in the north, crossing mountainous, roadless terrain."³⁴ Ferris further argues that Puerto Rico's jungle growth, long expanses, remoteness, and wind destruction caused a monumental catastrophe.³⁵

³⁰ "Be PREPA-ed."

³¹ Horowitz, "Hurricane Maria Is a Nightmare."

³² Dave Graham and Robin Respaut, "Fears of Dam Collapse Add to Puerto Rico's Misery after Hurricane," Reuters, September 23, 2017, <https://www.reuters.com/article/us-storm-maria/failing-dam-creates-new-crisis-on-puerto-rico-amid-flooding-from-hurricane-maria-idUSKCN1BY05J>.

³³ David Ferris, "Puerto Rico's Grid Recovery, by the Numbers," Environment and Energy Publishing, February 20, 2018, <https://www.eenews.net/stories/1060074219>.

³⁴ Ferris.

³⁵ Ferris.

The available literature regarding Hurricane Maria's impact on Puerto Rico's financial crisis concurs that it was detrimental and would increase the burden on an already devastated power grid. The results of this literature review have yielded sources that provide relevant information about Puerto Rico's financial crisis, electric power grid system, cost implications, PREPA's fossil fuel dependency and power transmission issues, and the effects of Hurricane Maria on Puerto Rico's power grid.

In conclusion, and based on the *National Electric Grid Security and Resiliency Action Plan*, the literature demonstrates that Puerto Rico's power generation and distribution system are inadequate and must be reformed. The selected literature was reviewed and deemed to have substantive information to be included in this research. However, although a comprehensive search process was used, it was important to conduct further investigation as some noteworthy works might have been inadvertently excluded.

E. RESEARCH DESIGN AND LIMITATIONS

Given Puerto Rico's financial predicament and the effects of Hurricane Maria on the island, this thesis explores Puerto Rico's power grid to understand its current state as well as its limitations and vulnerabilities and to offer suggestions for how to mitigate them. The goal is to provide valuable policy proposals that could invigorate Puerto Rico's power grid and, thus, enhance the island's quality of life and economic activity, which are critical goals of the Department of Homeland Security's *Energy Sector-Specific Plan* and PPD-21. One might question the reason why Puerto Rico's power grid continues to struggle without any apparent initiative to construct a more robust and resilient system. One might also argue that a combination of government apathy, an unfriendly political environment, and a lack of imagination contributed to this apparent inactivity. However, the scope of this research is limited to identifying methods to construct a more resilient electricity system in Puerto Rico and propose policy solutions that could help accomplish the construction of a new power grid. This thesis evaluates three generation methods (kinetic, chemical, and geothermal), a hybrid transmission solution, and a hybrid distribution source. It then explores the aforementioned generation methods given the abundance of renewable natural

resources in Puerto Rico that provide endless kinetic, chemical, and geothermal energy to power a new smart grid.

This thesis explores the vulnerabilities and weaknesses of Puerto Rico's power grid, specifically, the causes behind the long recovery of the generation, transmission, and distribution of electricity on the island. In addition, it investigates the historical facts of Puerto Rico's power grid to understand and identify past developmental and maintenance oversights that could have contributed to its collapse and long recovery. Lastly, it explores current cost-effective power-grid hardening measures and new alternative sources of energy, which could improve electrical system response and recovery, consistent with the Department of Homeland Security's *Energy Sector-Specific Plan* and PPD-21.³⁶ To accomplish this, the thesis compares Puerto Rico's current power grid operational costs to existing smart renewable energy power grids currently operating in the United States and other countries. In addition, it compares the costs associated with rebuilding Puerto Rico's power grid after Hurricane Maria against the cost to build a smart renewable energy power grid. This thesis quantifies and analyzes the damages of Puerto Rico's power grid after Hurricane Maria and estimates the damages and reconstruction cost of a smart grid under similar meteorological circumstances. Because hurricanes and similar atmospheric conditions are unpredictable and uncertain, this thesis uses an MOP to test whether the proposed decentralized power grid is more resilient than PREPA's old centralized grid, specifically measuring the amount of electricity available in megawatts and time to recover. Although it has been briefly mentioned, this research neither examines the reasons for Puerto Rico's financial bankruptcy nor scrutinizes Puerto Rico's political relationship with the United States. It only examines data relevant to Hurricane Maria's effects on Puerto Rico as they relate to the island's power grid.

This thesis concentrates on developing and analyzing data strictly from open-source literature and unclassified material such as periodicals, journals, books, audio-visual files, internet-based information, and other public records. To stay consistent with current

³⁶ Department of Homeland Security, *Energy Sector-Specific Plan* (Washington, DC: Department of Homeland Security, 2015), <https://www.dhs.gov/sites/default/files/publications/nipp-ssp-energy-2015-508.pdf>; and Interagency Security Committee, *Presidential Policy Directive 21 Implementation*.

homeland security practices and strategic goals, the analysis originated from government databases and scientific professional journals and studies. To obtain relevant information regarding Puerto Rico's bankruptcy and Hurricane Maria's impact on the territory's power grid, news reports and government-sponsored analytical studies were utilized.

This thesis develops an understanding of how Puerto Rico's power grid is exposed to weather hazards and how current best practices and new emerging technologies can enhance its reliability, resiliency, and efficiency. Based on Puerto Rico's model, this thesis offers a proposal to U.S. policymakers, supported by a thorough analysis, to consider the need for more sustainable sources of electric power in a security environment where optimal resiliency and stronger recovery options in the U.S. critical infrastructure are a priority.

II. OVERVIEW OF PUERTO RICO'S POWER GRID

A. POWER GENERATION, TRANSMISSION, AND DISTRIBUTION

During the mid-1930s, Puerto Rico's power generation, transmission, and distribution were handled by three private companies, each with its own independent power grid: the Ponce Electric Company, the Porto Rico Railway Light & Power Company, and the Mayagüez Light, Power & Ice Company.³⁷ Their lack of uniformity and regulatory oversight made them unreliable, inefficient, and expensive. To make matters worse, with Europe at war and looming prices and scarcity of oil, by 1940, these companies often faced oil shortages for their operations, exacerbating the constant blackouts in Puerto Rico.³⁸ In 1941, the government of Puerto Rico with the approval of the U.S. Congress authorized the creation of Autoridad de las Fuentes Fluviales, the first public corporation operated by Puerto Rico.³⁹ This corporation intended to provide a better and more reliable electric service to areas of Puerto Rico where private companies could not.

With the entrance of the United States into World War II in 1941, many military bases began construction in Puerto Rico, thus requiring an unprecedented and unavailable amount of electricity for their operations.⁴⁰ To rectify this problem, that same year, persuading then-President Roosevelt to use his war powers, Puerto Rico Governor Rexford G. Tugwell bought and expropriated all three private power companies, thus unifying Puerto Rico into one electrical power grid.⁴¹ Although it was one unified electrical power grid, Puerto Rico still did not have the electric generation capacity required for the multiple military installations, not to mention the population. Therefore, Puerto Rico resorted to building many hydroelectric plants that relied on artificial lakes and numerous rivers on the island to supply the much-needed electricity. However, by 1944, an extreme drought

³⁷ Fresneda, "El banco de fomento de Puerto Rico," 100–109.

³⁸ Fresneda, 102–108.

³⁹ Fresneda, 107–109.

⁴⁰ Fresneda, 107–109.

⁴¹ Fresneda, 108–110.

forced the rationing of electricity for 60 days, thus highlighting the vulnerability of hydroelectric power as a dependable source of energy production.⁴² It was not until the 1950s that the San Juan, Palo Seco, and Guayanilla thermoelectric plants were opened to aid hydroelectric plants, and by 1974, 98 percent of all electricity produced in Puerto Rico was generated by thermoelectric plants powered by petroleum products.⁴³

By 2016, PREPA had become a vertically integrated utility that provided electricity to approximately 1.4 million customers in Puerto Rico, with six fossil fuel, seven hydroelectric, and two privately owned plants (Costa Sur & AES) helping PREPA with electricity cogeneration.⁴⁴ Puerto Rico is approximately 35 miles wide and 100 miles long, requiring 2,478 miles of transmission lines, including 35 miles of underground 115 kV; approximately 31,485 miles of overhead distribution cables; and 334 power substations.⁴⁵ Figure 1 offers a better perspective of the overall transmission lines and power plant infrastructure in Puerto Rico.

⁴² Fresneda, 113.

⁴³ “History of PREPA,” Puerto Rico Electric Power Authority, accessed July 30, 2018, <https://www.aeepr.com/INVESTORS/History.aspx>.

⁴⁴ Puerto Rico Energy Resiliency Working Group, *Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico* (New York: New York State Power Authority, 2017), https://www.governor.ny.gov/sites/governor.ny.gov/files/atoms/files/PRERWG_Report_PR_Grid_Resiliency_Report.pdf.

⁴⁵ Puerto Rico Energy Resiliency Working Group, 8.

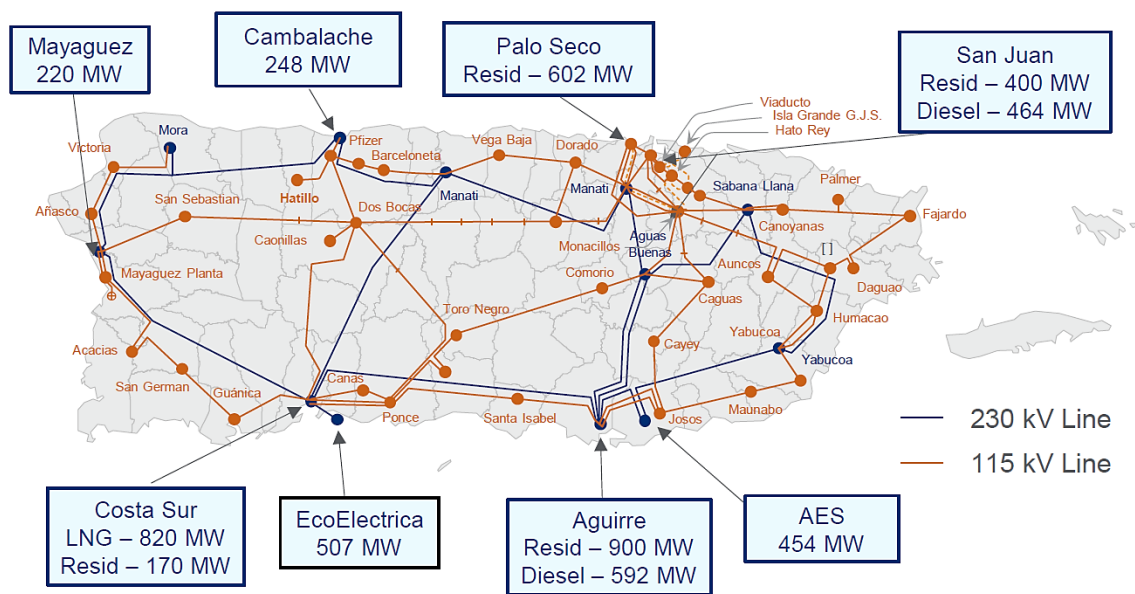


Figure 1. Geographic Footprint of Power Plants in Puerto Rico⁴⁶

Based on the data in Figure 1, most of Puerto Rico’s southern power plants generate 1,723 to 2,681 MW of electricity. In contrast, the north side of Puerto Rico produces 1,470–1,534 MW of electricity. This information is important because their locations are significant in describing their vulnerabilities against hurricanes in Section B of this chapter and in Chapter III.

⁴⁶ Source: Citigroup Global Markets Inc. and Rothschild & Co. “Puerto Rico Electric Power Authority – Process and Opportunity Overview” (presentation, June 2018), <http://www.p3.pr.gov/assets/prepa-market-sounding-2018-06-01.pdf>. www.p3.pr.gov/assets/prepa-market-sounding-2018.06.01.pdf.

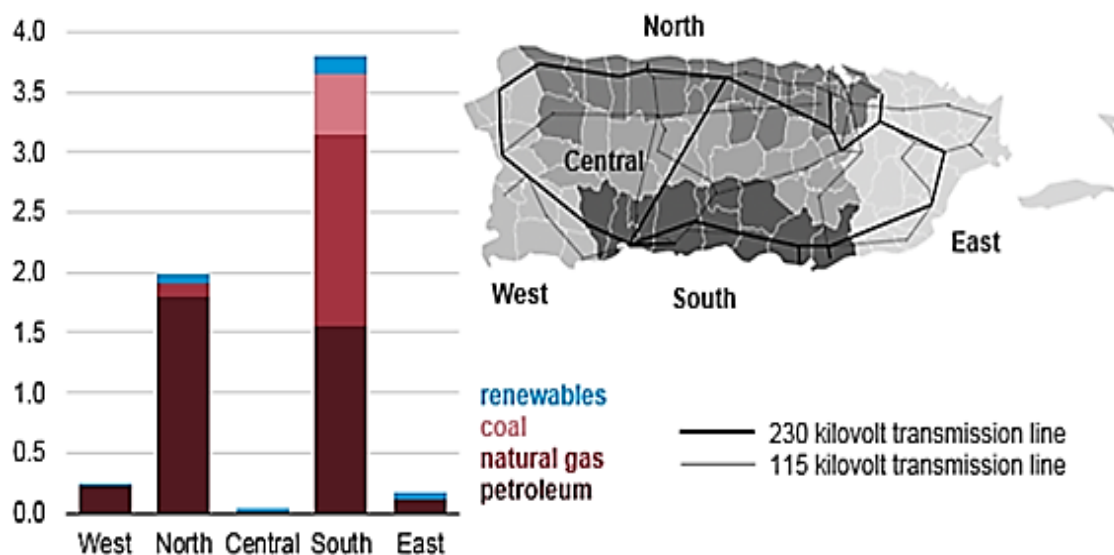


Figure 2. Electricity Generating Capacity in Puerto Rico, 2016⁴⁷

As previously noted, PREPA is a government-owned utility company with sole control over the production, transmission, and distribution of electricity in Puerto Rico. One might think that this unique dominating posture would generate millions of dollars in revenue, thus making PREPA a healthy and wealthy enterprise. However, for the last decade, PREPA has been struggling with operational inefficiencies and an impressive \$9 billion debt.⁴⁸ Its substantial dependence on oil products, specifically bunker and diesel fuels, makes PREPA vulnerable to fluctuating oil prices, thus making electricity rates in Puerto Rico 21 cents per kilowatt-hour.⁴⁹ With such high electricity rates, Puerto Rico's appeal to the economic market has declined over the years, thus losing its competitiveness.⁵⁰ In addition, PREPA's failure to update its power plants to more

⁴⁷ "Puerto Rico Electricity Generation Capacity by Region (2016)," Engineering 360, accessed February 3, 2019, <https://insights.globalspec.com/images/assets/900/6900/pr2.png>.

⁴⁸ Steven Mufson, "Puerto Rico's Power Company Was Already Bankrupt. Then Maria Hit," *Chicago Tribune*, September 21, 2017, <http://www.chicagotribune.com/news/nationworld/ct-puerto-rico-power-company-20170921-story.html>.

⁴⁹ Mufson.

⁵⁰ Mufson.

efficient gas turbines has made them obsolete and unable to meet federal environmental standards for sulfur and mercury dioxide byproducts.⁵¹ In addition, PREPA has never updated its aging rate structure to capture actual costs, never updated its information technology, and never restructured its customer service infrastructure.

All of its failures have prompted PREPA to default on its monetary obligations and operate on a cash basis while attempting to lower operational expenses, such as maintenance, for its power plants and lines.⁵² In an attempt to cover its expenses and keep up with financial obligations, PREPA has borrowed massively by issuing \$9 billion in bonds since its inception in 1941. As the financial predicament of Puerto Rico and its service degraded over the years, PREPA failed to provide adequate basic care to its infrastructure.⁵³ On July 2, 2017, with an escalating debt, declining cash flow, and crippling infrastructure, PREPA filed for bankruptcy, thus prohibiting its access to bond markets and bank financing to improve operational efficiency.

As PREPA continues to falter, in conjunction with its financial predicament, it has been forced to increase electricity rates to sustain its basic operations. Figure 3 demonstrates PREPA's financial performance since 2008.

⁵¹ Mufson.

⁵² Mufson.

⁵³ Mufson.

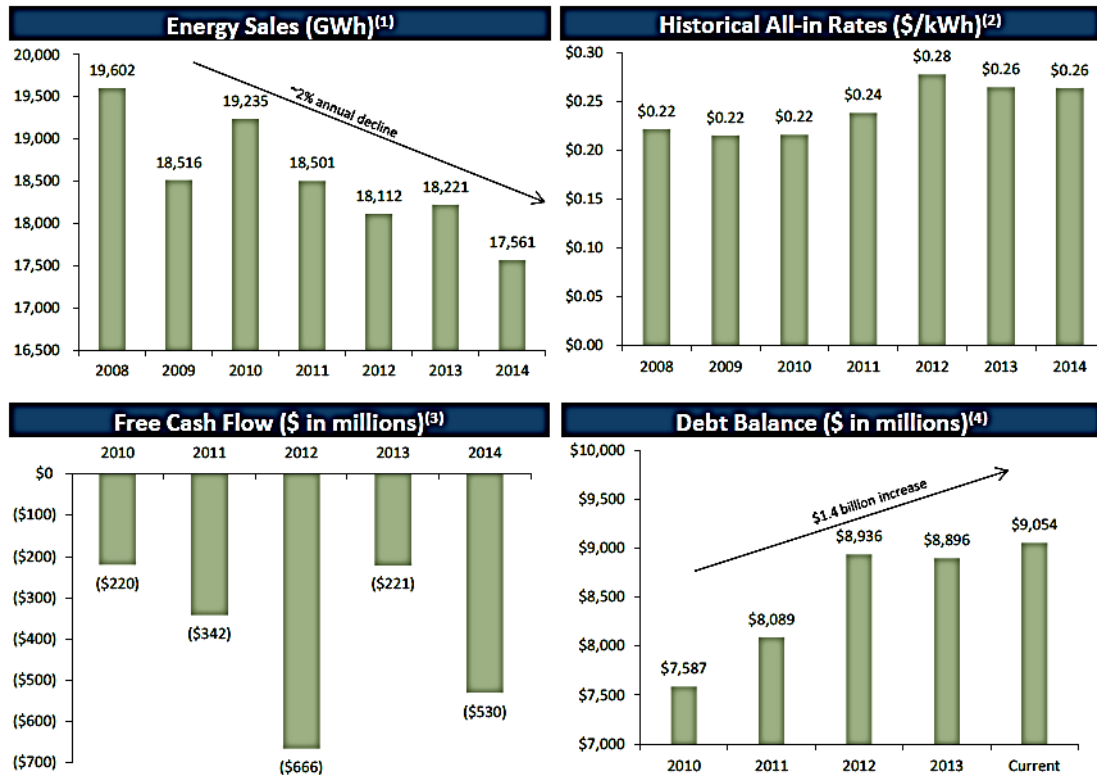


Figure 3. PREPA's Financial Performance⁵⁴

B. CURRENT GRID DESIGN AND TECHNOLOGY CONCERNS

During a normal day of operations, PREPA's power generating plants burn oil to produce steam, which spins turbines to power generators, thus sending electricity through transmission and distribution lines. However, PREPA operates the oldest equipment in the United States, with service failure rates far surpassing comparable utilities during normal weather conditions.⁵⁵

PREPA does not conform to current business practices and has fallen behind industry and environmental standards.⁵⁶ PREPA's median plant age is approximately 44

⁵⁴ Puerto Rico Electric Power Authority, *PREPA's Transformation: A Path to Sustainability* (San Juan: Government of Puerto Rico, 2015), 5, <http://www.gdb-pur.com/documents/PREPARRecoveryPlan6-1-15.pdf>.

⁵⁵ Puerto Rico Electric Power Authority.

⁵⁶ Puerto Rico Electric Power Authority.

years old compared to the industry's average of 18 years.⁵⁷ PREPA's biggest expense is fossil fuel, amounting to approximately 58 percent of its operating costs.⁵⁸ Between 2016 and 2017, PREPA spent \$2.828 billion in fuel alone, with an additional \$8.361 billion in projected fuel purchases over the next five years (see Table 1). These figures are particularly important because they can be utilized to compare cost efficiencies against renewable energy sources and as well as show that savings from fuel purchases can offset the cost of new renewable energy electricity plants in Puerto Rico.

Table 1. PREPA's Operating Expenses⁵⁹

Summary of Expenditures (\$ in millions)															
	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
Operating Expenses															
Fuel	(\$1,381)	(\$1,447)	(\$1,205)	(\$1,168)	(\$1,237)	(\$1,236)	(\$1,142)	(\$1,030)	(\$1,035)	(\$1,027)	(\$1,103)	(\$1,110)	(\$969)	(\$949)	(\$979)
Purchased Power	(827)	(863)	(868)	(923)	(963)	(984)	(991)	(990)	(995)	(1,030)	(1,040)	(1,045)	(1,071)	(1,088)	(1,084)
Labor	(497)	(494)	(488)	(485)	(486)	(491)	(496)	(501)	(506)	(511)	(516)	(521)	(527)	(532)	(537)
O&M and Other	(223)	(199)	(197)	(199)	(201)	(203)	(205)	(207)	(209)	(211)	(214)	(216)	(218)	(220)	(222)
Total Operating Expenses	(\$2,929)	(\$3,003)	(\$2,757)	(\$2,775)	(\$2,888)	(\$2,915)	(\$2,834)	(\$2,728)	(\$2,745)	(\$2,780)	(\$2,873)	(\$2,892)	(\$2,785)	(\$2,789)	(\$2,823)

In 2016, PREPA created an integrated resource plan to incorporate new technology into its power generation systems to reduce the utility's dependence on crude oil. Although a positive move toward modernizing its grid infrastructure, the plan concerned the Institute for Energy Economics and Financial Analysis (IEEFA).⁶⁰ The IEEFA argues that even when PREPA explores alternative sources of fuel, its plan lacks the necessary elements to make the utility less dependent upon fossil fuels as it relies solely on the price difference between oil and gas.⁶¹ IEEFA also critiques PREPA's operational plan because it does not function in an integrated manner. For example, IEEFA points out that PREPA neither integrates renewable energy as a primary source of electricity nor plans to reduce energy

⁵⁷ Puerto Rico Electric Power Authority.

⁵⁸ Puerto Rico Electric Power Authority.

⁵⁹ Source: Puerto Rico Electric Power Authority, *PREPA's Transformation*, 22.

⁶⁰ Cathy Kunkel and Anna Sommer, *Comments on the Puerto Rico Electric Power Authority's Integrated Resource Plan* (Cleveland: Institute for Energy Economics and Financial Analysis, April 29, 2016), <http://ieefa.org/wp-content/uploads/2016/04/Comments-on-the-Puerto-Rico-Electric-Power-Authoritys-Integrated-Resource-Plan-April-2016.pdf>.

⁶¹ Kunkel and Sommer.

production from its conventional fossil fuel plants. Furthermore, PREPA does not even attempt to project how much renewable energy and efficiencies could be obtained from renewable sources to meet projected load requirements at the lowest possible cost to the consumer.⁶² According to IEEFA, PREPA resists exploring renewable energy possibilities based on flawed data and a desire to continue using thermal energy for electricity production. PREPA does not have an energy storage plan, nor does it have enough evidence to defend its posture about the unavailability and expense of storage batteries.⁶³ PREPA currently generates 45 percent of its electricity from oil, compared to the 4 percent national average, and only 4 percent from renewables, compared to the 15 percent national average.⁶⁴

PREPA's antiquated systems make this utility company an unreliable enterprise compared to its industry peers. Ordinarily, PREPA customers lose power approximately five times per year, averaging 14.4 blackout hours per incident and taking roughly three hours to restore power. In 2016, Synapse Energy conducted an audit on PREPA to examine the status of the infrastructure of the power grid in Puerto Rico. Synapse's assessment prior to Hurricane Maria showed "cracking, corroding and collapsing" power lines, further stating that "PREPA's system appears to be running on fumes."⁶⁵ This structural weakness left PREPA vulnerable to inclement weather hazards, and given Puerto Rico's geographical location, hurricanes were a major concern.

C. HURRICANES AND PREPA

The island of Puerto Rico is a tropical landmass located in the Caribbean Sea, openly in the route of trade winds, which account for its tropical wet and dry climate. Since its discovery in 1493, the Spanish conquistadors heard the name "Juracan" from the local

⁶² Kunkel and Sommer.

⁶³ Kunkel and Sommer.

⁶⁴ Kunkel and Sommer.

⁶⁵ "Be PREPA-ed."

Taíno tribes, later learning it represented a storm that destroys all.⁶⁶ It was not until the late 1870s that Puerto Rico started officially recording hurricane activity, and thanks to those records, it is estimated that the island has been affected by a hurricane or tropical storm once every 3.4 years.⁶⁷ Given its Caribbean location, Puerto Rico is exposed not only to hurricanes but also to tropical storms and depressions that can cause flooding and wind damage. Most hurricanes tend to enter Puerto Rico through the southeastern part of the island and exit through the northwestern side (see Figure 4). This fact is important in Chapter IV, which suggests a new power grid with power plant locations and electricity storage facilities as important resilience factors.

⁶⁶ Mercedes Carrero Morales, “El huracán en la mitología taína” (San Juan: Center for Advanced Studies of Puerto Rico and the Caribbean, December 14, 2014), <https://aeghcea.files.wordpress.com/2014/12/14-el-huracc3a1n-en-la-mitologc3ada-tac3adna.pdf>.

⁶⁷ “San Juan, Puerto Rico’s History with Tropical Systems,” Hurricane City, accessed August 13, 2018, <http://www.hurricanecity.com/city/sanjuan.htm>.

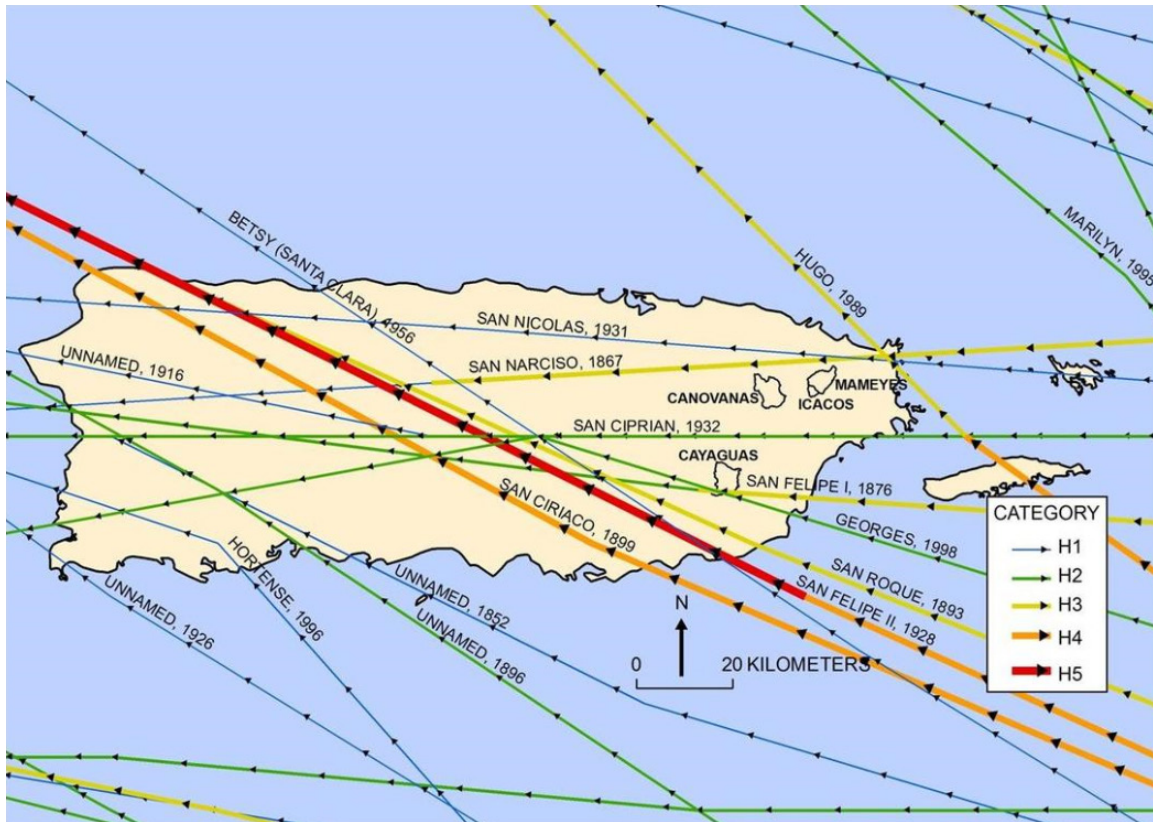


Figure 4. Puerto Rico Hurricanes Map: Historical View⁶⁸

On September 20, 2017, Hurricane Maria brought 150 mph winds to Puerto Rico and dumped 25 inches of rain while following a northwesterly track and entering the island through the southeastern corner, like all other previous hurricanes.⁶⁹ Puerto Rico's power grid was categorically destroyed, with 100 percent of PREPA's customers without power. Category 4 hurricane winds devastated transmission lines and lattice towers throughout the middle region of Puerto Rico because of their advanced age, with 85 percent of them unable to withstand such forces.⁷⁰ Furthermore, reduced standards were used to build the remaining 15 percent of the transmission lines in Puerto Rico; then again, almost all power lines had already been "cracking, corroding and collapsing," thus making them vulnerable

⁶⁸ Source: "Puerto Rico Hurricanes Map," U.S. Geological Survey, accessed February 3, 2019, <https://www.usgs.gov/media/images/puerto-rico-hurricanes-map>.

⁶⁹ Puerto Rico Energy Resiliency Working Group, *Build Back Better*, 10.

⁷⁰ Puerto Rico Energy Resiliency Working Group, 17.

to hurricane forces such as Maria.⁷¹ To complicate matters, one of the most important transmission corridors in Puerto Rico, the south to north lines, were exposed to dense forests and narrow access roads, hence making repairs difficult.⁷²

According to the Puerto Rico Energy Resiliency Working Group, “PREPA’s distribution system is made up of roughly 1,200 circuits, with over 30,000 miles of overhead and underground lines. Most circuits operate at voltages ranging from 4 kV to 13 kV, which is common among electric utilities.”⁷³ During Hurricane Maria, galvanized steel, concrete, and wood poles were significantly damaged or destroyed by high winds.⁷⁴ Like the transmission system, the distribution structure was no match for a Category 4 hurricane, and most of its system lacked sufficient feeder ties, redundancies, or backup service to restore electricity quickly.⁷⁵ The U.S. Army Corps of Engineers initially needed 50,000 new power poles and 6,500 miles of lines to start restoring the grid to pre–Hurricane Maria conditions, but the final number of poles and cable needed has yet to be defined as reconstruction continues and a final government damage assessment has not been finalized.⁷⁶

⁷¹ Puerto Rico Energy Resiliency Working Group, 17.

⁷² Puerto Rico Energy Resiliency Working Group, 17.

⁷³ Puerto Rico Energy Resiliency Working Group, 18.

⁷⁴ Puerto Rico Energy Resiliency Working Group, 18.

⁷⁵ Puerto Rico Energy Resiliency Working Group, 19.

⁷⁶ Jeannine Anderson, “Puerto Rico Needs 50,000 Utility Poles, 6,500 Miles of Cable,” American Public Power Association, October 10, 2017, <https://www.publicpower.org/periodical/article/puerto-rico-needs-50000-utility-poles-6500-miles-cable>.

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III. NEW TECHNOLOGY FOR AN OLD POWER GRID: BUILDING RESILIENCY

Puerto Rico must have a power grid with little to no reliance on fossil fuels for its power generation. One of the main disadvantages of fossil fuel power plants is their dependency on large amounts of fuel reserves to reliably produce large constant amounts of electricity.⁷⁷ In addition, fossil fuel availability depends on market prices, controlled primarily by the Organization of Petroleum Exporting Countries (OPEC), which controls almost half of the world's oil production.⁷⁸ OPEC screens the amount of petroleum that is consumed worldwide and regulates the production of oil to keep wanted prices, thus controlling the available supply.⁷⁹ It is reasonable to infer that a power plant that requires no fossil fuels for its operation, such as a tidal energy plant, will have fuel independence, thus making it resilient to fluctuating market prices and oil availability. Although it may sound like a novel idea, Puerto Rico will not have to invest large amounts of funding to research tidal wave technology as an alternative solution for fossil fuel independence. Scotland has proven the feasibility of this technology and is leading the world market in renewable energy production.⁸⁰

A. ELECTRICITY PRODUCTION AND FUEL RESILIENCY

With Edinburgh as its capital and with a population of approximately 5,425,000 people, Scotland is “an austere land, subject to extremes of weather. . . . Scotland has proved a difficult home for countless generations of its people, who have nonetheless prized it for its beauty and unique culture.”⁸¹ Scotland shares some unique commonalities

⁷⁷ Crystal Ayres, “15 Most Notable Advantages and Disadvantages of Fossil Fuels,” *Connect US* (blog), July 2, 2015, <https://connectusfund.org/15-most-notable-advantages-and-disadvantages-of-fossil-fuels>.

⁷⁸ Ayres.

⁷⁹ Ayres.

⁸⁰ Derry Alldritt and David Hopwood, “Renewable Energy in Scotland,” *Renewable Energy Focus* 11, no. 3 (May 2010): 28–30, 32–33, [https://doi.org/10.1016/S1755-0084\(10\)70064-8](https://doi.org/10.1016/S1755-0084(10)70064-8).

⁸¹ *Encyclopedia Britannica*, s.v. “Scotland,” last modified May 18, 2018, <https://www.britannica.com/place/Scotland>.

with Puerto Rico, thus making it a suitable and reasonable comparison. Like Puerto Rico, Scotland has vast shorelines and access to ocean currents, a source that is currently being used as part of its renewable energy policies. Strong coastlines give Scotland an unprecedented advantage over many countries racing for renewable energy, and Scottish politicians are using such benefits as a tool to promote and incentivize their economy.⁸²

So far, Scotland has had enormous success with its renewable energy production, supplying 68.1 percent of its energy demand with green energy initiatives, which contributed a renewable electricity capacity of 9.9 gigawatts in 2017. This indicates a surge of about 10 percent since 2016.⁸³ However, its success is not an isolated, random event but a well-planned process that culminated in the legislation and enactment of Scotland's Climate Change Act of 2009, which

creates the statutory framework for greenhouse gas emissions reductions in Scotland by setting an interim 42 per cent reduction target for 2020, with the power for this to be varied based on expert advice, and an 80 per cent reduction target for 2050. To help ensure the delivery of these targets, this part of the Act also requires that the Scottish Ministers set annual targets, in secondary legislation, for Scottish emissions from 2010 to 2050.⁸⁴

In essence, mandating the reduction of greenhouse emissions by 2020 forced Scotland to look for alternate methods of electricity production that could meet demand yet abide by the newly enacted law. In doing so, new forms of energy production were sought, and innovative technological systems became available on the open market, thus increasing competitiveness and investment opportunities as well as stimulating its economy. But what began as a greenhouse reduction initiative also became a movement toward fuel independence and security that has improved its power grid resiliency.

This competing environment created green industries that captured Scotland's natural elements in its quest to quench electricity demand. As such, wind farms,

⁸² Alldritt and Hopwood, "Renewable Energy in Scotland."

⁸³ Rob Smith, "Scotland Produced a Record Amount of Renewable Energy Last Year," World Economic Forum, April 10, 2018, <https://www.weforum.org/agenda/2018/04/scotland-produced-a-record-amount-of-renewable-energy-last-year/>.

⁸⁴ "Climate Change: Legislation," Scottish Government, July 11, 2017, <https://www.gov.scot/publications/climate-change-legislation/>.

hydroelectric dams, tidal and wave farms, and solar farms—among others—were introduced and are currently used to supply electricity. Figure 5 depicts Scotland’s diversified renewable energy production.

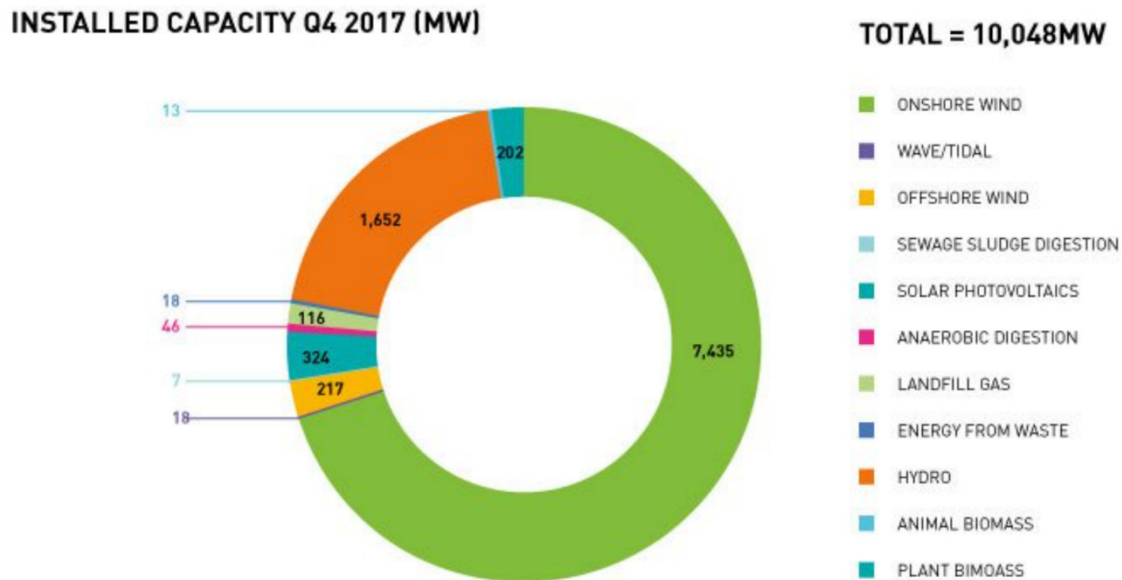


Figure 5. Current Installed Capacity of Renewable Energy in Scotland⁸⁵

Notably, only 18 percent of the renewable energy produced in Scotland is derived from wave and tidal energy, and most is produced by wind farms; however, those energy sources contribute about 1,808.64 megawatts of electricity, which is more than half of the electricity demand in Puerto Rico. It could reasonably be argued that exploring wind and solar energy for Puerto Rico, given the success in Scotland, is a more viable option; however, it could also be argued that because Scotland’s wind farms are not exposed to Category 5 hurricane winds, such as during Hurricane Maria, they could be vulnerable to such extreme forces.

The Scottish Government has committed to confronting climate change with a robust backing for renewable energy expansion through governmental lawmaking and

⁸⁵ Source: “Renewables in Numbers,” Scottish Renewables, accessed February 3, 2019, <https://www.scottishrenewables.com/sectors/renewables-in-numbers/>.

strategies.⁸⁶ The Scotland Climate Change Act of 2009 plans to have 100 percent of Scottish electrical energy requirements supplied by renewable technology by 2020.⁸⁷ As such, Scotland has resorted to its 16,500 km of coastline to use the ocean’s abundant wave and tidal energy to produce electricity.

The MeyGen project in the Inner Sound of Scotland is an array of underwater turbines that generates approximately 400 MW of electricity—enough to power 40,000 houses.⁸⁸ By comparison, Puerto Rico could implement similar renewable energy policies and use its 501 km of coastline for energy production. With a requirement of 3,060 MW of electricity, Puerto Rico’s power demand could be satisfied with eight underwater turbine arrays that could potentially generate 3,200 MW of electricity.⁸⁹ Figure 7 presents a rendering of a tidal turbine currently deployed in Scotland.

⁸⁶ Scottish Government, “Climate Change: Legislation.”

⁸⁷ Scottish Government.

⁸⁸ MeyGen Limited, *MeyGen Tidal Energy Project – Phase I: Non-Technical Summary* (Edinburg: MeyGen Limited, 2010), https://www.iema.net/assets/nts/Xodus/Meygen_Tidal_Energy_Project_NTS_August_2011.pdf.

⁸⁹ Puerto Rico Energy Resiliency Working Group, *Build Back Better*, 8–9.

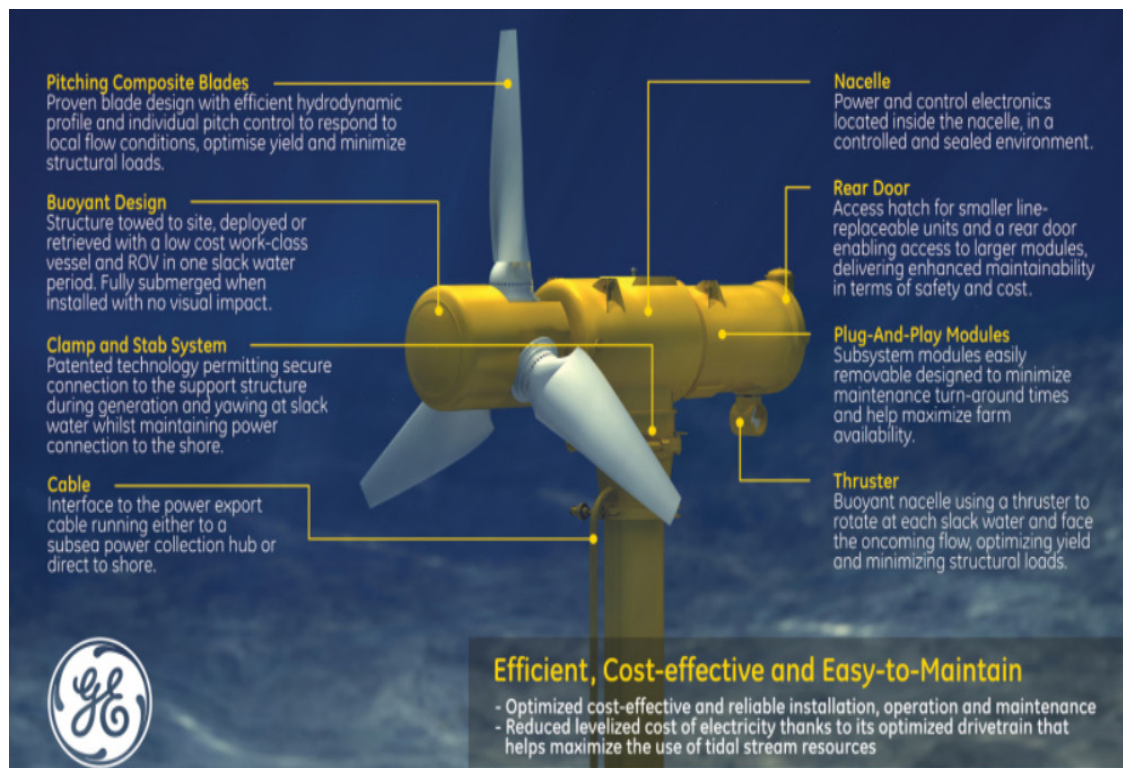


Figure 6. Tidal Stream Turbine⁹⁰

This new electrical power generation method should make Puerto Rico less dependent on fossil fuels that require constant foreign imports of oil, minimize the use of seaports for their delivery, especially if those ports are inoperable after a hurricane, thus making the grid more resilient and the recovery faster.⁹¹ Most of Scotland's power sites are located around remote islands, in channels between islands, or between Scottish islands and the mainland.⁹² Scotland's Pentland Firth Project is composed of a tidal array capable of producing 200 MW while the MeyGen project in the Inner Sound is capable of

⁹⁰ Source: "Oceade 1.4-18 Tidal Stream Turbine," General Electric, accessed February 15, 2019, https://siemreapnews.files.wordpress.com/2016/10/energy-production-tidal-oceade-technology_02.jpg?w=816.

⁹¹ For tidal current technology, the stream speed needs to be at least 1.5–2 m per second (m/s). Ruud Kempener and Frank Neumann, *Tidal Energy* (Abu Dhabi: International Renewable Energy Agency, 2014), 21. <https://www.irena.org/mwg-internal/de5fs23hu73ds/progress?id=jVcyxT9WfJojksIBuRK6H6s5QskAPvHs7-h68AoJEro,.>

⁹² Simon P. Neill et al., "The Wave and Tidal Resource of Scotland," *Renewable Energy* 114, pt. A (March 2017), <https://doi.org/10.1016/j.renene.2017.03.027>. Neill, 2017.

producing 400 MW—all because of the strong ocean currents available at these sites.⁹³ Similarly, and given its access to ocean resources, Puerto Rico can capture 67 percent of its wave energy in the inner coastal waters, thus producing 6.7 MW per kilometer with a single 10 MW array and can capture up to 89 percent per kilometer of deep water wave energy, accordingly producing 17.8 MW with a single 20 MW tidal array.⁹⁴ By extrapolating these figures and using a system similar to Scotland’s 400 MW Inner Sound project, Puerto Rico could potentially produce between 268 MW (using 67 percent of inner coastal water power) and 356 MW (using 89 percent of deep coastal water power). A representative rendering of an underwater tidal power array that could be used in Puerto Rico coastal waters is depicted in Figure 7.



Figure 7. Tidal Array Depiction⁹⁵

⁹³ Neill et al.

⁹⁴ P. Jacobson, *Mapping and Assessment of the United States Ocean Wave Energy Resource* (Palo Alto: Electric Power Research Institute, 2011).

⁹⁵ Source: “Tidal Array Depiction,” CNN, accessed February 3, 2019, <https://cdn.cnn.com/cnnnext/dam/assets/141211143521-meygen4-horizontal-large-gallery.jpg>.

For this underwater array to work and be feasible, it must be protected as much as possible from hurricanes and have a strong tidal current. First, strong maritime currents must be available to maximize the use of underwater turbines and effectively obtain their maximum capacity of 400 MW of electricity. As depicted in Figure 8, within the Straits of Florida, the looping currents feed the Gulf Stream.⁹⁶ This current is amplified by the Antilles current, which passes along the northern coast of Puerto Rico, thus becoming an ideal location for underwater turbines.⁹⁷

Location Proposal: Future Tidal Array Location in Puerto Rico

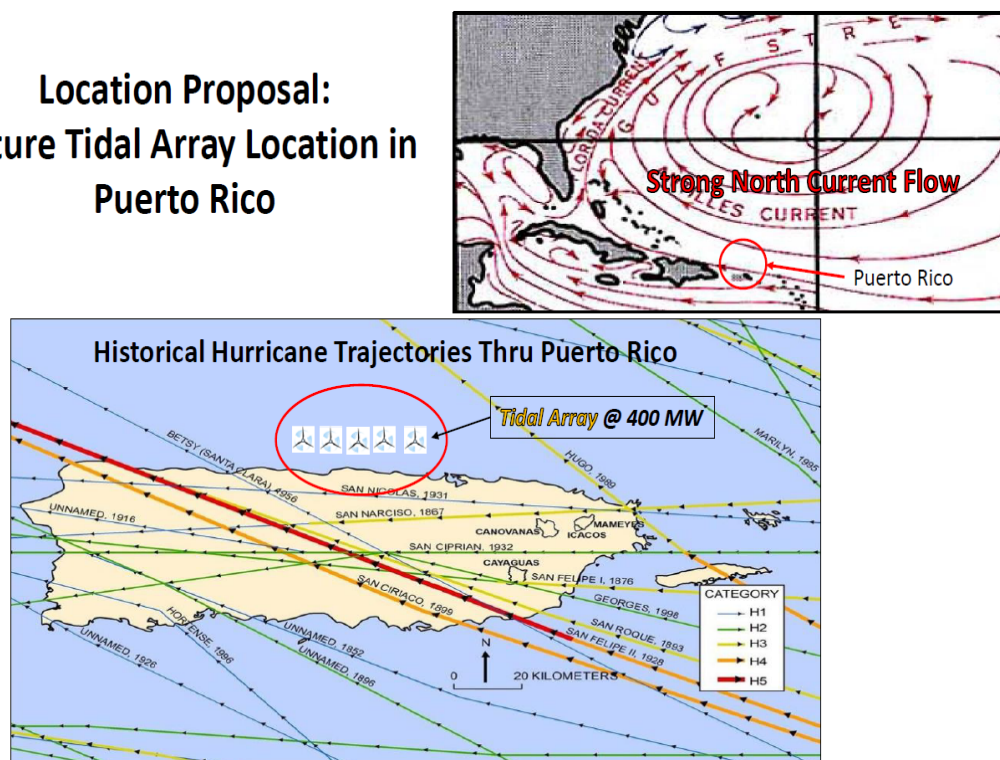


Figure 8. Tidal Array Location Proposal for Puerto Rico⁹⁸

⁹⁶ “Ocean Currents,” National Geospatial Intelligence Agency, accessed October 13, 2018, https://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/APN/Chapt-32.pdf.

⁹⁷ Elizabeth Rowe, Arthur J. Mariano, and Edward H. Ryan, “The Antilles Current,” Rosenstiel School of Marine and Atmospheric Science, accessed February 3, 2019, <https://oceancurrents.rsmas.miami.edu/atlantic/antilles.html>.

⁹⁸ Adapted from: National Geospatial Intelligence Agency, “Ocean Currents”; and U.S. Geological Survey, “Puerto Rico Hurricanes Map.”

Second, the array is naturally protected from hurricanes by the nature of the sub-surface implementation and, as depicted in Figure 8, the northern area between the cities of San Juan and Arecibo provides the best protection against the predominant track of hurricanes. Therefore, the northern side of Puerto Rico provides the optimal conditions for the successful deployment of an underwater tidal energy system.

B. TRANSMISSION LINE RESILIENCE

Continuing with Abi-Samra's posture regarding grid resiliency and the inevitability of power grid failure regardless of the amount of hardening, transmission lines must be designed for reparability to decrease recovery time after a catastrophic event. Chapter II described how the U.S. Army Corps of Engineers needed 50,000 new power poles and 6,500 miles of lines to restore the grid to pre-Hurricane Maria conditions. It also described how Puerto Rico's aging infrastructure was a contributing factor to the total collapse of the power system on the island, mostly caused by vegetation, inaccessibility, and the lack of system status information. The average age of substation transformers in the United States, including Puerto Rico, is approximately 42 years, with some in operation for 70 years.⁹⁹ Even when the age of these systems is a crucial factor, the lack of visibility and real-time data on the transmission system hinder workers from knowing the status of many substations as part of the main distribution network in Puerto Rico.

An article by S&P Global indicates, "PREPA has 370 miles of 230-kV line that loops the island and bisects it from north to south in two places. It also has 731 miles of 115-kV line that helps link a total of 344 substations."¹⁰⁰ These are the main lines that transmit and distribute power around the island; however, they are also the most vulnerable because they are exposed to the elements and do not have redundancies as alternate routes for power distribution.

⁹⁹ ABB Power Products, *Resiliency Planning for the Transmission Grid* (Zurich: ABB, 2013), <https://library.e.abb.com/public/041ac7ae0de9e6a7c1257bfe0065b3de/ABB-755-WPO.pdf>.

¹⁰⁰ Jeffrey Ryser, "DOE Pushes to Repair Puerto Rico Power System," S&P Global, October 2, 2017, <https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/100217-doe-pushes-to-repair-puerto-rico-power-system>.

When addressing the issue of transmission line disruption, it is important to note that, although possible, the breakdown of the metal line is not the most common cause of power line failure. As depicted in Figure 9, the collapse of the steel towers supporting transmission lines takes the longest time to repair and massive amounts of inventory to respond properly to a catastrophic event, such as Hurricane Maria.



Figure 9. Collapsed Transmission Tower in Puerto Rico¹⁰¹

In light of this, Puerto Rico should store standardized lightweight reusable modular aluminum restoration structures that are designed as temporary replacements for traditional steel towers (see Figure 10). These flexible smaller towers are easy to transport and install and are designed to restore power in the shortest amount of time.¹⁰² These towers are also a perfect choice for temporary emergency communications platforms to support first responders because permanent communication structures will likely collapse during the storm.

¹⁰¹ Source: “Collapsed Transmission Tower in Puerto Rico,” Environment and Energy Publishing, accessed February 3, 2019, https://www.eenews.net/image_assets/2017/12/image_asset_25855.jpg.

¹⁰² Keith E. Lindsey, *Transmission Emergency Restoration Systems for Public Power*, 07T-005 (Azusa, CA: Lindsey Manufacturing, 2015), <http://lindsey-usa.com/wp-content/uploads/2015/10/07T-005-ERS-PUBLIC-POWER.pdf>.

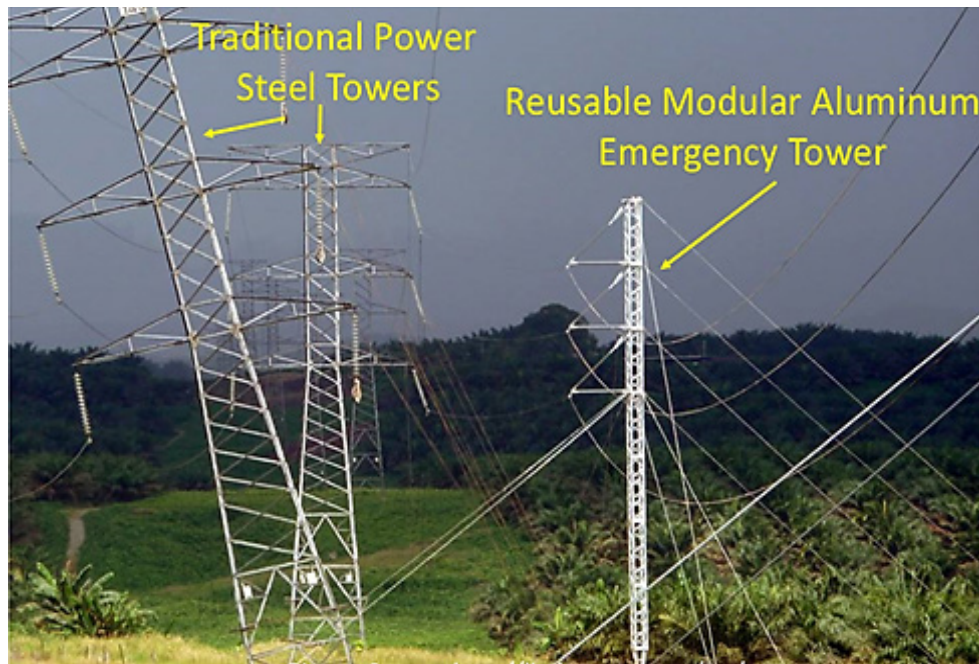


Figure 10. Lindsay Emergency Power Tower¹⁰³

Underground power lines are another alternative method for supplying electricity to consumers; digging trenches and burying miles of cable ensures the power lines will be protected from the elements and falling debris. This transmission option should be considered in Puerto Rico as a measure to increase the transmission and distribution network’s survivability during and after a natural disaster such as Hurricane Maria. Usually, the question of why overhead power lines are not underground gains relevance after a catastrophic event. The simple answer is that they can be underground but at an elevated cost compared to overhead lines. Regardless of cost, “generalized cost ratios of underground to overhead options should not be used because costs are site-specific,” and cost-effectiveness depends on the purpose and final goal of the underground cable.¹⁰⁴

¹⁰³ Source: “ERS with Lindsey,” Lindsey Manufacturing, accessed February 3, 2019, <http://lindsey-usa.com/ers/>.

¹⁰⁴ Public Service Commission of Wisconsin, *Underground Electric Transmission Lines* (Madison: Public Service Commission of Wisconsin, June 2007), <https://electrical-engineering-portal.com/res/Underground-electric-transmission-lines.pdf>.

Underground cable infrastructure is typically 14 times more expensive than an overhead line. For example, “a typical new 69 kV overhead single-circuit transmission line costs approximately \$285,000 per mile as opposed to \$1.5 million per mile for a new 69 kV underground line.”¹⁰⁵ In the case of Puerto Rico with its financial predicament, underground cabling should be considered on a case-by-case basis to determine what portion of the cable should be above or underground. Ken Buell, director of Emergency Response and Recovery with the U.S. Department of Energy, indicated that one of the biggest problems found in Puerto Rico after Hurricane Maria hit the island was the catastrophic damage done to most of the power lines that transmitted electricity from power plants to distribution centers in major populated areas.¹⁰⁶ These principal lines crossed mountainous areas and were exposed to wind damage and falling debris; however, two of three underground lines did survive the storm. Thus, although more expensive than traditional power lines, underground cables are better positioned to resist inclement weather. Therefore, suggestions for underground cable at critical points in the transmission and distribution networks in Puerto Rico, which could improve the electric power grid’s capacity to recuperate after a natural hazard such as a hurricane, are provided in Chapter IV.

C. SMART GRID

Part of improving the resiliency of Puerto Rico’s power grid is decentralizing the electricity supply chain and implementing a closed loop multidirectional flow of electricity, most commonly known as a smart grid. What makes this grid “smart” is its two-way communication ability between consumer and provider and the capability of sensors to provide data along transmission lines, thus allowing a rapid response to quick-changing electricity demands. Constructing a completely new power grid in Puerto Rico is not a reasonable proposition given the cost and time to replace all existing infrastructure;

¹⁰⁵ Frank Alonso and Carolyn Greenwell, “Underground vs. Overhead: Power Line Installation-Cost Comparison and Mitigation,” PennWell Corporation, February 1, 2013, https://www.elc.com/articles/powergrid_international/print/volume-18/issue-2/features/underground-vs-overhead-power-line-installation-cost-comparison-.html.

¹⁰⁶ Rachael Becker, “After Hurricane Maria, What Will It Take to Turn Puerto Rico’s Power Back On?,” *Verge*, September 25, 2017, <https://www.theverge.com/2017/9/25/16362410/hurricane-maria-puerto-rico-power-outages-electrical-grid-destroyed>.

however, transitioning to a smart grid could be accomplished by integrating new meters, sensors, and synchro phasors.¹⁰⁷ This would allow the grid in Puerto Rico to provide more efficient electricity transmission, restore its power faster after a power outage, reduce peak demand of electricity, allow for an easy integration of renewable energy such as tidal power, and integrate consumer-owned generation systems.¹⁰⁸

When Hurricane Maria hit Puerto Rico in 2017, the power grid suffered multiple catastrophic damages that resulted in a domino effect, which affected communications, the banking industry, traffic, hospitals, and security, among others. This was partially the result of the centralized nature of Puerto Rico's power grid, whereby electricity is generated and distributed in a one-way linear transmission to the end user. In other words, if there is an interruption at the power plant or the transmission lines, the customer has no power until the problem is identified and rectified. On the other hand, a smart grid and its loop multidirectional flow of electricity allow for the automatic rerouting of electricity by detecting and isolating the problem to avoid further damage and outages.¹⁰⁹ This automation and ability to reroute available electricity allow for the rapid redistribution of electricity to essential emergency services such as hospitals, police and EMS services, traffic lights, communications, and banking systems.

As previously mentioned, Puerto Rico's power grid is a centralized energy production system with eight fossil fuel-burning power plants that supply 3,060 MW of required electricity. One of this system's problems is its inability to easily incorporate renewable energy into its grid due to the incompatibility of electric stability.¹¹⁰ For example, electricity from renewable energy sources, such as solar and wind power plants,

¹⁰⁷ Schweitzer Engineering Laboratories defines synchronized phasors (synchro phasors) as a tool to "provide a real-time measurement of electrical quantities from across the power system." "Synchrophasors," Schweitzer Engineering Laboratories, accessed February 3, 2019, <https://selinc.com/solutions/synchrophasors/>.

¹⁰⁸ "What Is the Smart Grid?" U.S. Department of Energy, accessed February 3, 2019, https://www.smartgrid.gov/the_smart_grid/smart_grid.html.

¹⁰⁹ U.S. Department of Energy.

¹¹⁰ Jinju Zhou et al., "What's the Difference between Traditional Power Grid and Smart Grid?—From Dispatching Perspective," *Proceedings of the 2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference* (December 2013), <https://doi.org/10.1109/APPEEC.2013.6837107>.

fluctuates depending on wind conditions or solar light intensity, thus varies in voltage, and conflicts with the main power plant's electricity. However, a smart grid can identify fluctuations in voltage and automatically convert or reroute renewable energy to storage facilities where electricity could be stabilized and synchronized before it is consumed. Puerto Rico currently does not have the capability to store renewable and regular generated electricity in quantities that could significantly decrease power outages on the island, thus suggesting the need to incorporate new battery storage facilities across the island as part of a smart distribution grid network.

D. ELECTRICITY STORAGE

Lithium-ion batteries are generally lighter and smaller and have a higher electricity storage capacity.¹¹¹ The most important characteristic of lithium-ion batteries is that they can be charged quickly, are less prone to discharge over time, and have a longer lifespan when compared to a regular acid battery.¹¹² This characteristic makes these batteries suitable for permanent storage across the grid and residential and industrial storage in Puerto Rico. These storage facilities, commonly known as large-scale energy storage, hold back electricity when surplus energy is produced, thus exceeding demand and consumption. This stored electricity is then redistributed to the grid when energy requirements peak and production cannot meet demand.¹¹³ This battery energy configuration is designed to insert stable and regular amounts of electricity into the grid for extended periods, and although energy storage is not a stand-alone solution to supply Puerto Rico's electricity needs, it offers to improve reliability and better utilization by providing electricity when it is needed. Batteries also offer a great opportunity, not only because they store excess electricity produced by renewable energy sources but also because their small size is well suited as distributed sources of energy that can be located in several areas depending on Puerto Rico's energy needs.

¹¹¹ Kristoffer Bonheur, "Advantages and Disadvantages of Lithium Ion Battery," March 13, 2016, <http://www.versiondaily.com/lithium-ion-battery-advantages-disadvantages/>.

¹¹² Bonheur.

¹¹³ Bruce Dunn, Haresh Kamath, Jean-Marie Tarascon, "Electrical Energy Storage," *Science* 334, no. 6058 (November 2011): 928–935, <https://doi.org/10.1126/science.1212741>.

Battery-stored electricity systems distributed across Puerto Rico provide options to deal with emergencies and sustain vital services.¹¹⁴ For example, electricity storage is a vital component used as a reserve resource to maintain a continual supply of power during hazardous weather conditions or equipment malfunctions. These battery banks serve as electricity backup systems to supply power to remote areas of the island where the only power line might be disrupted, thus providing much-needed electricity. Figure 11 illustrates a grid battery power storage facility that could be incorporated in Puerto Rico.



Figure 11. Sample Battery Storage Bank¹¹⁵

The battery storage concept is not new in Puerto Rico, as proposals had been made to introduce this system. In 2016, SAFT Industries was awarded a contract to provide three Intensium Max 20P high-power lithium-ion batteries for a 10 MW photovoltaic facility in

¹¹⁴ “Grid Scale Energy Storage Systems,” Electropedia, accessed February 3, 2019, https://www.mpoweruk.com/grid_storage.htm.

¹¹⁵ Source: “Sample Battery Storage Bank,” PV Tech, accessed February 3, 2019, https://www.pv-tech.org/images/made/assets/images/editorial/Nas_batteries_low_res_750_500_80_s.jpg.

Puerto Rico (see Figure 12).¹¹⁶ According to SAFT officials, “In remote locations and islands, it is essential our batteries can handle substantial daily energy flows and high power outputs in order to stabilize solar farms.”¹¹⁷ However, PREPA refused to own the battery project since previous experiences with this kind of technology were negative, and the plan never materialized. In addition, the solar farm took a direct hit from Hurricane Maria’s eyewall, ripping the solar panels from their foundations and completely destroying them.¹¹⁸



Figure 12. A Solar Array in Puerto Rico prior to Its Destruction by Hurricane Maria in 2017¹¹⁹

¹¹⁶ Saft is a world world-leading designer and manufacturer of advanced technology batteries for industry. “Saft Lithium-Ion Battery Systems Enable Domestic Renewable Energy Generation in Puerto Rico,” Saft, March 15, 2016, <https://www.saftbatteries.com/press-releases/saft-lithium-ion-battery-systems-enable-domestic-renewable-energy-generation-puerto>.

¹¹⁷ Saft.

¹¹⁸ Dakota Smith, “Puerto Rican Solar Farms Heavily Damaged by Hurricane Maria,” *Weather Junkies* (blog), September 28, 2017, <http://www.theweatherjunkies.com/single-post/2017/09/28/Puerto-Rican-Solar-Farms-Heavily-Damaged-By-Hurricane-Maria#!>.

¹¹⁹ Source: Rich Dana, “Update: Solar Recovery in Puerto Rico,” *Solar Tribune*, December 11, 2017, <https://solartribune.com/update-solar-recovery-puerto-rico/>.

Grid storage capacity is an essential part of a resilient power grid, but it is only that—a portion of an overall plan to overhaul existing power grids into a modern renewable energy smart grid. Therefore, it is important that other means of energy generation and storage are integrated when planning to decentralize energy production, distribution, and storage, thus increasing the chances of infrastructure survivability when confronted with natural or manmade hazards. To help minimize the centralization of electricity storage, customer-sited energy storage should be incorporated to deliver standby power that can be used by individuals when the grid is inoperable.

E. CUSTOMER-SITED ENERGY STORAGE

The U.S. electric grid is undergoing technological changes toward the decentralization of electricity production, transmission, and distribution.¹²⁰ As such, much emphasis is given to empower individual homeowners and businesses to produce, store, and sell electricity, which could provide cost savings, improve electricity quality, better use grid resources, and increase grid resiliency.¹²¹ Electricity storage at individual residences or commercial buildings in Puerto Rico will not only have a positive environmental impact due to its compatibility with renewable green sources of electricity but also serve as an emergency backup source of power. Figure 13 shows how customer-sited energy storage works.

¹²⁰ “Accelerating Customer Sited Energy Storage,” Sustainable Development Technology Canada, accessed February 3, 2019, <https://www.sdtc.ca/en/projects/accelerating-customer-sited-energy-storage/>.

¹²¹ Sustainable Development Technology Canada.

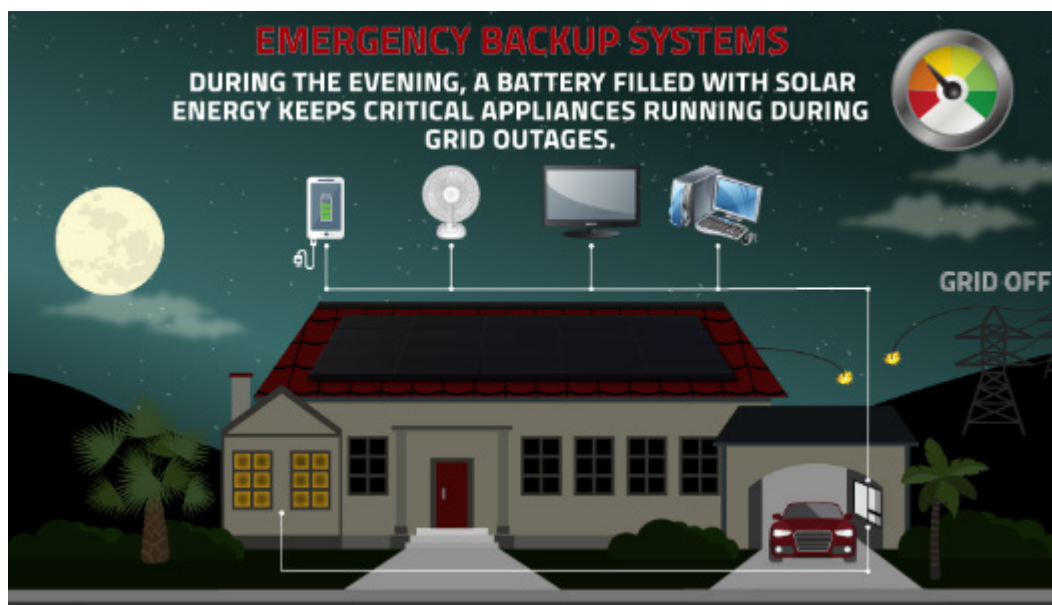


Figure 13. Backup Loads in Time of Crisis¹²²

According to Janice Lin, director and founder of the California Energy Storage Alliance, the continued utilization of customer-sited storages for the reduction of peak electricity demand proves its reliability and improves grid resiliency during an outage event when compared to a standalone battery or generator, which is used only during an outage.¹²³ The best example of customer-sited energy storage is the combination of solar panels and batteries at the residential level. With year-round tropical weather, Puerto Rico should take advantage of photovoltaic technology to capture year-round sunlight and store its energy in long-term batteries. Figure 14 shows the average monthly hours of sunlight in Puerto Rico. Based on these data, Puerto Rico receives an average of eight hours per day of strong solar light, thus making photovoltaic technology a logical resource for alternative electricity production.

¹²² Source: “Residential Battery Systems,” Sun Valley Solar Solutions, accessed February 3, 2019, <https://www.sunvalleysolar.com/battery-energy-storage-technology>.

¹²³ Janice Lin, “Renewable Energy: On-Site Energy Storage,” Facility Executive, October 3, 2016, <https://facilityexecutive.com/2016/10/renewable-energy-on-site-energy-storage-systems/>.

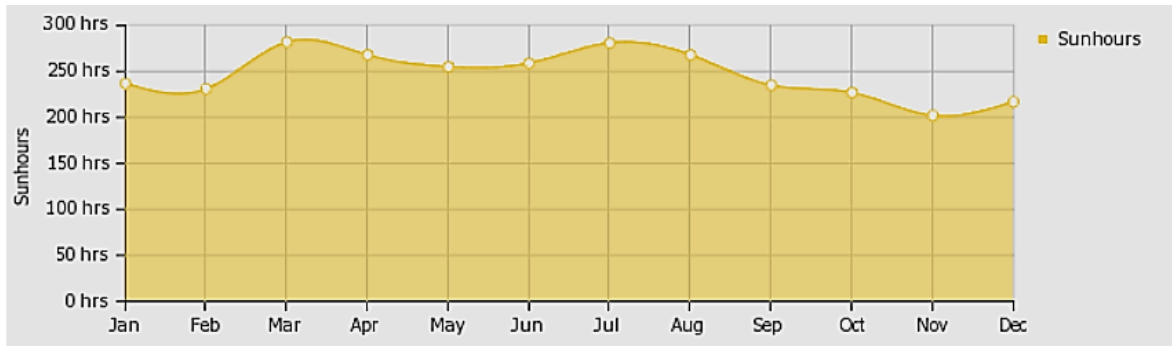


Figure 14. Average Monthly Sun Hours in Puerto Rico¹²⁴

As depicted in Figure 15, by capturing sunlight during peak hours of the day when the sun is at its brightest, residences could store an average of eight hours of electricity and utilize stored electricity during evening hours when supply stops while demand continues.

¹²⁴ Source: “Average Monthly Sun Hours in Puerto Rico,” World Weather and Climate Information, accessed February 15, 2019, <https://weather-and-climate.com/uploads/average-sunshine-puerto-rico-fajardo.png>.

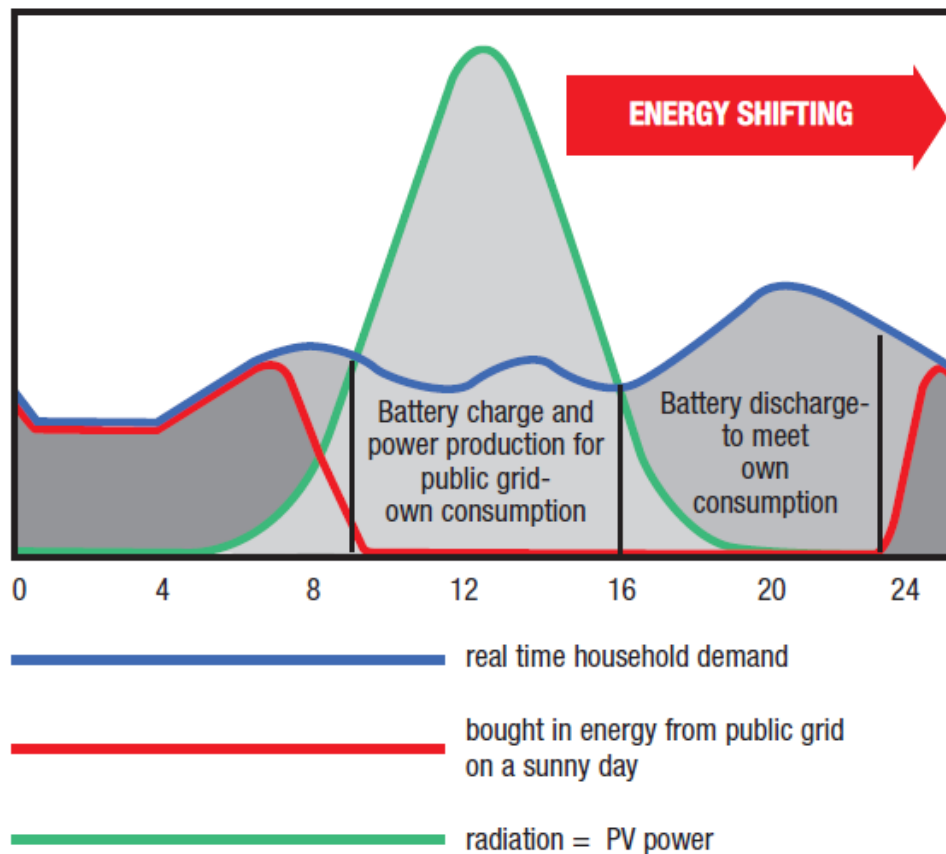


Figure 15. Direct Storage and Consumption of Residential Solar-Produced Electricity¹²⁵

The U.S. Energy Information Administration estimates that the average 2016 annual electricity consumption for a typical residence in the United States was 10,766 kilowatt-hours (kWh).¹²⁶ This means that the daily household consumption of electricity was approximately 29.28 kW per day.¹²⁷ According to EnerSys, a global industry leader

¹²⁵ Source: EnerSys, *Smart Decisions* (Zurich: EnerSys, 2014), 3, http://www.enersys-emea.com/reserve/pdf/EN-SP-4PP-003_0614.pdf.

¹²⁶ "Frequently Asked Questions," U.S. Energy Information Administration, accessed September 15, 2018, <https://www.eia.gov/tools/faqs/faq.php?id=97&t=3>.

¹²⁷ $10,766 \text{ kWh} / 8,760 \text{ h} = 1.22 \text{ kWh}$; $1.22 \text{ kWh} \times 24 \text{ h} = 29.28 \text{ kW}$.

in energy storage solutions, a typical residential solar system consisting of roof solar panels and a battery bank can store 9.2 kWh or 73.6 kW per day (see Table 2 and Figure 16).¹²⁸

Table 2. Residential Storage System¹²⁹

	48 V System 9.2
Storage System	
Energy content [kWh]	9.2
Nominal voltage [V]	48
Dimensions L x W x H [mm]	780 x 350 x 1001
Weight [kg]	300
Batteries	
Battery Type	pure lead (TPPL)
Number of blocs	4
Nominal voltage per bloc [V]	12
Wiring	4 blocs serial
Technology	pure lead (TPPL)
Capacity C10 [Ah]	190
Cyclic performance at 35% DOD	2500 cycles
Cyclic performance at 50% DOD	1800 cycles
Roundtrip efficiency	90%
Fast charge capability	yes

If the average household consumes 29.28 kW per day and this solar system can store 73.6 kW per day, the average residential consumer could sell back to the main power grid 44.62 kWh or 60 percent of what the residential solar system produces. These figures suggest that the average household will have electricity as needed during power outages, thus improving its ability to endure natural disasters by powering emergency medical and basic needs appliances.

¹²⁸ 9 kWh x 8 h = 73.6 kW.

¹²⁹ Source: EnerSys, *Smart Decisions*, 3.

Another approach to determine the effectiveness and viability of solar technology in producing electricity is to calculate per capita daily electricity consumption and the current solar electricity production capacity. If solar power on its own is capable of supplying consumers' electricity demands, it is possible to consider this renewable source as a viable alternative to replace all fossil fuel electricity generation in Puerto Rico. Research conducted by Dr. Thomas Makin of California Polytechnic State University reveals that Puerto Rico can expect 5.52 kWh/m²/day using a stationary flat panel collector, so a solar panel area of 2.81 m²/person is needed.¹³⁰

¹³⁰ Dr. Makin's calculations, relayed via personal communication, were based on data from the National Renewable Energy Laboratory Resource Assessment Program, as depicted in Figure 16.

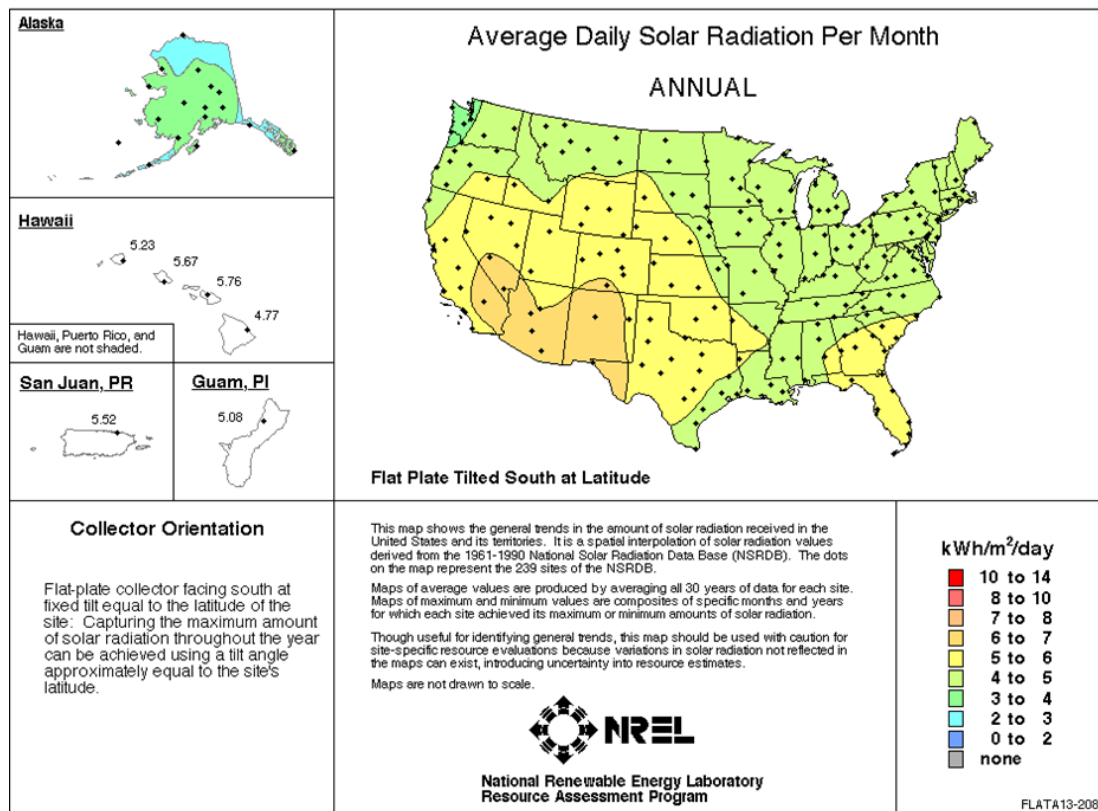


Figure 16. Average Solar Energy Flux Captured by a Stationary Flat Panel System as a Function of Location¹³¹

Makin argues that if Puerto Rico was to convert entirely from petroleum-based fuel transportation to electric transportation, solar panels would supply the energy equivalent of gasoline in addition to daily electricity needs. Utilizing data from the Energy Information Administration—showing Puerto Rico consumed 42,000 barrels of petrol per day in 2016 for transportation—and assuming that the average driver consumes fuel at a rate of 20 miles per gallon, Makin calculated that people in Puerto Rico traveled 35 million miles per day. Given that a 24 kWh battery pack has enough electrical charge to fuel a

¹³¹ Source: “Average Solar Energy Flux Captured by a Stationary Flat Panel System as a Function of Location,” National Renewable Energy Laboratory Resource Assessment Program, accessed February 15, 2019, <http://www.truthfulpolitics.com/images/average-daily-solar-radiation-map.jpg>.

vehicle up to 70 miles, the extra kWh required for transportation can be determined using the following formula:

$$\text{Transportation energy required/day} = 35 \times 106 \text{ miles} = \frac{35 \times 10^6}{70/24} = 12 \times 10^6 \text{ kWh/day}$$

If 12 multiplied by 106 kWh/day is divided by 3.337 million (the current residents of Puerto Rico), the result shows an additional need of 3.62 kWh/person/day, thus making the total electric need 19kWh/person/day (3.62 + 15.5 kWh/person/day). Utilizing the aforementioned energy production of 5.52 kWh/m²/day, the required solar panel area to produce this amount of electricity can be estimated at 3.44 m² of solar panels per person if the vehicles can also act as battery storage. This means that 3.44 m² of solar panel per person could supply the current electricity and energy demand of Puerto Rico. With a cost of \$7–\$9/watt per installed solar panel, the total installed cost to meet the needs of Puerto Rico is approximately \$11,000–\$14,250 per person. If a total rebuild of Puerto Rico’s power grid is sought, it will require approximately \$48 billion to accomplish.¹³²

F. MICROGRIDS

A microgrid is a local electricity system with independent control that can be disconnected from the main power grid, or macrogrid, and independently produce, transmit, and distribute electricity.¹³³ The most important characteristic of a microgrid is its ability to be powered by renewable energy sources such a solar power and, thus, the potential to run indefinitely. This kind of system can power smaller communities, making them energy independent, and in emergencies serve as backups to the main grid.

There are no specific guidelines that regulate how a microgrid should operate. Each microgrid, because it is independently operated and owned, can operate using various combinations of sources of fuel to generate its own electricity. However, to be identified as a microgrid, it must be controlled locally and must be able to operate connected to the

¹³² 3.337 million people in Puerto Rico x \$14,250 = \$47.5 billion

¹³³ Allison Lantero, “How Microgrids Work,” U.S. Department of Energy, June 17, 2014, <https://www.energy.gov/articles/how-microgrids-work>.

macrogrid or run independently as an electrical island. The Grid Integration Group at the Berkeley Lab, indicates there are several advantages to using microgrids:

- Improved energy efficiency
- Minimization of overall energy consumption
- Reduced environmental impact
- Improvement of the reliability of supply
- Network operational benefits such as loss reduction
- Congestion relief
- Voltage control, or security of supply of electricity
- More cost-efficient electricity infrastructure replacement¹³⁴

In the case of natural hazards and catastrophic events, fuel availability and distribution are mired due to inaccessible roads and degraded communications, as experienced after Hurricane Maria. Given Puerto Rico's fiscal predicament and the high cost of fuel powering the current grid, it is important to deviate from energizing microgrids with fossil fuels and resort to alternative renewable sources of fuel. For this reason, it is suggested that the Hachinohe Project in the Aomori Prefecture of Japan be used as a template for future microgrid developments in Puerto Rico.

The Hachinohe Project was operated from 2005 to 2008 and served as a test platform to develop new operating systems that could manage the effectiveness of new environmentally friendly technologies.¹³⁵ As part of this project, a microgrid was developed using only renewable sources of energy such as wind turbines, lead-acid batteries, and gas turbines fueled by sewage waste gas by-products, with a total capacity of electricity of 690 kW per day.¹³⁶ According to Berkeley Lab, the Hachinohe project used the local sewage plant to install a condensation boiler capable of producing a 907 kg of

¹³⁴ "About Microgrids," Berkeley Lab, accessed February 3, 2019, <https://building-microgrid.lbl.gov/about-microgrids-0>.

¹³⁵ Berkeley Lab.

¹³⁶ Berkeley Lab.

heat. This boiler structure was later integrated into the microgrid with a data reciprocating system that allowed electrical current to be sent to the local community using a private distribution line.¹³⁷

Currently, Puerto Rico has 62 sewage treatment plants, similar to the Hachinohe Project, distributed around the island (see Figure 17).



Figure 17. Sewer Treatment Plants in Puerto Rico¹³⁸

In theory, if all 62 sewage plants are converted into microgrids, and following Hachinohe’s model, Puerto Rico has the combined potential to generate 42,780 kW (62 plants x 690 kW each) or 42.78 MW (42,780 kW x 0.001 MW) of electricity per day that could be independently produced and distributed to local hospitals and other essential agencies, thus minimizing customer power outages, reinforcing the island’s power grid,

¹³⁷ Berkeley Lab.

¹³⁸ Source: “Generación y disposición de aguas sanitarias domésticas,” Departamento de Recursos Naturales y Ambientales, accessed February 15, 2019, 2, http://www.recursosaguapuertorico.com/Cap_tulo_9_Aguas_Sanitarias_en_Puerto_Rico.pdf.

and saving millions of dollars in fossil fuel purchases. However, this is only possible if each sewage plant produces the same amount of waste each day; therefore, to obtain a more accurate estimate of the energy generation for each plant, additional research must be conducted to identify the number of gallons of wastewater per plant in Puerto Rico. Nevertheless, assuming each sewer plant produces different amounts of electricity given the differential in wastewater processing and capabilities, even a small amount of electricity production and storage will augment PREPA's ability to power essential services after a catastrophic shutdown.

Because the lack of electricity is likely to lead to loss of life, as witnessed in Puerto Rico after Hurricane Maria, hospitals are great candidates to build clean, renewable energy microgrid systems.¹³⁹ Lessons learned after the Boston Marathon attack, the flooding in Houston, Hurricane Irma in Florida, and Hurricane Maria in Puerto Rico have changed the perspective of hospitals that economics is not a factor in considering microgrid installation as part of their emergency plans.¹⁴⁰ Medical institutions see themselves as the last line of defense when the population is in crisis.¹⁴¹ In other words, hospitals cannot fail to provide essential services because of a lack of power and must be able to operate independently from the main power grid. In addition, current regulations require hospitals to maintain some sort of backup power system, such as diesel generators, to provide essential services.¹⁴² Nevertheless, when Superstorm Sandy hit New York, generators and electrical systems from the Bellevue University and Coney Island Hospitals failed. Most recently, during Hurricane Maria in Puerto Rico, most hospitals ran out of diesel fuel to run their generators and could not provide required emergency services.¹⁴³ Another reason for the inadequacy of generators is that they are not operated on a regular basis and, although they

¹³⁹ George Washington University, *Ascertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico* (Washington, DC: Milken Institute, 2018).

¹⁴⁰ Peter Maloney, "Clean Energy Microgrids for Hospitals Make Electricity More Reliable," Buffalo Niagara Medical Campus, November 6, 2017, <https://bnmc.org/clean-energy-microgrids-hospitals-make-electricity-reliable/>.

¹⁴¹ Maloney.

¹⁴² Maloney.

¹⁴³ Maloney.

are tested, they fail because they sit idle most of the time.¹⁴⁴ Microgrids, on the other hand, are constantly used and monitored, thus avoiding surprises during emergencies.¹⁴⁵

An ideal example of a hospital-based microgrid is the Huntington Hospital in Long Island, New York, where a 2.8 MW fuel cell and battery storage is part of a microgrid project that will enable the hospital to become an off-grid power island.¹⁴⁶ The Buffalo Niagara Medical Campus indicates, “In addition to providing resiliency and reliability, an intelligent hospital microgrid can monitor grid electricity prices throughout the day and switch to its own lower cost energy when grid prices spike.” Therefore, there is also an economic incentive for hospitals to incorporate microgrids as part of their emergency planning that, with governmental incentives and tax breaks, could alleviate the initial financial burden they may face.¹⁴⁷ Puerto Rico has 72 main primary hospitals around the island, each with its own basic backup systems.¹⁴⁸ Using Huntington Hospital as an example of fuel cell usage, each hospital has the potential to produce and store 2.8 MW of electricity that could be combined to generate 201.6 MW of electricity (72 hospitals x 2.8 MW).¹⁴⁹

G. ELECTRIC VEHICLES FOR ELECTRICITY STORAGE

As mentioned in Section C of this chapter, the electric smart grid is a network of communication and controlling structures that manage energy supply and demand more efficiently than in traditional power grids. The goal of the smart grid is to precisely control

¹⁴⁴ Maloney.

¹⁴⁵ Maloney.

¹⁴⁶ Maloney.

¹⁴⁷ Maloney.

¹⁴⁸ “Directorio de hospitales,” Asociacion de Hospitales de Puerto Rico, accessed February 5, 2019, http://hospitalespr.org/?page_id=12.

¹⁴⁹ “A fuel cell uses the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products. Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer.” “Fuel Cells,” U.S. Department of Energy, accessed February 5, 2019, <https://www.energy.gov/eere/fuelcells/fuel-cells>.

power production and distribution at specific moments.¹⁵⁰ Electric vehicles (EVs) represent an alternative method of energy storage that is able to communicate with a smart grid, thus becoming a massive electricity storage resource that is readily available on demand.¹⁵¹ EVs are effective storage appliances that are typically capable of storing the equivalent of three days of a typical home's energy consumption (29.28 kW x 3 days = 87.84 kW).¹⁵² In essence, EVs can collect and produce electricity, pump extra energy to the grid as needed, and maintain a steady and reliable flow of electricity and, given their geographically disperse locations, are less susceptible to collapse collectively in hazardous weather conditions.¹⁵³

EVs are a great resource to any smart grid given that they can store electricity as needed. For example, when too much electricity is produced because of lack of demand or additional alternative sources of energy providing electricity to the grid, EVs can pull electricity off the grid, thus becoming a reserved source when demand for electricity peaks.¹⁵⁴ When thinking about EVs, it is important to understand that a single EV's battery is small compared to the storage needs of the power grid, but EVs must be viewed as a collective of millions of vehicles that together have the potential to store large amounts of electricity, thus becoming an effective tool for any smart grid.¹⁵⁵ It is projected that EV sales in the United States could reach up to three million vehicles by 2020, and although no specific numbers can be forecasted for Puerto Rico, the island could see an increase in EV purchases (see Figure 18).¹⁵⁶

¹⁵⁰ Brad Berman, "Electric Vehicles and the Smart Grid," Plugin Cars, October 14, 2014, <https://www.plugin cars.com/guide-electric-vehicles-and-the-smart-grid.html>.

¹⁵¹ Berman.

¹⁵² Berman.

¹⁵³ Berman.

¹⁵⁴ Berman.

¹⁵⁵ Berman.

¹⁵⁶ Berman.

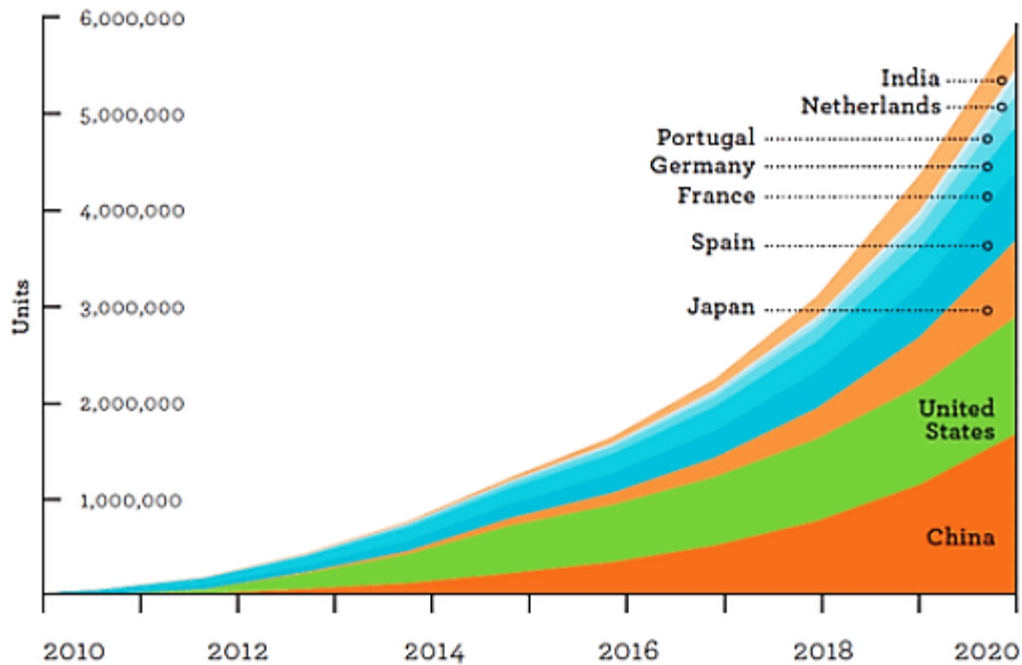


Figure 18. EV Sales Targets for Select Electric Vehicle Initiative Countries¹⁵⁷

However, rather than relying solely on consumers interested in EVs to use them, as previously mentioned, current government and privately owned vehicle fleets could be utilized. For example, in 2014 the U.S. Postal Service had approximately 212,500 vehicles, 42,500 of which were electric alternative fuel vehicles with battery storage capacity, as depicted in Figure 19.¹⁵⁸

¹⁵⁷ Source: Berman, “Electric Vehicles and the Smart Grid.”

¹⁵⁸ “Electric Vehicles in the Postal Service,” U.S. Postal Service, April 2014, <https://about.usps.com/who-we-are/postal-history/electric-vehicles.pdf>.



Figure 19. U.S. Postal Service Electric Vehicles¹⁵⁹

Not only are EVs an alternative source of energy storage when peak demand requires additional electricity, but they also help minimize wear and tear on the electric grid by reducing power congestion when high demands require additional electricity.¹⁶⁰ In addition, EVs are a great storage instrument for microgrids that depend on an alternative source of electricity production such as solar power.¹⁶¹ Finally, EVs could be an emergency source of electricity when power fails due to a natural disaster such as Hurricane Maria.¹⁶²

¹⁵⁹ Source: U.S. Postal Service, “Electric Vehicles in the Postal Service.”

¹⁶⁰ Berman, “Electric Vehicles and the Smart Grid.”

¹⁶¹ Berman.

¹⁶² Berman.

IV. MODELING AND MEASURING RESILIENCY: OLD VERSUS NEW GRID

Measuring resiliency is a subject that continues to be of interest at many levels of the U.S. government and the private sector. The National Security Council (NSC)'s Office of Resilience has adopted resiliency as the controlling standard to increase the nation's safety. According to the NSC, "If communities can increase their resilience then they are in much better position to withstand adversity and to recover more quickly than would be the case if there were few or no investments in building community resilience."¹⁶³ The NSC and the research community cannot agree on a standard guide to measure resiliency and have not agreed on whether resilience is a process or an outcome. Without a standard to measure resiliency, it was necessary to develop a method that could empirically demonstrate how additional technological enhancements to Puerto Rico's power grid could enhance its resiliency.

In their article for the *Journal for Homeland Security and Emergency Management*, Susan Cutter, Christopher Burton, and Christopher Emrich propose baseline indicators to measure resilience empirically before and after improvements are made to an existing system or community. Cutter, Burton, and Emrich note that in the engineering realm, resilience is often conceptualized as structural improvements, redundancies, resourcefulness, and rapidity of systems, with the ultimate goal of mitigating the consequences and recovering to the pre-event state. To produce a measurement for disaster resilience, it is necessary to use a comparative method that quantifies resiliency as an outcome; therefore, this research used time and quantities as indicators to produce an aggregate measure of performance to illustrate the magnitude of change between the current grid in Puerto Rico and the new proposed system. Specifically, this research measured the following:

- Total amount of electricity available during a black out.=

¹⁶³ Susan Cutter, Christopher Burton, and Christopher Emrich, "Disaster Resilience Indicators for Benchmarking Baseline Conditions," *Journal of Homeland Security and Emergency Management* 7, no. 1 (2010).

- Island-wide power outage percentage
- Electricity storage reserves (MW capacity)
- Fuel requirements to operate, if any
- Days without total electricity

To help illustrate the measurement of resiliency, a spreadsheet was created with data that reflect the power capacity of the eight main power plants that were operating in Puerto Rico before and during Hurricane Maria.¹⁶⁴ Each power plant was identified by name and assigned a number along with its electricity production capacity in megawatts and divided into one of two groups depending on its geographical location on the island (see Table 3).

Table 3. Power Plants in Puerto Rico¹⁶⁵

<u>POWER PLANTS : North Side</u>
1. Palo Seco: 602 MW
2. San Juan: 464 MW
3. Cambalache: 248 MW
4. Mayaguez: 220 MW
<u>POWER PLANTS : South Side</u>
5. Costa Sur: 820 MW
6. EcoElectrica : 507 MW
7. AES: 454 MW
8. Aguirre: 900 MW

After adding all power plants' production potential, the combined total electricity production of all eight power plants was 4,215 MW. Given that Puerto Rico's power demand is 3,060 MW, Puerto Rico was generating an additional 37.75 percent of its needed electricity; nevertheless, without any electricity storage facilities and the antiquated

¹⁶⁴ See Appendix A.

¹⁶⁵ See Appendix A.

conditions of the grid, this surplus power was not available during and after Hurricane Maria.

To exemplify the impact of each power plant in the island's grid, 16 scenarios were created, each one simulating the disruption of one or more power plants. The result showed that the disruption of power plants under scenarios 9, 10, 11, and 15 caused electricity production to fall below the required 3,060 MW (see Table 4).

Table 4. Scenarios 9, 10, 11, and 15: Power Production below the Required Rate¹⁶⁶

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17
	100% Capacity	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	100% Outage (Hurricane Maria)	Alternative Power Only
POWER PLANTS - North Side		1	2	3	4	5	6	7	8	7,8	6,7,8	5,6,7,8	4	3,4	2,3,4	All	
1. Palo Seco: 602 MW	602	0	602	602	602	602	602	602	602	602	602	602	602	602	602	0	0
2. San Juan: 464 MW	464	464	0	462	464	464	464	464	464	464	464	464	464	464	464	0	0
3. Camalache: 248 MW	248	248	248	0	248	248	248	248	248	248	248	248	248	0	0	0	0
4. Mayaguez: 220 MW	220	220	220	220	0	220	220	220	220	220	220	220	0	0	0	0	0
POWER PLANTS - South Side																	
5. Costa Sur: 820 MW	820	820	820	820	820	0	820	820	820	820	820	0	820	820	820	820	0
6. EcoEléctrica: 507 MW	507	507	507	507	507	507	0	507	507	507	0	0	507	507	507	507	0
7. AES: 454 MW	454	454	454	454	454	454	454	0	454	0	0	0	454	454	454	454	0
8. Aquine: 900 MW	900	900	900	900	900	900	900	0	0	0	0	0	900	900	900	900	0
Proposed Alternative Sources of Electricity																	
Underwater Array (x 1)	400																400
Fixed Battery Grid Storage (x 1)	10																10
Customer-Sited Energy (x 10,874 residence)	100																100
Sewer Microgrids (62 treatment plants)	42.78																42.78
Hospital Microgrids (72 main hospitals)	201.6																201.6
Electric Vehicles (Evs) (x 6,287 vehicles)	563.9																563.9
Total MW	1318.28																
Total MW (100% Capacity)	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	654
Total MW (Operating)	4,215	3,613	3,751	3,965	3,995	3,395	3,708	3,761	3,315	2,861	2,354	1,534	3,995	3,747	3,283	2,681	0
Absolute Decrease in MOP (Capacity)	0	602	464	250	220	820	507	454	900	1,354	1,861	2,681	220	468	932	1,534	4,215
%Decrease in MOP (Capacity)	0.00%	14.28%	11.01%	5.93%	5.22%	19.45%	12.03%	10.77%	21.35%	32.12%	44.15%	63.61%	5.22%	11.10%	22.11%	36.39%	100.00%
Total Peak MW Demand in Puerto Rico	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060
RAMOP (100% Capacity)	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%
RAMOP (Operating)	137.75%	118.07%	122.58%	129.58%	130.56%	110.99%	121.18%	122.81%	108.33%	93.50%	76.93%	50.13%	130.56%	122.45%	107.29%	87.61%	43.08%

After Hurricane Maria, Puerto Rico suffered an island-wide power outage due to the direct impact on the production, distribution, and transmission network. To simulate this effect, scenario 16 shuts down all power plants in Puerto Rico, thus completely disrupting all power production, distribution, and transmission (see Table 5).

¹⁶⁶ See Appendix A.

Table 5. Scenario 16 Illustrating Complete Power Outage¹⁶⁷

Scenario 16	
100 % Outage (Hurricane Maria)	
	4,215
	0
	4,215
	100.00%
	3,060
	137.75%
	0.00%

Given that Puerto Rico's grid had no power production or distribution redundancies, the collapse of major power lines such as the 115 kV and 230 kV lines during Hurricane Maria did not allow for the provision of essential emergency services. Hospitals, police departments, and communications systems relied on diesel generators to provide limited power and, after running out of fuel, were unable to provide much-needed services.

To illustrate how alternative sources of power could be introduced to Puerto Rico's current power grid as a power-generating redundancy to increase its resiliency, scenario 17 includes all alternative sources of electricity, as described in Chapter III (see Table 6).

¹⁶⁷ See Appendix A.

Table 6. Proposed Alternative Sources of Electricity¹⁶⁸

<i>Proposed Alternative Sources of Electricity</i>	
Underwater Array (x 1)	400
Fixed Battery Grid Storage (X 1)	10
Customer-Sited Energy (x 10,874 residence)	800.32
Sewer Microgrids (62 treatment plants)	42.78
Hospital Microgrids (72 main hospitals)	201.6
Electric Vehicles (Evs) (x 6,287 vehicles)	563.9
	2,019

As mentioned in Chapter III, ideally eight 400 MW underwater arrays could supply all the required electricity in Puerto Rico. Nevertheless, for simplicity and illustration purposes, only one underwater power array was considered for this scenario to demonstrate its usefulness, even when limited, in providing auxiliary power only during emergencies. Scenario 17 includes the use of EVs as alternate sources of electricity during blackouts, but there is little or no statistical data to show how many electric vehicles are currently in Puerto Rico. Still, there are ample data to show how many they are in the United States and extrapolate how many electric vehicles could be on the island. There are approximately 268.8 million vehicles in the United States, including 764,666 EVs, which comprise 0.28 percent of the total vehicles ($764,666 \div 268,000,000 \times 100\%$).¹⁶⁹ Puerto Rico has approximately 2,417,277 vehicles, and if the same 0.28 percent is used as a baseline, the results show there could be approximately 6,287 EVs in Puerto Rico ($0.28\% \times 2,417,227 \div 100$). In theory, if every EV can store up to 89.84 kW (0.0897 MW) in its batteries, the total potential electricity storage for all 6,287 EVs in Puerto Rico is 563.9 MW ($6,287 \times 0.0897$ MW).¹⁷⁰

¹⁶⁸ See Appendix A.

¹⁶⁹ “Number of Motor Vehicles Registered in the United States from 1990 to 2016,” Statista, accessed February 5, 2019, <https://www.statista.com/statistics/183505/number-of-vehicles-in-the-united-states-since-1990/>.

¹⁷⁰ “Worldwide Passenger Cars,” Chartsbin, accessed February 5, 2019, <http://chartsbin.com/view/1113>; and “Puerto Rico Population,” Worldometers, accessed February 5, 2019, <http://www.worldometers.info/world-population/puerto-rico-population/>.

In addition, under scenario 17, the same approach was utilized to determine how many residences could be utilizing solar-powered electricity and could potentially be introduced as part of a smart grid. It is estimated that approximately one million houses have and use solar power, which is 0.79 percent of the 126.2 million houses in the United States ($1,000,000 \div 126,200,000 \times 100\%$).¹⁷¹ In 2017, Puerto Rico had 1,376,531 houses, and using the U.S. ratio of 0.79 percent, Puerto Rico could have approximately 10,874 houses using solar power ($0.79\% \times 1,376,531 \div 100\%$) with combined maximum electricity storage and production of 800.32 MW per day.¹⁷² Figure 20 depicts what the integration of EVs and customer-sited energy could look like for Puerto Rico

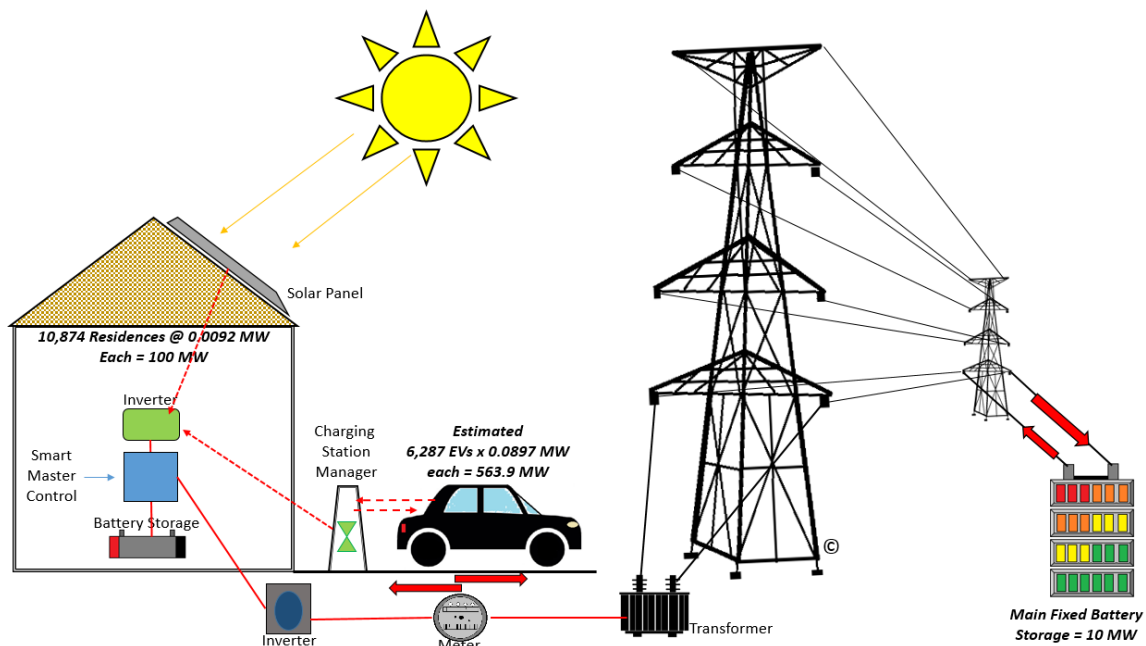


Figure 20. Electric Vehicles and Customer-Sited Energy Storage Modeling for Puerto Rico

Regarding hospitals, all 72 main hospitals were selected for this scenario given that all hospital facilities are required by law to have a built-in self-sufficient power-generating

¹⁷¹ Rebecca Harrington, "The US Is about to Hit a Big Solar Energy Milestone," *Business Insider*, October 13, 2015, <https://www.businessinsider.com/solar-panels-one-million-houses-2015-10>.

¹⁷² $10,874 \times 76.6 \text{ kW/day} = 800,326.4 \text{ kW/day} \times 0.001 \text{ MW} = 800.32 \text{ MW/day}$.

capacity, and their conversion and connection to a microgrid could be quickly incorporated with available technology.¹⁷³ In addition, and given Puerto Rico's fiscal predicament, the cost could be deferred and absorbed by individual hospitals since diesel purchases will no longer be necessary, and life-cycle costs will make this initial investment a reasonable business practice. Following the Huntington Hospital model, a 2.8 MW fuel cell installed in 72 hospitals could produce a total of 201.6 MW of electricity (72 x 2.8 MW).

Similarly, all 62 sewage treatment plants on the island were selected for this scenario because steam boiler technology is a readily available and proven technology that uses by-products typically representing 50 percent of the boiler fuel.¹⁷⁴ Given that fuel accounts for 96 percent of the operational cost, the overall investment and lifecycle cost will be significantly less given that 50 percent of the fuel will be derived from free sewage, thus making this alternative source of energy feasible and more affordable.¹⁷⁵ Taking into account all 62 sewer facilities on the island and following the Hachinohe Project model, each treatment plan could generate 42,780 kW (62 plants x 690 kW each) or 42.78 MW (42,780 kW x 0.001 MW) of electricity per day. Lastly, one 10 MW fixed battery grid storage was considered under scenario 17 to be used in conjunction with the tidal array structure, demonstrating that building resiliency does not necessarily require the complete overhaul of current systems but rather a gradual process of introducing new technology with existing capabilities that can be fully integrated as much as needed or able.

When Hurricane Maria hit Puerto Rico, it crippled the existing power grid, thus leaving the entire island without power (see Appendix A, scenario 16). Under scenario 17, however, if those systems were in place and operational during Hurricane Maria, Puerto Rico could have utilized 65.97 percent of total capacity to power critical emergency

¹⁷³ NFPA 99 “establishes the minimum criteria for the installation, performance, and operation of a wide range of systems and equipment in health care facilities to ensure the safety of patients, staff, and the public from electrical failures, fires, and other hazards.” Vahik Davoudi, “Emergency and Standby Power in Hospitals,” *Engineer*, October 15, 2015, <https://www.csemag.com/single-article/emergency-and-standby-power-in-hospitals/be2ba7589929868a4ea191a27e56730b.html>.

¹⁷⁴ “Industrial Combustion Boilers,” Energy Technology Systems Analysis Programme, May 2010, https://iea-etsap.org/E-TechDS/PDF/I01-ind_boilers-GS-AD-gct.pdf.

¹⁷⁵ Energy Technology Systems Analysis Programme.

response components that would have saved lives and expedited recovery efforts. Puerto Rico is composed of 78 cities, 72 major hospitals, and 62 water treatment plants around the island (see Figure 21).

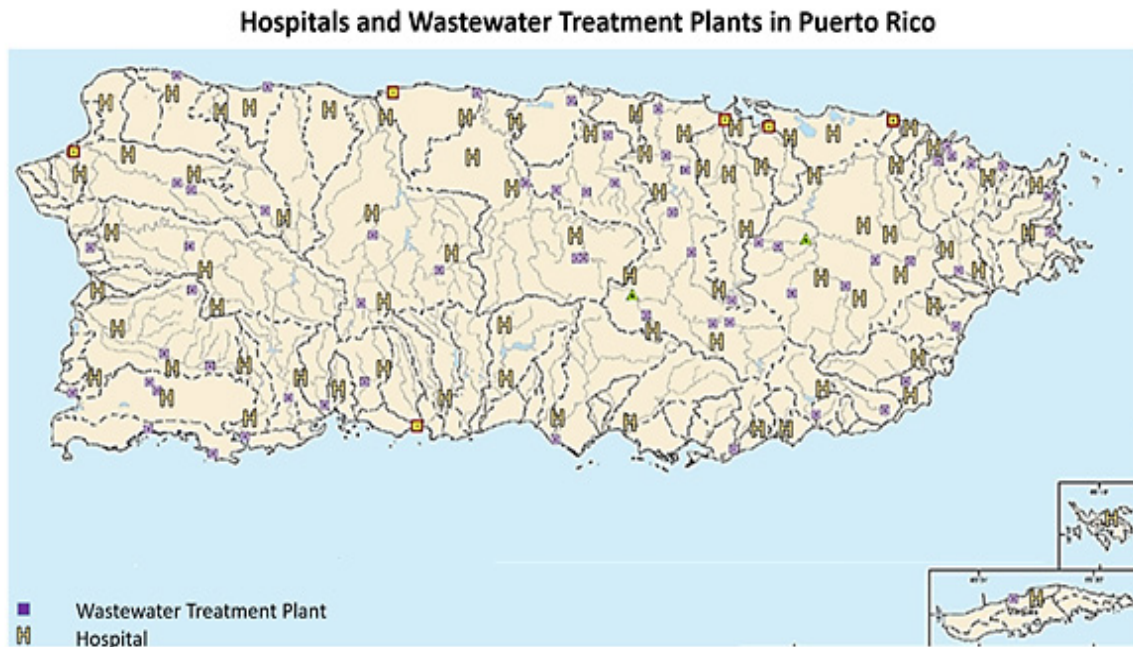


Figure 21. Hospitals and Wastewater Treatment Plants in Puerto Rico¹⁷⁶

If equally divided, each city could have received 3.13 MW of emergency electricity.¹⁷⁷ This could have been enough to partially power essential medical services and at least one police or EMS department with their respective communication assets per city, thus being able to respond to immediate post-hurricane medical needs. Figure 22 depicts how the proposed microsystem would look and how it could have powered essential services in Puerto Rico during and after Hurricane Maria.

¹⁷⁶ Adapted from Departamento de Recursos Naturales y Ambientales, “Generación y disposición de aguas sanitarias domésticas”; and David Wagman, \$17 Billion Modernization Plan for Puerto Rico’s Grid Is Released, IEEE Spectrum, December 12, 2017, <https://spectrum.ieee.org/energywise/energy/the-smarter-grid/17-billion-modernization-plan-for-puerto-rico-is-released>.

¹⁷⁷ $(72 \times 2.8 \text{ MW}) + (62 \times .69 \text{ MW}) = 244.38 \text{ MW}$; $244.38 \text{ MW} \div 78 = 3.13 \text{ MW}$.

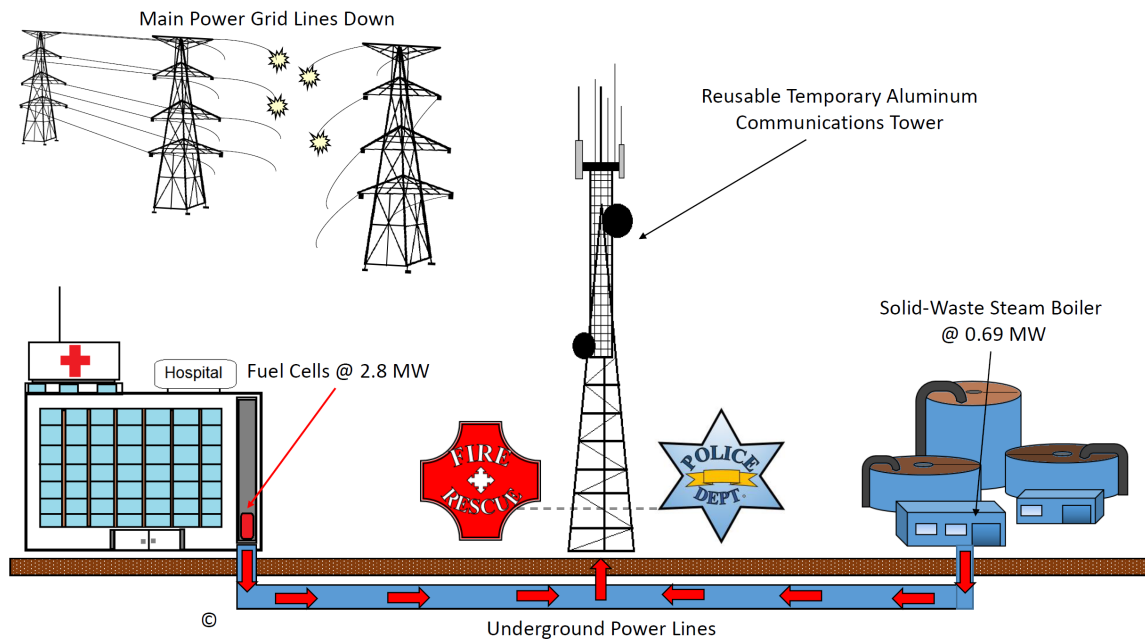


Figure 22. Emergency Microgrid Sample: Isolated Community

When all recommended alternate sources of energy production and storage are added, as shown in Figure 23, a total of 2,018.60 MW (65.97 percent of Puerto Rico's total electricity demand) could be produced and transmitted with the combination of all proposed alternative sources of electricity as illustrated in scenario 17 (see Figure 28). Even though scenario 17 is a hypothetical concept utilizing estimates and approximations, these figures serve to demonstrate the principle that energy sustainability, through the use of alternative sources of electricity, is feasible and a key factor in improving the resiliency of Puerto Rico's power grid. Figure 23 is an illustration of the proposed alternate sources of electricity storage and production.

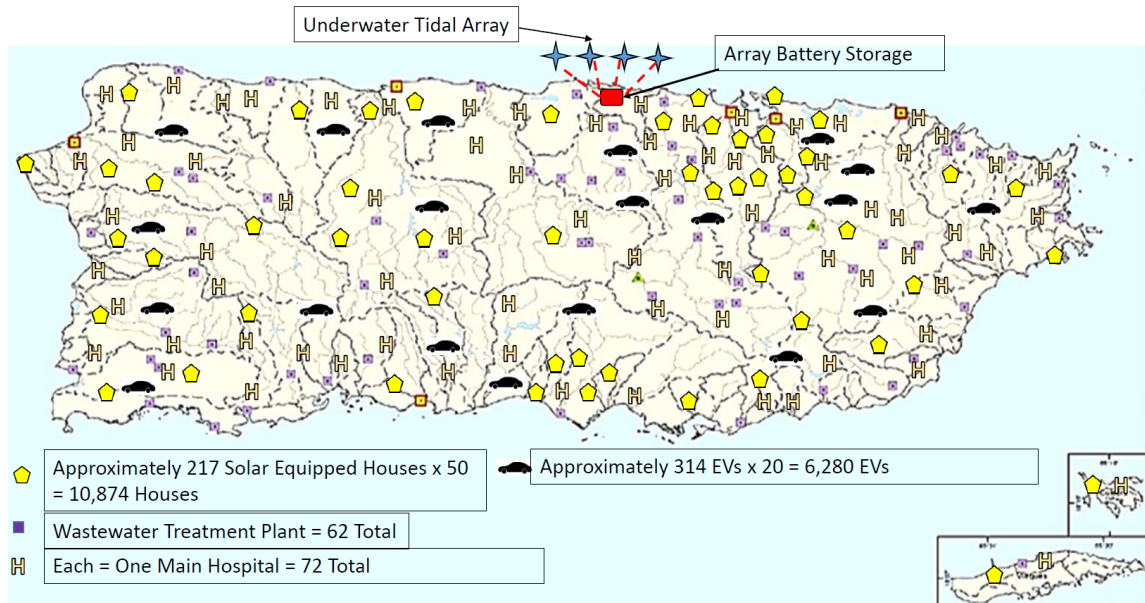


Figure 23. Scenario 17: All Recommended Sources of Energy Production and Storage in Puerto Rico¹⁷⁸

Improving Puerto Rico's power grid resiliency is a matter of establishing new sources of alternative power not only to serve as emergency electricity reserves but also to be available on demand as soon as practicable after a catastrophic event such as Hurricane Maria. Figure 24 shows PREPA's power restoration timetable, indicating the effort to restore power on the island as power load percentages from October 2017 to February 2018. Note that it was not until November 9, 2017, that PREPA was able to restore more than 40 percent of Puerto Rico's energy peak load. This was approximately 51 days after Hurricane Maria hit the island.

¹⁷⁸ Adapted from: Departamento de Recursos Naturales y Ambientales, "Generación y disposición de aguas sanitarias domésticas," 2; and Wagman, \$17 Billion Modernization Plan."

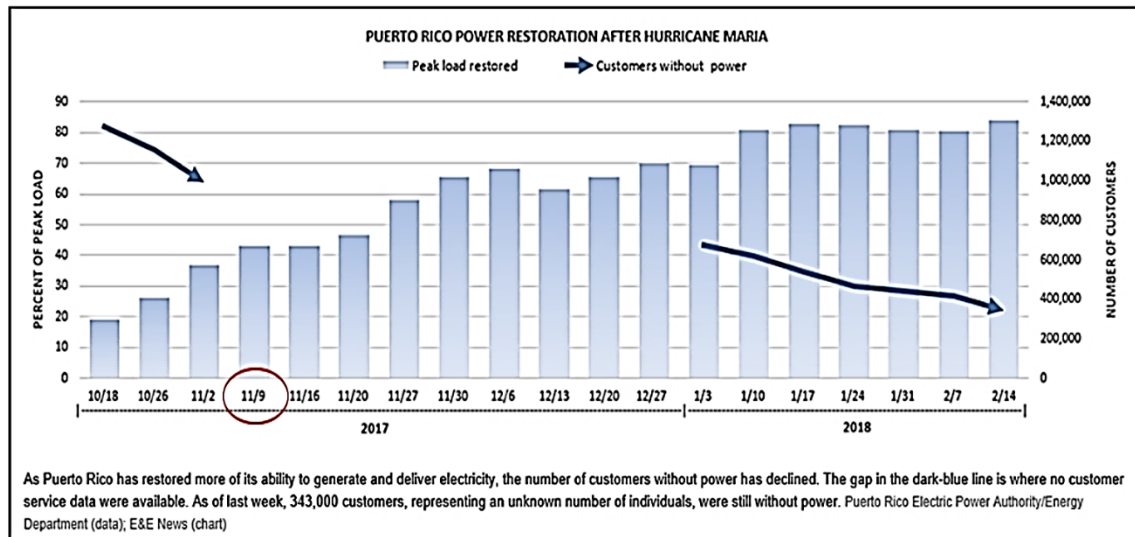


Figure 24. Puerto Rico Power Restoration after Hurricane Maria¹⁷⁹

In contrast, under scenario 17, potentially 65 percent of Puerto Rico’s electricity requirements could have been available immediately or within hours after Hurricane Maria if all proposed sources of alternative power had been operational. Under the same scenario, even if only the individual microgrids survived Maria’s impact—because of their location inside hardened structures—approximately 7.9 percent (244 MW) of the electricity would have been available to provide emergency power to some hospitals and EMS services. This could have been possible because all 134 hospitals and sewer plants would have operated independently under a microgrid concept and could have transmitted their electricity locally, thus bypassing major transmission lines that were knocked down by hurricane winds. It is uncertain whether all of the hospitals could survive a major catastrophe such as Maria, but even if some did, their ability to provide their own electricity and help power their local EMS systems would be preferable to having none available, as was experienced after Hurricane Maria. As shown in Figure 25, PREPA reached 42 percent power capacity on November 9, 2017, while in scenario 17 (see also Figure 24), the same power load could have been reached 40 days sooner with a 65 percent alternative power reserve. With only

¹⁷⁹ Adapted from: Ferris, “Puerto Rico’s Grid Recovery.”

7.9 percent reserves, the current grid was able to reach 26 percent around October 26, 2017, while in scenario 17, the same power load could have been reached eight days sooner.

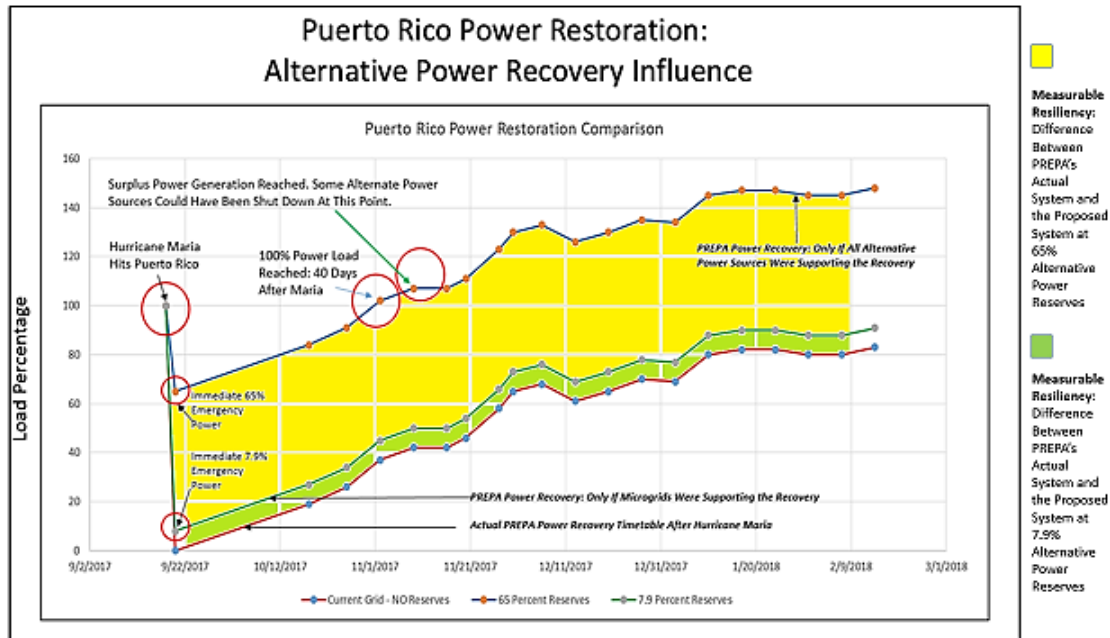


Figure 25. Puerto Rico Power Restoration Comparison¹⁸⁰

To improve transmission and distribution resiliency—and considering how expensive underground lines are, as described in Chapter III—it is recommended that the main lines from all microgrids be underground, thus assuring transmission of electricity to local police and EMS assets. In theory, 72 hospitals and at least 72 police or EMS departments could have been operational, or at least partially, almost immediately after the hurricane, instead of 51 days later. Regardless, even a restoration of 40 percent power did not guarantee that it was available to hospitals and first responders because major power lines were still down, and there was no equitable distribution of electricity around the island, thus highlighting the importance of independent and interconnected power microgrids. Lastly, note that PREPA was not able to reach 100 percent load capacity, even after five and a half months of restoration efforts (see Figure 24). Conversely, in scenario

¹⁸⁰ See Appendix B for an enlargement of Figure 25.

17, 100 percent capacity would have been reached approximately within the first week of November 2017 and surplus electricity by mid-November. This surplus power could have meant that microgrid emergency power could have been turned off as needed as the main grid was re-powering the island. A comparison of PREPA's response to the hypothetical decentralized power grid using the electricity available in megawatts and time to recover as measures of performance yields the resiliency graph depicted in Figure 26, clearly indicating that a decentralized grid is more resilient than PREPA's centralized system.

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V. CONCLUSIONS

Resilience isn't a single skill. It's a variety of skills and coping mechanisms. To bounce back from bumps in the road as well as failures, you should focus on emphasizing the positive.

—Financial editor Jean Chatzky¹⁸¹

A. OVERVIEW

The ability to bounce back from adversity and return to normal is better known as resiliency. However, this term describes not only a quality in people but also the ability of objects or places to remain or recover to their original shape or function. In the case of the Puerto Rico Electric Power Authority (PREPA), its antiquated infrastructure, its centralized power production and distribution network, and Puerto Rico's financial bankruptcy all hindered its ability to return to its original functioning state after Hurricane Maria. In light of this, to improve PREPA's ability to rapidly recover in the future, Puerto Rico must re-design its power grid with measures to enhance its network connectivity, decentralize its power production and distribution, and introduce electric storage capacity. Therefore, new technology—in the form of renewable energy production and storage, the inclusion of the smart grid concept, and the establishment of independent microgrid systems—was proposed to design a system that could improve PREPA's ability to recover after a natural or manmade disaster. Assessing grid performance using power in megawatts and recovery time as key measures of performance (MOPs), a decentralized grid proves more resilient than PREPA's centralized system because under the proposed decentralized system, more electrical power would be available in the shortest amount of time. This speeds recovery after a natural or manmade disaster. In conclusion, this research found that the combination of ocean tidal power, implementation of a smart grid, electricity storage through batteries, the inclusion of microgrids, and substantial solar energy in Puerto Rico can improve the power grid's reliability, resiliency, and efficiency. Furthermore, the results

¹⁸¹ “Jean Chatzky,” Famous Quotes on Resilience and Leadership, accessed February 20, 2019, <https://wbu.gmu.edu/famous-quotes-on-resilience-and-leadership/>.

of the resiliency graphic prove our hypothesis that a decentralized, renewable energy smart grid would be more efficient and resilient than a centralized, conventional power grid.

This research discovered the lack of a unique method of measuring resiliency, and results for each design trial or experiment varied depending on the variables and the desired measures of performance. Furthermore, as mentioned in Chapter IV, Cutter, Burton, and Emrich argue that the research community continues to struggle in determining whether resilience is an outcome or a process. Based on the research literature, the method used to complete this investigation and the final resiliency graphic finds resilience to be both a process and an outcome. In determining whether a decentralized power grid is more resilient than a centralized one, Figure 26 was created to approach the problem and standardize the steps to produce an end-product.

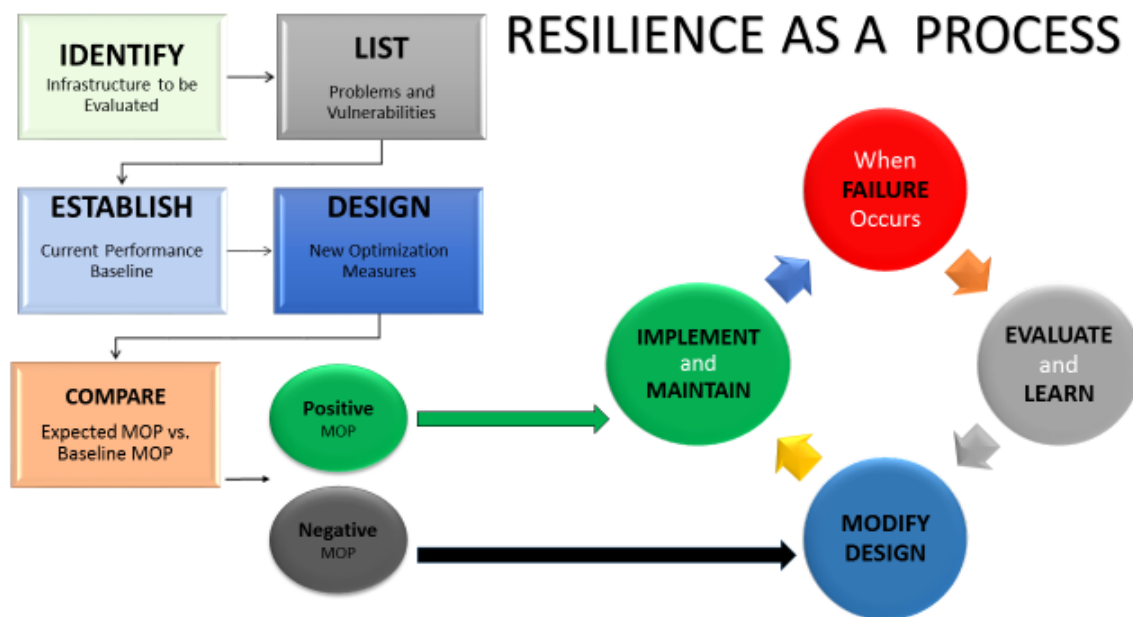


Figure 26. Resiliency as a Process Model

This routine could be applied regardless of the kind of infrastructure to be evaluated and could even be used when attempting to measure resiliency as a human quality. However, a process must have a purpose, and in this case, it measures the differences in MOPs between two systems. The end product or *outcome* markedly differs between MOPs,

as reflected in Figure 27. By definition, an outcome means “something that follows as a result” of or “consequence” of.¹⁸² If following the outlined process improved Puerto Rico’s grid, then resilience would be the measured difference in the MOPs.

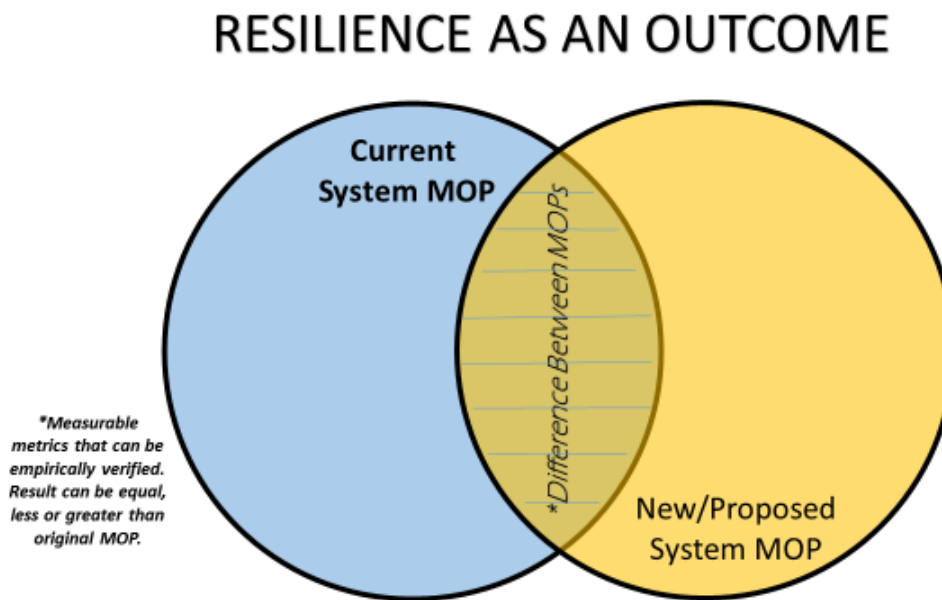


Figure 27. Resilience as an Outcome Model

When discussing critical infrastructure, phrases such as “building resiliency” and “making it more resilient” are often used to describe the hardening efforts of strengthening a structure or system. To accomplish this, a *process* must be created, and a *result* must be obtained. Thus, resilience could be the term to encompass both principles. This conceptualization of the term resilience could help set priorities, measure progress and aid in decision-making processes across the U.S. homeland security enterprise, thus helping policymakers understand and identify prevailing conditions and take corrective measures before emergency events.

¹⁸² *Merriam-Webster*, s.v. “outcome,” accessed February 15, 2019, <https://www.merriam-webster.com/dictionary/outcome>.

B. IMPLEMENTATION CHALLENGES AND RECOMMENDATIONS

This thesis aimed to find alternative renewable sources of electricity production and management that could be incorporated into Puerto Rico's power grid to improve its resiliency. Although it successfully identified suitable and efficient renewable sources of electricity production, storage, and management, major innate obstacles remain when incorporating new technology into an existing power grid, especially one that is antiquated and managed by a bankrupt government.

1. Cost and Funding

Renewable energy is usually less expensive to operate and maintain, but its initial cost could be higher than traditional electricity generation methods.¹⁸³ For example, in 2017, the typical cost of solar systems ranged from \$2,000 to \$3,700 per kilowatt while electricity from a new natural gas plant might cost around \$1,000/kW.¹⁸⁴ Nevertheless, over the lifespan of a renewable energy system, the initial higher cost will be offset by its reliability and low operational and maintenance costs, not to mention the elimination of fossil fuel purchases. Considering Puerto Rico's financial predicament, new government tax incentives (e.g., in the form of credits, lower rates, or zero duties for a specific period) should be enacted so that private stakeholders can invest capital and technology, thus minimizing the government's financial burden.

2. State Energy Policy

Puerto Rico should legislate "policies that contribute to creating an enabling environment for attracting investments."¹⁸⁵ To ease its transition and incorporation into the renewable energy market, Puerto Rico could seek assistance from the International Renewable Energy Agency to identify policymaking best practices and trends, develop

¹⁸³ "Barriers to Renewable Energy Technologies," Union of Concerned Scientists, last modified December 20, 2017, <https://www.ucsusa.org/clean-energy/renewable-energy/barriers-to-renewable-energy>.

¹⁸⁴ Union of Concerned Scientists.

¹⁸⁵ "Policies," International Renewable Energy Agency, accessed February 5, 2019, <https://www.irena.org/policy>.

support mechanisms to adapt to the new energy markets, and design new policies that could foster the integration of the aforementioned new renewable technologies.¹⁸⁶

The International Renewable Energy Agency specifically suggests that when developing renewable energy policies, governments should follow key specific guidelines to maximize their successful implementation, and as such, we recommend that Puerto Rico implement the following recommendations in their new policies.¹⁸⁷

- Puerto Rico's new renewable energy policies must concentrate on customer benefits, not only on power generation and management.
- New policies must also include language to incorporate financial generation-based incentives and taxes on carbon emission generation.
- Puerto Rico's new policies should also integrate the transportation sector in an effort to decarbonize vehicles on the island, especially those used by the government.

C. FUTURE RESEARCH

This thesis uncovered methods that could enhance Puerto Rico's power grid resiliency. In Chapter III, several new sources of renewable energy, storage, and management were identified and deemed appropriate to be incorporated as part of new resiliency measures; however, further research is needed to identify funding sources and opportunities that could help finance the proposed measures. Also, further research on other renewable sources of energy, such as geothermal, wind, and other tidal technology, should be explored as alternative sources of energy for Puerto Rico, thus allowing the island to diversify its electricity production. Finally, future research should be conducted to identify new market opportunities that could identify potential joint ventures and alliances to expedite tailored technological innovations to fast-track Puerto Rico's power grid re-design and reconstruction.

¹⁸⁶ International Renewable Energy Agency.

¹⁸⁷ International Renewable Energy Agency.

D. FINAL REMARKS

Puerto Rico is a small Caribbean island, of roughly 3,500 square miles, with a population of approximately 3.34 million residents. Its unique geographical location makes this small territory prone to devastating hurricane forces every year, and it is only a matter of time before Puerto Rico is hit again by another natural disaster such as Hurricane Maria. Lessons learned after Maria have taught us that the inability to recover after a natural disaster may be worse than the actual natural event. George Washington University's Milken Institute determined that approximately 2,975 people died because of Hurricane Maria, most of them from the lack of electricity that crippled all medical and emergency services, communications, and basic utilities, such as water and sewer, on the island.¹⁸⁸ Had Puerto Rico had the power grid redundancies recommended in this thesis, power recovery time could have been shortened, and thousands of lives could have been saved.

Building resiliency in Puerto Rico is not a matter of politics, profits, or appearances; it is an obligation that government representatives must undertake to prevent and mitigate the effects of the next catastrophe because another hurricane, earthquake, or manmade disaster is not only likely but certain to happen. Regardless, Mother Nature taught Puerto Rico a lesson that should be viewed as an opportunity to learn from the mistakes of laziness, inappropriateness, carelessness, underestimation, inattention, and neglect. This experience should be valued by other regions, states, and countries so that future generations can prepare for similar events. We cannot bring back those 2,975 souls who were lost in Puerto Rico, but we can certainly prevent more from being lost. The technology is here, the tools are available, and the capabilities are certain; all that is required is the will to change and, in the case of Puerto Rico, the need to restructure the power grid. In the end, previous mistakes can become a lesson, but making the same mistake twice becomes a choice. Therefore, it is important for the people of Puerto Rico that policymakers learn from history and choose not to make the same mistake again.

¹⁸⁸ "GW Researchers: 2,975 Excess Deaths Linked to Hurricane Maria," George Washington University, August 29, 2018, <https://gwtoday.gwu.edu/gw-researchers-2975-excess-deaths-linked-hurricane-maria>.

APPENDIX A. MEASURE OF PERFORMANCE SCENARIOS FOR PUERTO RICO

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17
	100% Capacity	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	Plant Outage	100 % Outage (Hurricane Maria)	Alternative Power Only
	MW (Megawatts)	1	2	3	4	5	6	7	8	7,8	6,7,8	5,6,7,8	4	3,4	2,3,4	1,2,3,4	All	
POWER PLANTS : North Side																		
1. Palo Seco: 602 MW	602	0	602	602	602	602	602	602	602	602	602	602	602	602	602	0	0	
2. San Juan: 464 MW	464	464	0	462	464	464	464	464	464	464	464	464	464	464	464	0	0	
3. Cambalache: 248 MW	248	248	248	0	248	248	248	248	248	248	248	248	248	248	248	0	0	
4. Mayaguez: 220 MW	220	220	220	220	0	220	220	220	220	220	220	220	220	0	0	0	0	
POWER PLANTS : South Side																		
5. Costa Sur: 820 MW	820	820	820	820	820	0	820	820	820	820	820	0	820	820	820	820	0	
6. EcoElectrica : 507 MW	507	507	507	507	507	507	0	507	507	507	0	0	507	507	507	507	0	
7. AES: 454 MW	454	454	454	454	454	454	454	0	454	0	0	0	454	454	454	454	0	
8. Aguirre: 900 MW	900	900	900	900	900	900	900	900	0	0	0	0	900	900	900	900	0	
Proposed Alternative Sources of Electricity																		
Underwater Array (x 1)	400																	400
Fixed Battery Grid Storage (X 1)	10																	10
Customer-Sited Energy (x 10,874 residence)	100																	100
Sewer Microgrids (62 treatment plants)	42.78																	42.78
Hospital Microgrids (72 main hospitals)	201.6																	201.6
Electric Vehicles (Evs) (x 6,287 vehicles)	563.9																	563.9
Total MW	1318.28																	
Total MW (100% Capacity)	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	4,215	654
Total MW (Operating)	4,215	3,613	3,751	3,965	3,995	3,395	3,708	3,761	3,315	2,861	2,354	1,534	3,995	3,747	3,283	2,681	0	1,318
Absolute Decrease in MOP (Capacity)	0	602	464	250	220	820	507	454	900	1,354	1,861	2,681	220	468	932	1,534	4,215	-664
%Decrease in MOP (Capacity)	0.00%	14.28%	11.01%	5.93%	5.22%	19.45%	12.03%	10.77%	21.35%	32.12%	44.15%	63.61%	5.22%	11.10%	22.11%	36.39%	100.00%	-101.57%
Total Peak MW Demand in Puerto Rico	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060	3,060
%MOP (100% Capacity)	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	137.75%	21.37%
%MOP (Operating)	137.75%	118.07%	122.58%	129.58%	130.56%	110.95%	121.18%	122.91%	108.33%	93.50%	76.93%	50.13%	130.56%	122.45%	107.29%	87.61%	0.00%	43.08%

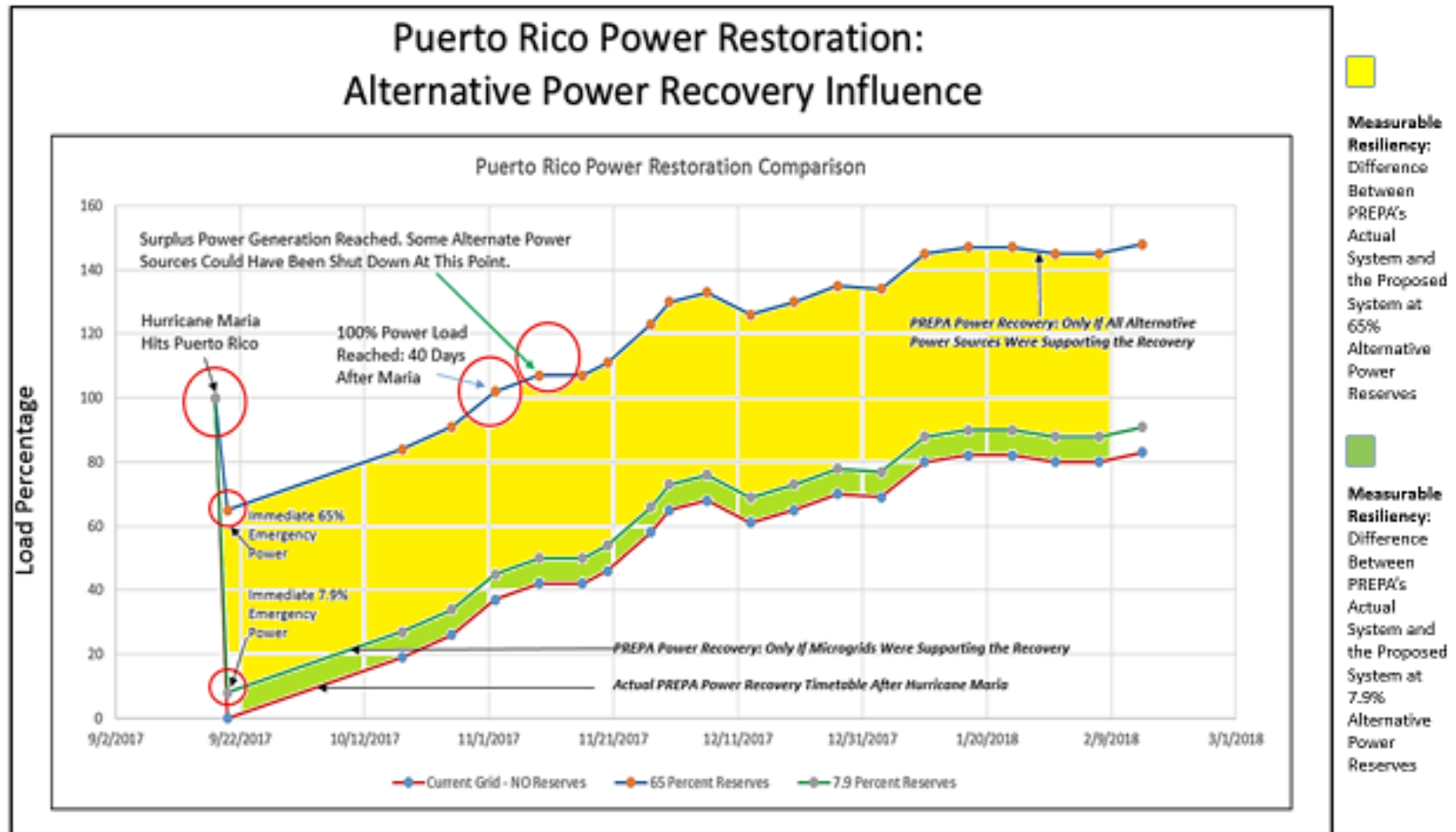
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APPENDIX B. LOAD RESTORATION COMPARISON

Date	% Load Restored With Current Grid	% Load Restored With 43% Emergency Reserves	% Load Restored With 7.9% Emergency Reserves
9/18/2017	100	100	100
9/20/2017	0	43	7.9
10/18/2017	19	62	26.9
10/26/2017	26	69	33.9
11/2/2017	37	80	44.9
11/9/2017	42	85	49.9
11/16/2017	42	85	49.9
11/20/2017	46	89	53.9
11/27/2017	58	101	65.9
11/30/2017	65	108	72.9
12/6/2017	68	111	75.9
12/13/2017	61	104	68.9
12/20/2017	65	108	72.9
12/27/2017	70	113	77.9
1/3/2018	69	112	76.9
1/10/2018	80	123	87.9
1/17/2018	82	125	89.9
1/24/2018	82	125	89.9
1/31/2018	80	123	87.9
2/7/2018	80	123	87.9
2/14/2018	83	126	90.9

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APPENDIX C. ALTERNATIVE POWER RECOVERY INFLUENCE



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