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RE: Resilience Energy Justice and Rooftop Solar Photovoltaic Mitigation Alternatives

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1. *Key Insights*

- The main recommendation to capture an effective metric for Resilience Energy Justice is to use the total time of power service restoration to 100% of the clients affected by a major event. Special emphasis to the last 5% of the customers restored is needed to effectively identify mitigation strategies to overcome the vulnerability to long power outages.
- The number of deaths resulting from a long power outage needs to be prominently included in resiliency metrics although its analysis requires a complex systems approach.
- The focus on the resiliency of electric services, which includes the electric grid, needs to replace the explicit or implied emphasis on grid resiliency. People need resilient electric power service, and often the grid is not the best way to deliver it.

While in some major events the last 5% could take weeks or maybe more than a month, back to back events of great magnitude could result in a power outage of months in regions that never experienced such a long impact before. Another important metric for Resilient Power is the Customer Hours of Lost Electricity Service (CHoLES), which could be used to establish a baseline measure of regional impact without accounting for equity and justice aspects of disaster preparedness and energy mitigation.

The study of power system resilience is becoming more important with the increase of low probability / high impact events that are now more frequent with climate change impacts (Pastori, 2023). Different groups have taken broad approaches to power resiliency focusing on quantification (Stanković et al., 2015), metrics (Ouyang et al., 2012, Ayyub, 2015) definitions and taxonomy (Gholami et al., 2018). Even an IEEE Task Force tackled the framework, methods and metrics for power resilience (Chiu et al., 2020), which includes the two DOE defined resilience metrics supported in this study: 1) restoration time to recovery, which is the proposed energy justice metric and 2) CHoLES defined as cumulative customer-hours of outages. However, this report concludes that "it is impossible to have simple, industry-accepted resilience metrics addressing all-inclusive events affecting resilience". This statement represents a lost opportunity to ascertain the importance of the most simple and broadly accepted resilience metric, which is the total days without power resulting from a major event. Another flaw of the IEEE Task Force analysis is the prominence of the resilience trapezoid based on misguided resilience level measure. While the report includes 8 case studies, they are all from the utility perspective, not from the customer perspective that suffers the lack of resiliency, and it didn't include the longest power outage ever recorded, caused by Hurricane María in 2017 and 2018 (Castro-Sitiriche et al., 2018). Mechanisms that enforce the investment in data collection (and mitigation actions) for the last 5% of customers with power restored after a major outage is the ultimate goal of Resiliency Energy Justice.

2. *Resilient Power Service*

It is important to focus on the resiliency of electric services, which includes the electric grid. The focus is on Power Resiliency, which is different from Grid Resiliency. Community resilience is better served from the bottom-up, as established by the National Research Council report (2012). For example, the alternative of installing rooftop photovoltaic systems equipped with batteries in hundreds of thousands of homes and businesses needs to be studied and compared with grid hardening options. The metric to compare both alternatives need to be primarily the total time of power service restoration to 100% after a major event.

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There is a limitation in the available data that describes the amount of clients without power after the first 95% of the clients had grid power restored after Hurricane María almost 200 days later. While the last 62,000 clients only represent less than 5% of the total number of customers, the additional 128 days that it took to restore the grid power represent 40% of the total duration of the power outage. The data collected beyond day 196 was obtained from the official Twitter account of PREPA. Data from January to April 2018 was collected from the official Twitter account of PREPA which was consistent with the DOE weekly Situation Reports published by the Office of Cybersecurity, Energy Security, and Emergency Response (CESER). The data of customers without power before January 2018 is not available and only an estimate based on power generation was available. The first Situation Report that included percent of total customers without power was 675,000 on January 3, 2018 with PREPA announcing on January 2, 2018 that 57% of customers had grid power restored. The days with good data are the first 8 days of the power outage because all 100% of customers didn't have power. Because the power variations do not depend only on the number of customers with power restored, the resulting estimate is noisy. The curve using power generation estimates is clearly varying in ways that customers connected to the grid would not vary in contrast to the curve based on customer data after 105 days as shown in Figure. To improve the estimate for this period an exponential function was used to better represent the data from day 9 to day 104 as shown in Figure 3.

Figure 1. Customers without power in Puerto Rico after Hurricane María from day 1 to day 329 (Castro-Sitiriche, 2022).

3. Basic Resilience Metrics

Define a major event of a power outage where T_e is the total event duration from the day of the disruption until 100% of the power service to the customers is restored, and N is the total number of customers in the region affected by the outage. Figure 2 is a representation of resilience based on the Resilience Triangle from a 2015 paper (Ayyub, 2015). The area resulting from the integral in the equation is the customer hours of service provided while the area of the "resiliency triangle" represents the CHoLES. The area marked in red is the total potential CHoLES if all customers were without power during all the duration of the power outage.

CHoLES is the total Customer Hours of Lost Electricity Service due to an event such as a hurricane. The equation for the CHoLES is built from the addition of the hours of power outage from each customer where the total number of customers is N and the length of the power outage for a customer *i* is $T_{D,i}$.

$$CHoLES = \sum_{i=1}^{N} T_{D,i}$$

CHoLES is a metric of vulnerability because a greater amount of CHoLES shows a greater vulnerability. There are two ways to determine the vulnerability using average metrics based on the CHoLES. The average power outage duration is the CHoLES divided by the total number of customers N defined as V_T for outage time vulnerability. The average customers without power during the whole power outage is the CHoLES divided by the total duration of the event T_e, defined V_C as customers without power vulnerability.

These two vulnerability metrics represent two ways of slicing the CHoLES emphasizing the average length of the power outage or average number of customers without power.

$$V_T = \frac{\sum_{i=1}^{N} T_{D,i}}{N} = \frac{CHoLES}{N}$$

$$V_C = \frac{\sum_{i=1}^{N} T_{D,i}}{T_e} = \frac{CHoLES}{T_e}$$

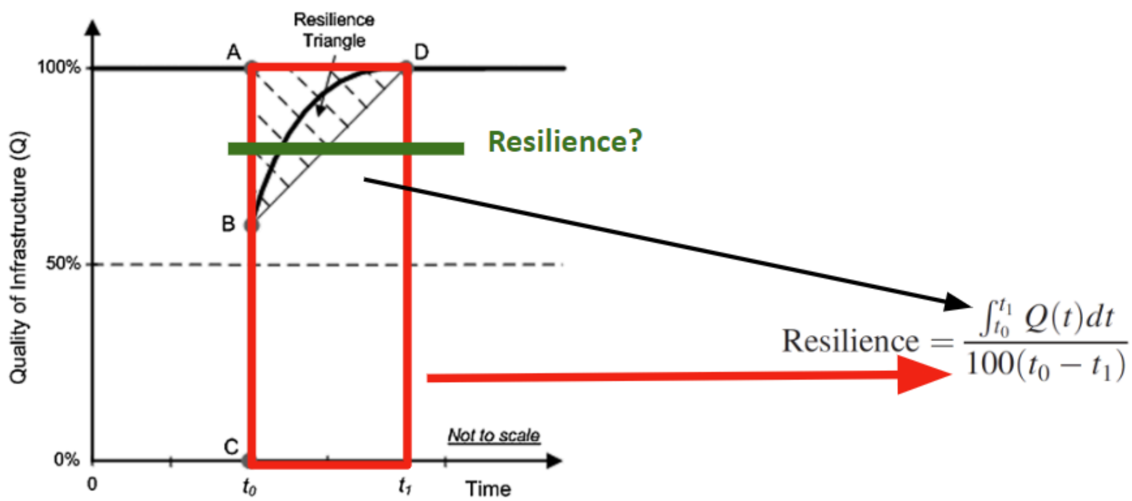

Figure 2. The resilience triangle, adapted from Ayyub (2015).

R is sometimes defined as a power resiliency metric that is characterized with the average percentage of customers with power service during the length of an event. However, the average distort the reality for a longer outage with its second half of the time period with more than 95% of customers with power such as Huricane María, improving its R because of a very slow restoration completion in the last mile.

$$R = \frac{N \cdot T_e - \sum_{i=1}^{N} T_{D,i}}{N \cdot T_e} = 1 - \frac{\sum_{i=1}^{N} T_{D,i}}{N \cdot T_e}$$

The Resiliency could also be defined in terms of the CHoLES or the vulnerability metrics as shown in the equation below. Vulnerability is the complement of resiliency.

$$R = 1 - \frac{CHoLES}{N \cdot T_e} = 1 - \frac{V_T}{T_e}$$

4. Resiliency Potential of Rooftop Solar PV Systems

As stated earlier, a better approach to define a resiliency metric is to study T_e, the total time of power service restoration to 100%. The mitigation actions needed to minimize the T_e can lead to bottom-up strategies such as rooftop solar PV systems. With 200,000 additional rooftop solar PV systems with batteries the Resiliency metric would actually deteriorate from R_{Grid}=0.73 to R_{Power}=0.59, which is not consistent with a reduction from 329 days without power to 156 days of power outage. The curves comparing the restoration of power service including 200,000 rooftop solar PV systems with batteries for the last 200,000 customers that had the power restored more than 156 days after Hurricane María and the historic grid restoration curve. The impact of Hurricane María on rooftop solar systems is estimated as 1.2% of those 200,000 clients have their systems damaged, which means that 2,400 systems also need to be restored in remote areas in less than 156 days. This assumption is reasonable considering that the estimate damage to solar PV by Hurricane María is less than 1.2% of the 30,000 PV systems according to recent analysis (Elizondo et al., 2023) and the current rate of monthly solar rooftop installations with battery in net-metering is more than 4,000 every month (NEPR, 2023).

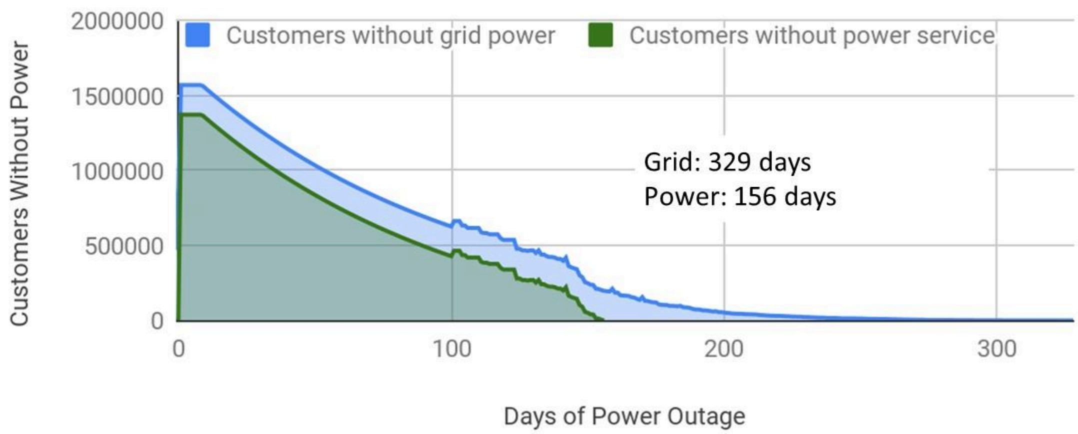

Figure 3. Customers without service and without grid after Hurricane María: 200,000 rooftop PV scenario

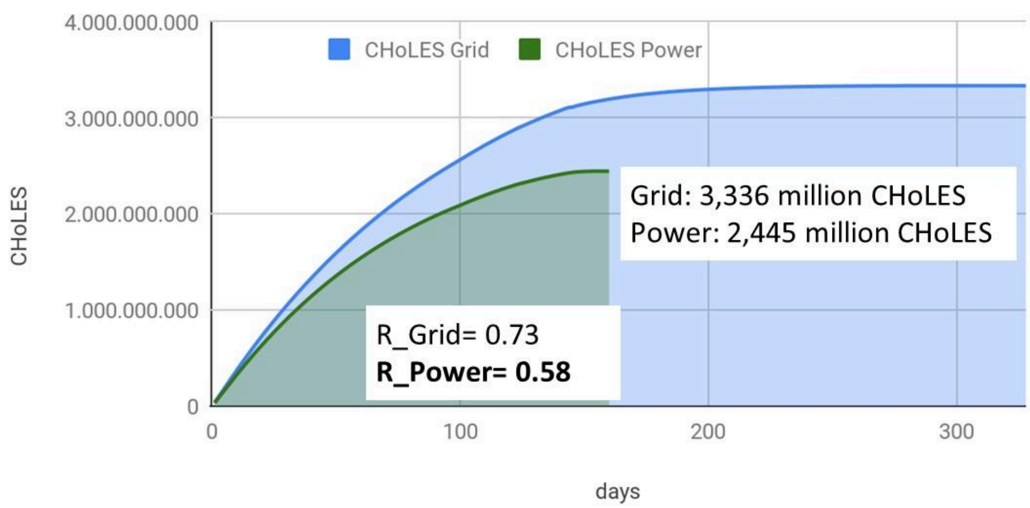

Figure 4. CHoLES for grid power and power service after Hurricane María: 200,000 rooftop PV scenario

5. Policy for the last 5%

The first step is to collect the data usually on the situation reports until the restoration is completed 100%. The main recommendation is to collect data from the community that provides a multidisciplinary view of the vulnerabilities that add to the power vulnerability. Social and geographical vulnerabilities will be important to analyze and drive mitigation strategies for those communities.

Figure 5 provides a map with the communities that had customers without power for more than 124 days and up to 329 days where 500,000 customers had their power restored. Figure 6 shows the barrios with the last 5% of the customers without power that endured more than 197 days without power. These communities need urgent mitigation actions before the next major hurricane affects Puerto Rico because there is no appropriate disaster response that could provide them resilience and the grid cannot do them justice.

Table 1 provides a comparison for different levels of geographically located Solar Rooftop adoption with their resulting total days of power outage. The impact on vulnerability metrics and CHoLES is also included. Even though the R as defined by Ayuub (2015) is not recommended, it is included in the table to compare it with the proposed metrics.

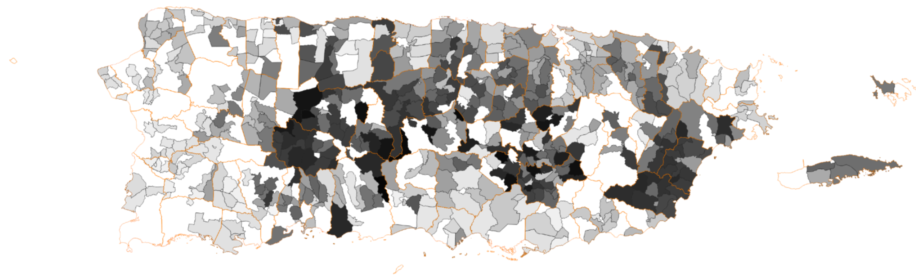

Figure 5. Communities with power restored more than 124 days after Hurricane María. Adapted from: Moscoso et al., 2023.

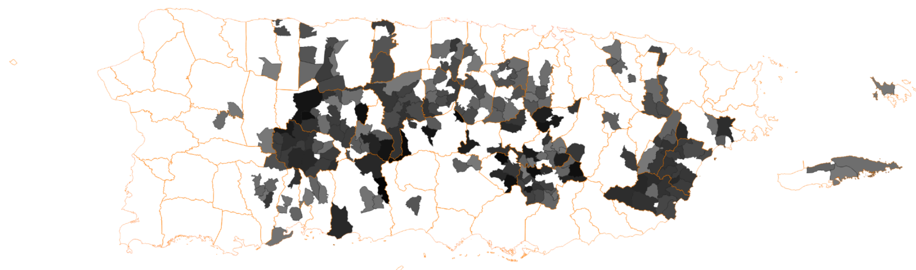

Figure 6. Communities with power restored more than 197 days after Hurricane María. Adapted from: Moscoso et al., 2023.

Table 1: Resiliency Metrics for Hurricane Maria and Solar Rooftop Scenarios

Scenario	**T_e: total time of power outage**	V_T (days)	V_C (customers)	CHoLES (millions)	R
Grid Outage	**329 days**	89	422,000	3,336	0.73
Power Outage 200k	**156 days**	65	653,000	2,445	0.58
Power Outage 500k	**124 days**	38	482,000	1,434	0.69
Power Outage 1M	**55 days**	11	311,000	410	0.80

As stated in the first paragraph, special emphasis to the last 5% of the customers restored is needed to effectively identify mitigation strategies to overcome the vulnerability to long power outages. To invest in the last 5% (62,000 customers) would result in a reduction in time of 40%. To obtain a reduction of an additional 40% a total of one million customers needs to be equipped with solar systems. Table 2 shows the impact that the different scenarios would have on the total number of days without power and the total accumulated CHoLES.

Table 2: Resilient Energy Justice Metrics for Hurricane Maria and Solar Rooftop Scenarios

Scenario	T_e: total time of power outage	Improvement in T_e	CHoLES (millions)	Improvement in CHoLES
Grid Outage	**329 days**	**Baseline case**	**3,336**	**Baseline case**
62k	197 days	132 (40%)	2,990	346 (10%)
Power Outage 200k	156 days	173 (53%)	2,445	891 (27%)
Power Outage 500k	124 days	205 (62%)	1,434	1,902 (57%)
Power Outage 1M	55 days	274 (83%)	410	2,926 (88%)

Table 3 has the numbers related to the last 5% of customers restored after Hurricane María and the impact that those 5% were equipped with rooftop solar systems with batteries. While the last 62,000 clients restored only represent 5% of the total customers but the percent of CHoLES was twice as much (10%). The 132 days to restore the last 5% of customers was 40% of the total 329 days of power outage for Hurricane María. The 17 days to restore the last 5% of customers was 51% of the approximately 35 days long power outage for Hurricane Fiona. The DOE Office of Cybersecurity, Energy Security, and Emergency Response (CESER) needs to work in collaboration with the Office of Energy Justice and POlicy Analysis to provide insight for the last 5% of customers that are reconnected after an event.

Table 3: Energy Justice for the last 5% in Hurricane Fiona and Hurricane María

	T_e: total time of power outage	Improvement in $T_{e5\%}$
María Grid Outage	**329 days**	**Baseline case**
Power Outage 62k	197 days	132 (40%)
Fiona Grid Outage	**35 days**	**Baseline case**
Power Outage 62k	17 days	18 (51%)

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