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White Paper (1)

Infrastructure Resiliency in the Context of Puerto Rico

Resilience (n.)—the "act of rebounding," from Latin resiliens,
present participle of resilire "to rebound, recoil,"
from re- "back" + salire "to jump, leap"
https://www.etymonline.com/word/resilience

Introduction

Infrastructure resiliency has become a much-talked about topic over the last several years as cities, states and nations see the prospect of more frequent climate change-induced disasters. Many of these discussions center on the post-disaster performance of critical infrastructure such as power, water, transportation and telecom.

A team of Cornell graduate students in the fields of public administration and regional planning spent a week in Puerto Rico in January 2020 with the objective of understanding what infrastructure resiliency means in a practical and actionable sense. The large question we wanted to answer was, how is Puerto Rico using resiliency as a design and investment objective in the rebuilding of the Island's utility infrastructure after a series of natural disasters? The answer to this question was the basis for a set of recommendations at the end of this paper.

Puerto Rico's infrastructure was severely compromised as a consequence of two hurricanes that struck the Island in 2017. "On September 6, 2017, Hurricane Irma — a category five storm — skirted the northern part of the island, causing

(1) This white paper was prepared as a product of a Cornell Institute of Public Affairs winter term practicum in Puerto Rico in January 2020. Participants in the practicum are master's degree candidates in public administration and regional planning, and included Victor Benito, Andreea Barb, Angel Benitez Collante, Anjali Fisher, Julia Godinez, Kara Guse, Ankur Gupta, Zai Liu, Alekhya Mukkavilli, Ryan Sequeira and Mahrusah Zahin. The faculty lead was John Foote. Questions should be sent to jhf25@cornell.edu.

significant flooding and leaving more than 1 million people without power. Two weeks later, on September 20th, Hurricane Maria passed east-to-west across the entire Island. Hurricane Maria caused a complete loss of power, and it damaged thousands of housing units, as well as telecommunication towers, roads, bridges, schools, and 80% of the Island's crop value." (Source: "ReImagina Puerto Rico Report", Resilient Puerto Rico Advisory Commission, June 2018 https://www.resilientpuertorico.org/wp-content/uploads/2019/03/GENERALREPORT_RePR_ENG_03042019.pdf.)

According to a 2018 U.S. Department of Energy (DOE) report, "Hurricane Maria was the second strongest storm on record to hit Puerto Rico. As of 8:00pm on September 20 [note: Maria hit Puerto Rico in the morning hours of September 20th], the Puerto Rico Electric Power Authority (PREPA) reported near 100% of total customers in Puerto Rico without power, with the exception of facilities running on generators. The outage threatened the health, safety, and economic wellbeing of the nearly 3.5 million U.S. citizens who inhabit the territory and further stressed the regional economy. (Source: "Energy Resilience Solutions for the Puerto Rico Grid", US Department of Energy, June 2018. https://www.energy.gov/sites/prod/files/2018/06/f53/DOE%20Report_Energy%20Resilience%20Solutions%20for%20the%20PR%20Grid%20Final%20June%202018.pdf)

Approximately eleven months after Hurricane Maria, power was finally restored to 100% of the Island. Puerto Rico now has the distinction of having the second largest power outage in the world measured in customer-hours of lost electricity service. (Source: "Puerto Rico's Power Outage Is Now the Second-Largest Blackout on Record", Doug Criss, CNN, April 16, 2018. https://www.cnn.com/2018/04/16/us/puerto-rico-blackout-second-largest-globally-trnd/index.html)

While the Island has recovered most essential services, Irma and Maria exposed the vulnerabilities of the Island's infrastructure. Puerto Rico's ongoing challenge is improving the resiliency of this infrastructure. The DOE report referenced above states,

> "Maintaining and enhancing the resilience of the electric grid at fair and reasonable costs can provide service and value to Puerto Rican communities. Yet, no single investment in energy infrastructure at one point in time will achieve resilience. The energy infrastructure of Puerto Rico must be designed, built, managed, and maintained in such a way to withstand environmental and man-made disasters, ameliorate disruptions when they inevitably occur, recover quickly, and incorporate lessons learned into post-event planning and operations. This is a continual process of improvement, one involving a reassessment and adaptation of solutions and technologies to address changing needs."

While the DOE report focused on the Island's power sector, the observations in the report are fully applicable to all of the Island's physical infrastructure.

This paper has several parts; the first a review of infrastructure resiliency concepts and practices, the second is a synthesis of the team's observations about how resiliency is being incorporated into Puerto Rico's rebuilding plans, and the last is a suggested approach to achieve the objective of resiliency in a more effective manner.

Resiliency in Concept and Practice

A survey of various national governments, multi-national organizations and NGO's reveal that the term resiliency is defined in various ways. (Source: "What Is Resilience?", United Kingdom Department for International Development, May 2016.
https://assets.publishing.service.gov.uk/media/57a08955ed915d3cfd0001c8/EoD_Topic_Guide_What_is_Resilience_May_2016.pdf).

a. The United Nations Office for Disaster Risk Reduction (UNISDR): The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its

essential basic structures and functions.
http://www.unisdr.org/we/inform/terminology#letter-r

b. Canada: The ability of individuals, households, governments, regions, and systems to mitigate, resist, absorb, and recover from the effects of shocks and disasters in a timely, sustainable, and efficient manner.
http://www.acdicida.gc.ca/INET/IMAGES.NSF/vLUImages/Evaluations2/$file/CIDA-learns-eng.pdf
c. European Commission: The ability of an individual, a household, a community, a country or a region to withstand, to adapt, and to quickly recover from stresses and shocks**.**
http://ec.europa.eu/echo/files/policies/resilience/com_2012_586_resilience_en.pdf
d. Germany Federal Ministry for Cooperation and Development: The ability of people and institutions–be they individuals, households, communities or nations – to deal with acute shocks or chronic burdens (stress) caused by fragility, crises, violent conflicts and extreme natural events, adapting and recovering quickly without jeopardizing their medium and long term future.
http://www.bmz.de/en/what_we_do/issues/transitional-development-assistance/index.html
e. Organisation for Economic Co-operation and Development (OECD): The ability of individuals, communities and states and their institutions to absorb and recover from shocks, while positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty.
http://www.oecd.org/dac/May%2010%202013%20FINAL%20resilience%20PDF.pdf
f. United States Agency for International Development: The ability of people, households, communities, countries and systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth.
http://www.usaid.gov/sites/default/files/documents/1870/USAIDResiliencePolicyGuidanceDocument.pdf

The definition we adopted that captures most of the salient concepts embedded in the definitions above is, the "ability to adapt to, recover from, and respond to a variety of threats to physical infrastructure, operations, cybersecurity, terrorism, and all hazards". This definition is included in a 2019 RAND paper titled "Incorporating Resilience into Transportation Planning and Assessment" (Sarah Weilant, Aaron Strong, Benjamin M. Miller, RAND, 2019. https://www.rand.org/pubs/research_reports/RR3038.html)

Implicit in RAND's definition is the notion that resilience is a post-event quality, i.e., resilience is how a system responds to an event. Another paper on which we relied in order to understand the concept of resiliency observes,

> "Traditionally, the performance of critical infrastructure (e.g., power grid, telecommunication or water supply systems) has been analysed by classical risk assessment methods for their safe and reliable design and operation. However, more recently it has become apparent that additional efforts and considerations are needed beyond the well-established state-of-the-art to ensure efficient recovery from low probability high-impact disruptive events. This view is strongly supported by the notion that not all hazards and threats can be averted, as major disasters repeatedly demonstrated in the past decades.
>
> These events highlight the necessity to be prepared for a disaster and its consequences, and to be able to recover in a reasonable and timely manner from sudden, unexpected changes that pose a risk to the proper functioning of critical infrastructures and associated services upon which modern society relies."

Source: "A Review on Resilience Assessment of Energy Systems", Sustainable and Resilient Infrastructure, Patrick Gasser, Peter Lustenberger, Marco Cinelli, Wansub Kim, Matteo Spada, Peter Burgherr, Stefan Hirschberg, Božidar Stojadinovic & Tian Yin Sun, 2019.
https://doi.org/10.1080/23789689.2019.1610600)

The focus of this paper and recommendations is on the post-disaster recovery stage. The RAND paper referenced above segments this recovery stage into three phases which RAND calls "capacities":

a. Absorptive or resistive capacity—the ability of the system to absorb shocks and stresses and maintain normal functioning. Absorptive capacity can be increased by hardening assets and/or reducing exposure to risks.
b. Adaptive capacity—the ability of the system to change in response to shocks and stresses in order to maintain normal functioning. Adaptive capacity can be increased by having alternate services available.
c. Restorative capacity—the ability of the system to recover quickly following a shock or stress and return to normal functioning. Restorative capacity can be increased by putting in place resourced disaster response plans and quick response capabilities.

These capacities correspond to the progression of a system from the occurrence of an event (disaster) through the recovery stage, as shown in the diagram below. The drawdown portion of the curve corresponds to the absorptive capacity of the system, and the draw-up portion of the curve corresponds with the adaptive and restorative capacities.

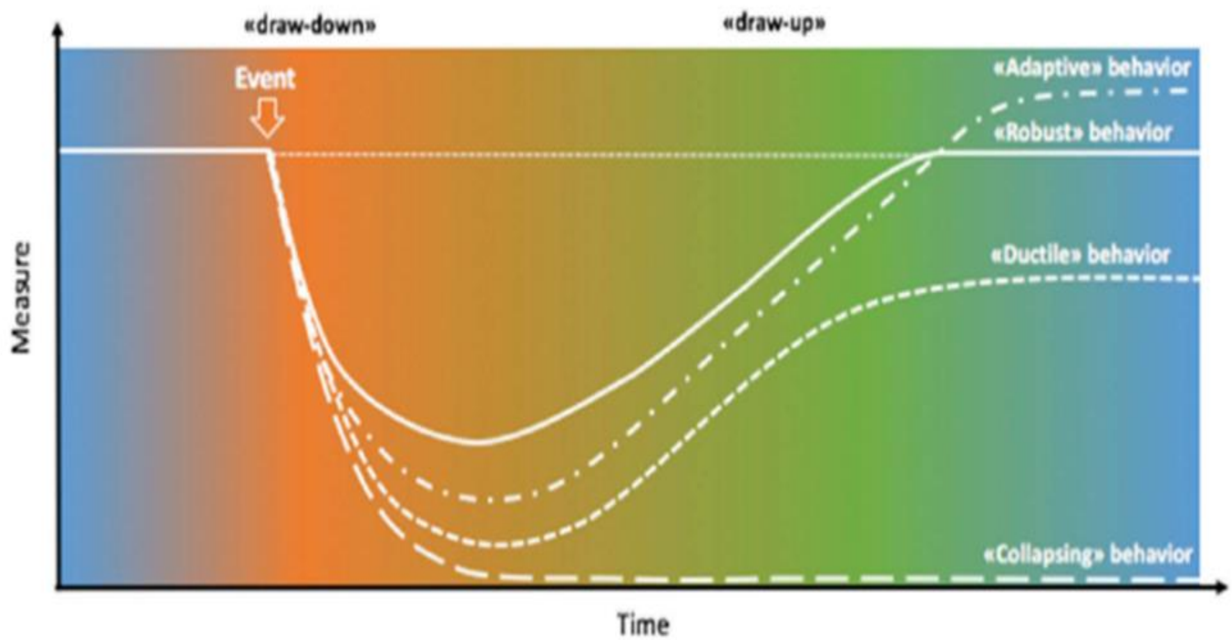

Figure 1. Resilience Curve

The occurrence of a disruptive event results in a 'draw-down' or loss of the system's performance, which is then followed by a bounce back or 'draw-up' phase, reflecting the recovery behaviour of the system. The use of this 'swoosh' shaped resilience curve (involving a possible 'draw-down' and 'draw-up' shape) provides a conceptually sound representation of the various resilience functions of the system under study that can then be analysed by means of quantitative performance indicators. Source: "A Review on Resilience Assessment of Energy Systems", Sustainable and Resilient Infrastructure.

To illustrate this progression with a real-world example, Figure 2 is a diagram of the recovery of Puerto Rico's power system in the aftermath of Hurricane Maria. The Y-axis is the percentage of customers who had power restored. As reflected in the diagram, forty percent of households did not have power four months after Maria and thirty percent did not have power six months after Maria.

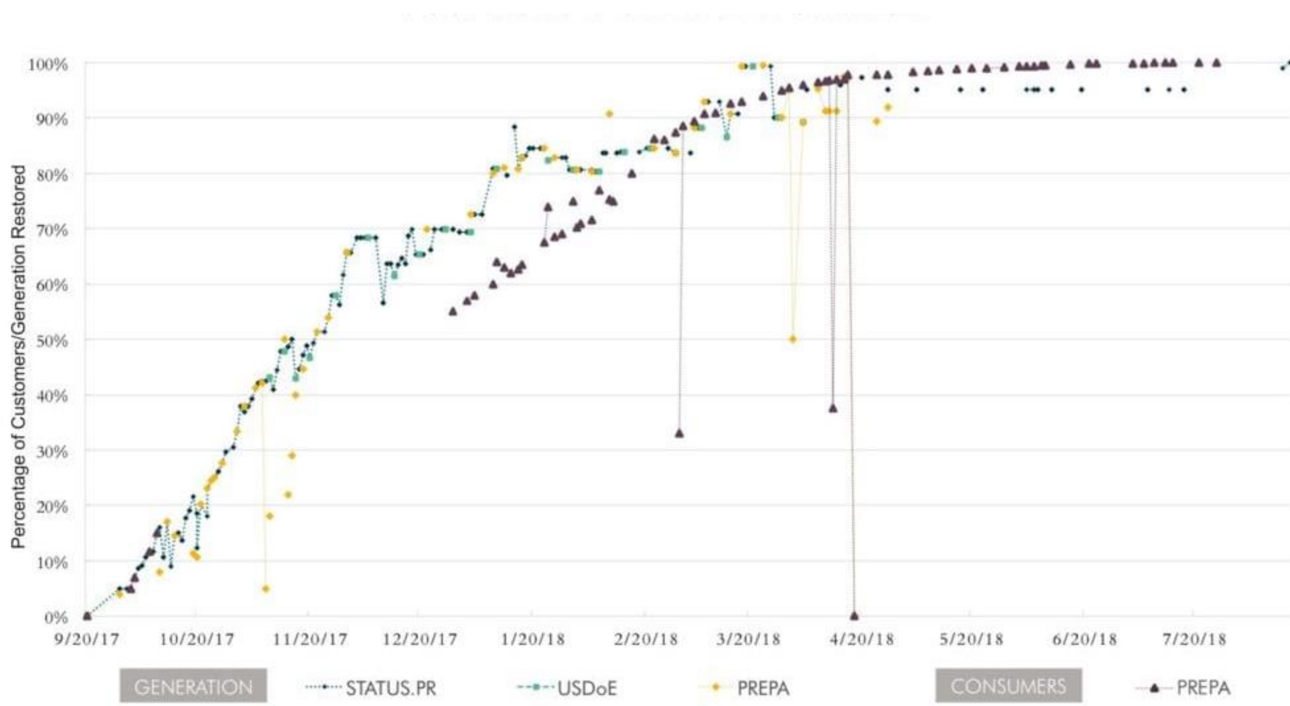

Figure 2. Post-Maria Power Restoration

Source: "The Puerto Rico Renewable Microgrid Toolkit: A Data-Driven Approach to Resilience", Rocky Mountain Institute, December 2018. https://rmi.org/the-puerto-rico-renewable-microgrid-toolkit-a-data-driven-approach-to-resilience/

Adopting the nomenclature used in “A Review on Resilience Assessment of Energy Systems”, the resilience of a system can be characterized qualitatively as following one of four behaviors, or patterns (shown in Figure 1):

- Adaptive behavior-the system compensates for loss in its performance, and even reaches an improved state compared to the initial state, reflecting not just a simple recovery, but a (partial) reconfiguration.
- Robust behavior-the system returns to its initial state.
- Ductile behavior-the system comes back to a certain level, but its functionality is not completely restored.
- Collapsing behavior-the system is not able to recover and completely loses its functionality.

The authors of “A Review on Resilience Assessment of Energy Systems” go onto state,

> “These four generic resilience curve patterns do not represent all the possible shapes of the resilience curve, but aim to capture some key outcomes and bounding cases. Hence, there may be substantial variation in the steepness and extent of the ‘draw-down’, and the duration and level of recovery of the ‘draw-up’. It can be argued that the smaller the performance loss (‘draw-down’) and the faster the bounce back (‘draw-up’) of a system after a disruption, the higher is its resilience. It follows that a more resilient system could be achieved with investments either to avoid performance loss (‘draw-down’) or to boost the bounce back (‘draw-up’)”.

The resilience pattern that best describes the post-Maria progression of Puerto Rico’s power infrastructure is “ductile”; while power has been restored to one hundred percent of the Puerto Rico Power Authority’s (PREPA) customers, the system is considered to be “fragile”. (Source: “The Lights Are Back On, But After $3.2B Will Puerto Rico's Grid Survive Another Storm?”, Impact 2020, McClatchy Washington Bureau, 2018. https://www.mcclatchydc.com/news/nation-world/national/hurricane/article217480370.htm)

Observations About Infrastructure Resiliency in Puerto Rico

The specific purpose of the field study was to observe how Puerto Rico is using resiliency as a design and investment objective in the rebuilding of the Island's utility infrastructure. During our week in Puerto Rico, we met with representatives of Commonwealth and U.S. government agencies charged with the responsibility of rebuilding the Island's physical infrastructure. We met also with community groups, NGO's, and subject matter experts. The purpose of these meetings was to learn how these groups are thinking about resiliency, and specifically how resiliency fits into the Island's rebuilding plans.

The questions we posed in these meetings were:

- How do you "define" resiliency?
- What investments are you making with the objective of resiliency?
- What are the planned outcomes of these investments?
- How are these investments evaluated and prioritized?
- Once an investment is made, how do you measure its efficacy?

Our key observations were:

- There is no universal definition of resilience being used by the various governmental and NGO organizations that are engaged in the rebuilding of Puerto Rico.
- The term "resiliency" was being used interchangeably with redundancy, hardening, decentralization, preparedness and maintenance. As discussed below, resiliency incorporates these concepts, but, to be more accurate, it is about the ability to rebound from, as opposed to withstand, a disaster event. This ability to rebound is not a central theme of the rebuilding efforts on the Island.
- Implementing actions to improve resiliency is difficult for a variety of reasons, including:
    - Some resiliency strategies run against entrenched ways of doing things, e.g., incurring significant inventory costs associated with stockpiling materials that may or may not be used;

    - Political, organizational, financial and regulatory constraints;
    - FEMA, which is integral to the rebuilding of Puerto Rico and is a primary funder of the Island's rebuilding effort is not in the resiliency "business". FEMA's mission is to restore things to the condition they were before the event;
    - The Commonwealth and U.S. government agencies are not engaged in rigorous cost-benefit analysis to prioritize infrastructure investments despite the fact that resources (financial and human) are limited. Instead, investments are being undertaken on an opportunity-driven basis, e.g., if funding is available;
    - The benefits associated with (i.e., return on) resiliency investments are both long term and uncertain (given the nature of disasters). This makes it difficult to prioritize these investments in the face of other competing demands; and
- The focus in post-Maria Puerto Rico is to "build back better", i.e., repair what was damaged, but to a higher standard. (Source: "Build Back Better: Request for Federal Assistance for Disaster Recovery", November 2017. https://nlihc.org/sites/default/files/Build_Back_Better_PR_Request_94B.pdf) Building to stricter and more up-to-date codes and using stronger designs and materials, to call out two "building better" approaches, may make infrastructure systems less susceptible to damage, but will not ensure these systems are impervious to disruption. For example, the damage that Maria wreaked on Puerto Rico's power system was primarily to the transmission and distribution (T&D) network. Significant efforts were made post-Maria to rebuild and strengthen this T&D infrastructure. Then, in January 2020 a series of earthquakes hit the Island, and while the T&D infrastructure was not affected, 30% of the power generation capacity of the Island was disabled, leading to Island-wide blackouts.
- Resiliency is being addressed more directly and effectively at the community level.

In summary, we concluded that it is not practically possible to bulletproof infrastructure systems. Further, building back better is not resilience. Instead, resilience is the capability, measured in both degree and time, to recover from a disaster. We observed that making Puerto Rico's infrastructure resilient, i.e., able to recover better and faster in the face of the next natural disaster (which is certainly bound to occur), is not an explicit investment objective or priority on the Island.

Practical Approach to Resiliency

Based on our field observations, we became convinced that a useful way to think about resiliency is to focus on what we want the resiliency curve to look like. This requires an "outcomes first" approach. This approach is embodied in the Theory of Change (sometimes called the logic model). Using the Theory of Change, one begins with outcomes and then moves backward to activities and finally to inputs.

Outcomes are directly related to a specific goal, e.g., resilience. Activities are the specific actions associated with meeting this goal. For example, in a project to reduce the incidence of HIV/AIDS, an outcome would be a target per capita infection rate. Activities to achieve this outcome could include conducting community meetings to sensitize the public on prevention measures, installing condom dispensers at hot-spots, collecting periodic data to monitor project progress, among others. (Source: Difference Between Inputs, Activities, Outputs, Outcomes and Impact, https://impact-evaluation.net/2013/06/10/difference-between-inputs-activities-outputs-outcomes-and-impact/.)

To apply the Theory of Change approach to resiliency planning, we undertook the task of envisioning resilient outcomes for the power and water sectors in Puerto Rico. In other words, what did we think the future should look like in the wake of the next natural disaster?

This required us to think about the shape of the resiliency curve in Figure 1. This curve has two dimensions; the time of recovery and the degree of recovery. (Note: The previously referenced RAND paper [p.36] suggests that there is a third dimension, i.e., equity, or how is the recovery “distributed” among the population.) Our first step was to determine the appropriate unit of measurement for the Y-axis that relates to the degree of recovery, or post-disaster performance. In the case of the power infrastructure in Puerto Rico, the measure used by PREPA to evaluate the “quality” of the recovery post-Maria was the percentage of customers who were back “on-line”, as shown in Figure 2. The question we asked ourselves was, is this the best measure of resilience? Instead, perhaps the measure should be the percentage of key institutions (e.g., hospital, schools, community centers, etc.) that have access to power.

Once we decided on the “right” outcome, our next step was to develop a set of actions to achieve this desired outcome. For this step, we focused on the what needs to be done (activities), leaving the how should it be done (inputs) for another day. (Also, while the Theory of Change appears to be unidirectional—outcomes dictate activities which define inputs—it is really an iterative process where the process of determining appropriate activities may cause modifications to the outcomes.)

Below are our resiliency outcomes and activities for the water and power sectors in Puerto Rico.

Water-The desired outcome, represented by the resiliency curve in Figure 3, is every individual within each household should have access to potable water in the following amounts and in the time frames shown below. (Access to potable water is defined as water available via the centralized water system or a local source.)

- 5 liters in 24 hours;
- 8 liters in 48 hours;
- 12 liters in 7 days (or 168 hours); and
- 20 liters in 14 days (or 336 hours). Note: 20 liters per capita is considered the minimum quantity of treated water essential for basic hygiene and consumption. (Source: “Technical Notes on Drinking-Water, Sanitation and Hygiene in Emergencies”, World Health Organization Water Engineering

Development Centre, 2013.
https://www.who.int/water_sanitation_health/publications/technotes/en/)

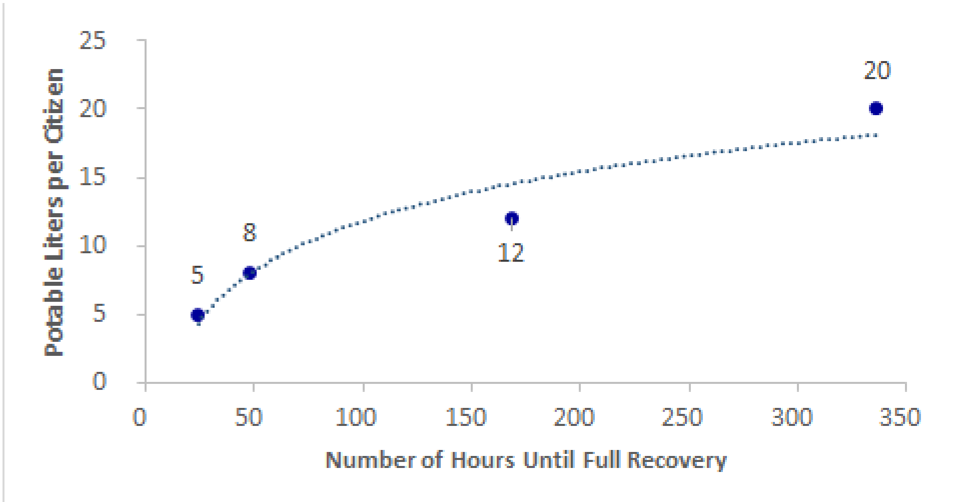

Figure 3. Potable Water Resiliency Outcomes

Activities to achieve outcomes:

1. Develop localized water sources.
2. Install redundant (back-up) power systems for centralized and local water treatment plants and pumping stations.
3. Upgrade central water infrastructure system infrastructure to minimize damage as a consequence of a future disaster.
4. Build-up emergency stockpiles of water in each municipality and prepare a distribution plan, as described below.
5. Plan for post-disaster response:
    a. Develop a formal framework to foster cooperation and collaboration among stakeholders (public sector, non-profit sector, private sector, and community groups) to distribute efficiently and equitably emergency water and water treatment supplies; and
    b. Establish process/systems to identify damaged infrastructure and a response/repair plan.

Power-The first 72 hours of a disaster response are widely accepted by many government organizations, such as FEMA and the UN Office for Coordination of Humanitarian Affairs, as the window in which to save lives and return communities to normal. After 72 hours, the chance of finding survivors significantly decreases and provisions of food, water and medicine become scarce. In keeping with this standard, the desired resiliency outcome is for power to be restored to all communities within a period of 72 hours. Intermediate outcomes are described below and represented by the resiliency curve in Figure 4.

- Ensure all critical institutions (hospitals, schools, community centers, the water supply, and telecommunications) that directly support human life have access to power within 8 hours.
- Provide power to essential commercial businesses (supermarkets, commercial telecommunications, pharmacies, ports, banks) and at-risk households (i.e., households with high medical risks) within 8 to 48 hours
- Provide power to all residential and other commercial businesses within 48 to 72 hours.

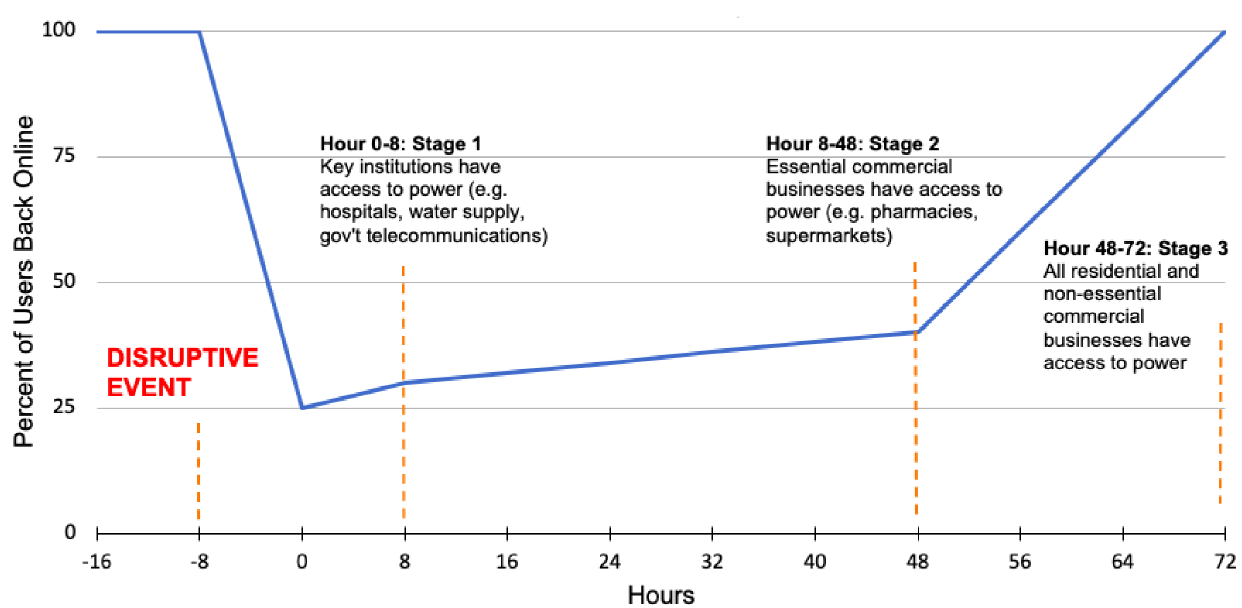

Figure 4. Power Resiliency Outcomes

Activities (in order of priority) to achieve these outcomes are:

1. Ensure that every community is connected to a localized, alternative power system (i.e. solar powered batteries, back-up generators, and fuel cells). This will allow communities to operate independently of the main grid in the event of a disruption where the main grid is not functional.
2. Reinforce critical power infrastructure elements (transmission, distribution, and generation) to withstand damage caused by a disaster event.
3. Establish a scheduled maintenance protocol of all critical power infrastructure elements (transmission, distribution, and generation).
4. Diversify power generation methods from imported oil and coal to renewables such as solar and wind.

It is interesting to note that the power resiliency outcome above contrasts with the outcome articulated by the Puerto Rico Electric Power Authority (PREPA) in a public hearing held by Puerto Rico House of Representatives' Committee on Economic Development, Planning, Telecommunications, Public-Private Partnerships and Energy in June 2020. At this hearing PREPA's executive director said, "it is not acceptable for the people of Puerto Rico to take 11 months for the light to reach them. We had the ability to learn and do things differently. If an event similar to Maria's came, I don't see more than two and a half months without electricity. I think everyone can be [back on-line] within that period." The executive director went onto explain that PREPA has taken the following actions; stockpiled an inventory of materials, established "rapid response" agreements with various utility groups off Island, engaged in preventative maintenance, and organized an ad hoc emergency communications network composed of amateur radio operators.
(Source: "They Anticipate 'No More' Than Two and a Half Months Without Electricity If a Hurricane Destroys the Electricity Grid", *El Nuevo Dia*, June 2, 2020 https://www.elnuevodia.com/noticias/locales/nota/anticipannomasdedosmesesymediosinluzsiunhuracandestrozalaredelectrica-2573020/?utm_source=Center+for+a+New+Economy&utm_campaign=67c538d077-Weekly-Review-June-4-

2020&utm_medium=email&utm_term=0_6289136981-67c538d077-509790689&mc_cid=67c538d077&mc_eid=5931756c05.)

Conclusion

Investments in infrastructure that have the stated objective of improving resiliency should be tested against desired outcomes. Specifically, will the investment result in a less deep draw-down and/or a faster and higher draw-up?

Mapping these investments onto the resiliency curve allows the planner to answer two important questions. The first is, is the investment really designed to improve resiliency or is the term “resiliency” simply a convenient rationale for the investment?

The second question is related to the return on a resiliency investment. These investments, like any other, should be subject to a rigorous investment analysis. The resiliency curve allows the planner to calculate the value of the benefits associated with a particular investment in order to determine its return, as well as to prioritize competing investments.

It is imperative for planners and managers to make deliberate, unambiguous and considered investments that will allow critical infrastructure to rebound effectively when the next disaster hits. An outcomes-based resiliency approach allows them to do this.