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Hurricane Maria Effects on Puerto Rico Electric Power Infrastructure

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ABSTRACT This paper discusses the effects of Hurricane Maria on Puerto Rico's electric grid. Arguably, the most significant effect of Hurricane Maria on Puerto Rico was the electric power outage that initially affected the entire island and lasted more than ten months. Although the damage to the conventional electric power generation infrastructure was relatively minor, both the transmission and distribution portions of the grid suffered much worse damage than that observed during other hurricanes that affected the U.S. in the past decade. This extensive damage added to logistical limitations and the island orography were important factors that contributed to an extremely slow restoration process leading to a very low resilience for the island's power grid. This paper describes all these aspects in detail and supports the explanation of the hurricane effects with photographic evidence collected during a damage assessment conducted in the early December 2017 when about half of the electricity customers were still without service. This paper concludes by exploring some lessons from these observations including potential options to increase resilience, such as the use of microgrids.

INDEX TERMS Power distribution, power generation, power transmission, natural disaster, restoration, resilience.

I. INTRODUCTION

This paper describes the effects of Hurricane Maria on Puerto Rico's power grid and the service restoration activities that followed the extensive power outage caused by such event. Hurricane Maria's eye made landfall on Puerto Rico near the town on Yabucoa on the Southeastern coast of the island at 10:15 UTC on September 20th. At this time, the hurricane maximum sustained winds were just under 155 mph, which made Maria a very strong category 4 hurricane according to the Saffir Simpson scale, just 1 mph less than the level for the maximum category of 5. Hurricane Maria then crossed Puerto Rico following a northwestern path and about 8 hours after making landfall its eye left the island through the municipality of Camuy, on the northwestern coast of Puerto Rico with maximum sustained winds of approximately 110 mph [1]. Like all hurricanes, additional damaging actions included storm surge in coastal areas and torrential rains.

At the time when Hurricane Maria affected Puerto Rico, the island's electric system had a generation capacity of 5,839MW [2] with a mix of technologies mainly based on burning fossil fuel (steam, combustion, combined cycle and diesel). The main power plants were Costa Sur (990MW), Aguirre (900MW + 592MW) and AES (454MW) located in southern Puerto Rico, and Cambalache (247MW), Palo Seco (602MW) and San Juan (400MW + 400MW) in the north of the island. This generation capacity represented an aging system with about 60% of the installed systems dating about 50 years old and with a relatively low efficiency of at most 30%. Until Hurricane Maria, the electrical system had 2,416 miles of transmission lines with the main lines shown in Fig. 1. The island's electricity demand had been decreasing since 2,005 when it reached a peak of 3,685MW. Demand did not exceed 3,000MW in the months before the hurricane. This decrease in electricity consumption had been observed in all sectors (residential, commercial

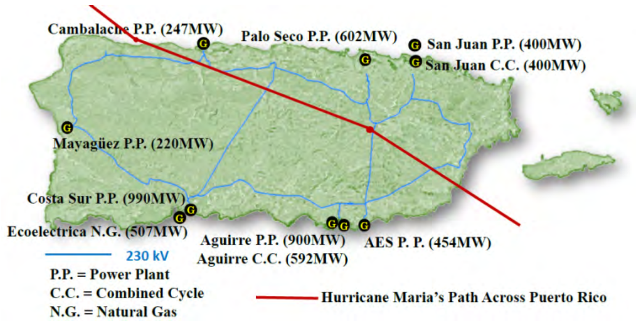

FIGURE 1. **Main transmission and generation assets of Puerto Rico's power grid.**

and industrial) [2]. An increase in technical and non-technical losses had also been observed leading to a deteriorating quality of service. While demand decreased, there was an accelerated growth in renewable energy systems integration supported by net metering and a high interest for distributed generation installations.

From [3], about 40% of the island's population lives in the larger metropolitan area of San Juan. The rural population is approximately 6% of the total, located mostly in the difficult to access mountainous areas at the center of the island. Puerto Rico's population has been declining for the last ten years and the rate increased after hurricane Maria in no small part due to the lack of electricity for several months after the storm. The largest demand of electricity occurs in the metropolitan areas of the north, making the transmission lines that cross from south to north to be particularly critical.

Section II explains Puerto Rico's electric power regulatory and economic conditions when the hurricane made landfall. Section III describes the effects of Hurricane Maria on the island's power grid. Section IV recounts the initial restoration efforts. Section V discusses the performance of Puerto Rico's grid based on quantitative resilience metrics and compares these values with those of past hurricanes. Finally, this paper discusses lessons from this hurricane in Section VI and presents conclusions in Section VII.

II. PUERTO RICO's ELECTRIC POWER ENVIRONMENT

The Puerto Rico Electric Power Authority (PREPA) is a public power company created through Act 83 of 1941 to plan, design, construct, operate and maintain Puerto Rico's electric infrastructure. Before that, private companies dominated the electric sector focusing on areas where their business could prosper, while not serving rural and remote areas. Integrating all electric power systems in Puerto Rico was a socio-economic development strategy in which economies of scale would make electricity less costly, making it affordable to more people and promoting industrial activity. Electrification of Puerto Rico was accomplished by the early 1970s but calls for reforms to the state-owned utility begun to appear. This reform movement was fueled by the effects of the 1973 OPEC embargo and led to starting various initiatives, including the creation of a state energy office in 1977 to lead energy policy development and implementation in Puerto Rico. Once the 1970s and early 1980s oil crises passed, many of those reforms were abandoned or limited [4]. The corporation's initial electrification mission did not change.

During the 1980s and 1990s many ideas were presented to reform PREPA but its management would oppose any proposed transformations arguing that it was against their given mission of providing electricity at the least possible cost. Such opposition to changes, exemplified in [5], was still observed until Hurricane Maria impacted the island and was similar to the private companies opposition to the integration of the disconnected electrical systems in Puerto Rico before the 1970s: not meeting Puerto Rico needs from its electrical infrastructure [6] and providing little access to the public [4]. PREPA's planning and operating vision was based on hierarchical control, centralized generation and top-down planning. New technologies and practices, and new opportunities were missed because of the protective actions of the last 40 years, including many instances to begin an ordered and comprehensive transformation in the electric infrastructure, business structure and customer service. Rates had not changed since the late 1980s, which the political interventions that affected the corporation. The industrial clients' exodus that began in the late 1990s culminated with a deep economic recession in 2006, leaving Puerto Rico with a power infrastructure built for an industrial economy that no longer existed, based mostly on burning imported oil. To address the challenges of reduced revenues from industrial clients, PREPA's board decided to borrow money more frequently from the municipal bond market instead of complying with its fiduciary obligations to PREPA and the public it supposedly served [2]. These conditions also led to a reduced investment in maintenance activities and an increasingly aging infrastructure.

In 2014, Act 57 gave PREPA a new mission: to support sustainable energy in Puerto Rico, change the electric infrastructure, maximize renewable energy use and become a transparent service-oriented company. Act 57 also created the PR Energy Commission in charge of regulating Puerto Rico's electric sector including overseeing the first Integrated Resource Plan (IRP) process [7]. However, these reforms seem to have been implemented late. Due to high debt, high power generation cost from mostly oil-based plants, and lower revenue, PREPA had severe financial issues and the power grid was in inadequate conditions due to lack of proper maintenance and insufficient upgrades. The 2014 to 2016 restructuring effort seemed to have left PREPA disorganized and ill-prepared to face strong hurricanes. Electric service had degraded as power disruptions become a daily occurrence including a major blackout that affected the entire island one year before Hurricane Maria made landfall. This complete outage, caused by failures of two main 230 kV lines following a fire at a circuit breaker located at the Aguirre power plant, already highlighted the inadequate conditions and layout of the island's power grid. Eventually, high costs, high debt levels and low revenues forced PREPA in early July 2017 to file for bankruptcy protection under Title III of the 2016 Puerto Rico Oversight, Management, and Economic Stability Act (PROMESA). Such federal law also established a Finance Oversight and Management Board (FOMB) with the authority to oversee Puerto Rico's budgets and its government financial activities preventing Puerto Rico to fully control its electric energy sector. During 2018 local laws were passed to reorganize the regulatory framework and to establish the policies to privatize PREPA assets and potentially grant concessions for T&D and grid operations.

III. HURRICANE MARIA EFFECTS ON PUERTO RICO's ELECTRIC POWER INFRASTRUCTURE

A. ELECTRIC POWER GENERATION

Puerto Rico's generating capacity when Maria struck the island was of 5,839 MW, distributed in 31 major generating units in 20 facilities. The location of the most important of these facilities is shown in Fig. 1. However, power generation was already operating at reduced capacity before Maria due to economic limitations and because the largest power plant in Palo Seco had its operations restricted on August 25th after a report indicated serious personnel safety issues and risk of some structures to collapse. Damage to the power generation facilities from Maria was minor compared to that of other assets but, still, several power plants experienced flooding. The most affected power plant was Cambalache due to flooding. A damage assessment conducted in early December 2017 also showed limited damage in other power plants, such as various portions of the AES Power Plant coal conveyor belt with moderate to minor damage.

Renewable energy sources are also part of the generation mix in Puerto Rico. The effect of Hurricane Maria on these power generation systems are discussed in detail in [8]. At the time Hurricane Maria affected Puerto Rico there were two main wind farms operating in the island. With an installed capacity of 95 MW, Santa Isabel is the largest of the two wind farms. This wind farm had no damage from Hurricane Maria. However, the second wind farm in Punta Lima, had all of its 13 wind turbines damaged. Two failure modes could be observed in these wind turbines. As Fig. 2 shows some blades of the wind turbines experienced delamination. and other blades broke at their neck. The surviving blades configuration suggest that the wind turbines were feathered, and their rotors were blocked from rotating. However, due to the wind farm geographic location in the northeastern quadrant of the hurricane, the 1.8 MW wind turbines in this farm experienced the strongest winds generated by the storm with maximum sustained winds of no less than 125 mph. The wind farm in Santa Isabel experienced instead more moderate winds, which helped its wind turbine survive the storm.

In September 2017, there were five utility-scale photovoltaic (PV) plants generating about three quarters of all of Puerto Rico's solar powered electricity. The remaining quarter was 88 MW of PV power generated in a distributed

FIGURE 2. A damaged wind turbine with two of its blades broken at their neck and the third blade delaminated. (Photo: A. Kwasinski).

FIGURE 3. The PV "farm" at Humacao. The bottom image, facing north, shows a general view of this facility. A hill at the center of this image may have protected the central area of this facility. A detail on the top and right of this general view shows the nearly completed expanded area from the eastern side, facing west, towards the central hill. The detail on the top left shows damage west of the hill as seen looking from the south of the facility. (Photo: A. Kwasinski).

fashion at the premises of 8,500 PREPA's customers [9]. The five utility-scale PV plants experienced different damage during Hurricane María. While the PV plant in Loíza was practically undamaged, the PV plant in Humacao experienced significant damage, as Fig. 3 shows. The other utility-scale PV plants in Isabela, Salinas and Guayama experienced light to moderate damage, although none of them were as severely damaged as the PV plant in Humacao, which is located near Hurricane Maria landfall point. At that time, about a third of this PV system was been expanded to make the total plant capacity reach almost 100 MW, which would had make it the largest PV power generation facility in the island. However, the expanded area was almost completed destroyed by the storm. Although the other two areas (operating before Maria) had much less damage, about 50% of such area still suffered considerable damage. As Fig. 3 suggests, a hill located north of the central area of this PV facility may have protected the less damaged areas from the prevalent north-south hurricane winds. The failure mode in all of these PV plants was PV modules blown away by the wind. A detail description of

FIGURE 4. **A fallen transmission wooden pole. (Photo: A. Kwasinski).**

FIGURE 5. **Multiple broken concrete poles in Punta Santiago. (Photo: A. Kwasinski).**

these failure modes and of damaged observed in residential and building PV sites is presented in [8].

B. ELECTRIC POWER TRANSMISSION

One of Hurricane Maria's most significant effects on Puerto Rico's power infrastructure was damage caused to transmission lines. Before Hurricane Maria struck Puerto Rico, the island had 2,478 circuit miles of transmission lines divided among 375 circuit miles of 230 kV lines, 727 circuit miles of 115 kV lines and 1,376 circuit lines of 38 kV lines [10]. A small part of these lines were underground including 35 miles of 115 kV cable, 63 miles of 38 kV cable. Additionally, there were 55 miles of 38 kV submarine cable. The overhead transmission line support structures included both wooden (Fig. 4), concrete or metal poles and lattice towers, many of them supported by guy wires.

Transmission lines in Puerto Rico presented important vulnerabilities. In addition of having many structures installed in difficult to access mountainous locations with thick vegetation, reports indicated that only 15 % of the lines could withstand wind forces caused by a Category 4 hurricane [11]. As a result, almost all transmission lines in the eastern half of the island experienced severe damage. Although preliminary reports suggested that 55% of the transmission towers fell [12] later reports indicated that 847 transmission structures had fallen due to Maria [13], which is consistent with the observations made during a damage assessment in early December of 2017. In comparison, hurricanes Gustav and Ike caused the failure of Entergy's 260 structures and 980 structures, respectively, over a much larger area than that occupied by Puerto Rico. Many monopole structures, including wooden and concrete poles (see Fig. 5) broke due to the effects of strong winds and flying debris or fallen vegetation. Arguably, the most critical failures were those observed in 230 kV structures, such as the one in Fig. 6. A detailed view in Fig. 7 shows fractured braces in this lattice tower. Failures in the 230 kV structures were exacerbated by the vulnerable PREPA's grid layout shown in Fig. 1 with a significant portion of the generation assets located south of the island and the largest demand center located across the mountainous inland region on the northern coast of the island.

FIGURE 6. **One of the many fallen transmission towers in Puerto Rico. (Photo: A. Kwasinski).**

FIGURE 7. **Detail of damage in a transmission tower with fractured braces. (Photo: A. Kwasinski).**

Fig. 8 shows an overview of, arguably, the most critical transmission area in Puerto Rico located just north of the Coquí community where the transmission lines from the Aguirre power plants and A.E.S. power plant meet. That is, this is the area where the lines carrying the power from 40 % of the capacity from all of the main generation plants in the

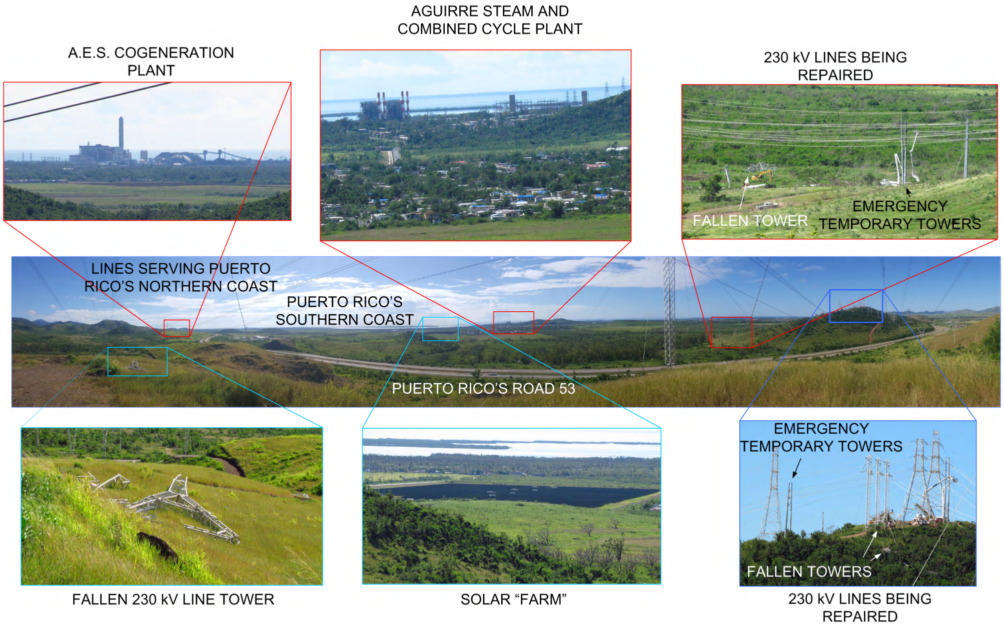

FIGURE 8. Overview of the condition at the critical location north of Aguirre and AES power plants on December 3rd, 2017. (Photo: A. Kwasinski).

island or from 33 % of all of the generation capacity in the island converge. As Fig. 8 shows, there were multiple transmission structure failures that were still being repaired in early December 2017 when these images were taken. None of these towers showed obvious signs that corrosion may have been a contributing factor for their failure so a more detailed analysis of their failure cause by examining standards, such as [14] and performing lab stress tests would require a more extensive analysis out of the scope of this paper.

Reports [13] also indicated that 74% of the nearly 350 substations experienced some damage. Yet, this damage seems to have been less severe than that observed in transmission poles and towers. Damaged observed substation components included capacitor banks, disconnect switches, switchgear support structures and perimeter fences. Maintenance issues, such as support structure corrosion or bird nests were also observed in some substations. However, determining how much these issues were a contributing factor to power outages or slow restoration is out of the scope of this paper.

C. ELECTRIC POWER DISTRIBUTION

Puerto Rico had about 30,000 miles of distribution lines when Hurricane Maria affected the island. Hence, it is possible to estimate that approximately half a million poles were used in Puerto Rico to distributed electric power with overhead lines. A damage assessment showed that at least 10 percent of these distribution poles were damaged in the island and although there are no exact figures provided by PREPA, this percentage is consistent with reports indicating that more than 50,000 poles needed to be replaced [15]. This percentage is considerable higher than a typical 1 to 3 percent observed in

FIGURE 9. A 30 ft long fallen pole with an oval showing its buried portion. This buried portion measured approximately 3.7 ft., which is less than the 5 ft. 6 in. used in a utility in Florida [22]. (Photo: A. Kwasinski).

areas affected by hurricanes in the past [16]–[18]. For example, Entergy had to replace 8,194 poles after Hurricane Ike and 11,708 poles after Hurricane Gustav, in areas much larger and more densely populated than the island of Puerto Rico. Some reports [19] attributed this higher failure rate to poles that may have been buried not deep enough. Although the damage assessment was able to confirm such reports in a few locations (see Fig. 9), the damage assessment also observed many more broken poles than fallen poles. Broken poles include not only wooden ones but also concrete poles. This performance can be explained by Puerto Rico's dense vegetation that is much more costly and difficult to control through tree trimming programs typically implemented in the continental U.S. Fallen vegetation was identified as a key factor for distribution line failures. Another possible reason for this performance is Puerto Rico's mountainous geography that tends to increase wind speeds by channeling wind through valleys

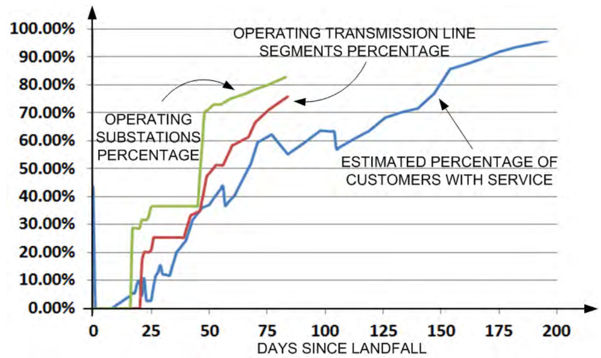

FIGURE 10. **Electric system restoration process progression, adapted from [24].**

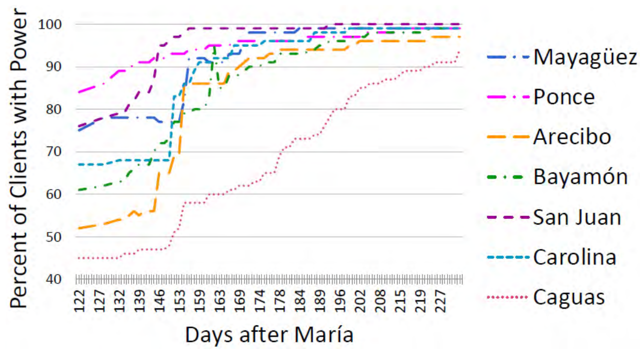

FIGURE 11. **Final electric system restoration process by region [24].**

and through the natural increase of wind speed at higher elevations. Additional contributing factors for pole failures included overloaded poles and poles installed at a time with less demanding wind speed withstanding requirements.

IV. ELECTRIC POWER RESTORATION

After Hurricane Maria passed through Puerto Rico, the power plants started operating in island mode, supplying power to the neighboring areas (Mayaguez on September 25, Costa Sur on October 2, Cambalache on October 4 and Aguirre on October 5). Cambalache was one of the most affected plants because it was flooded. Palo Seco, which was taken offline about one month before Maria impacted Puerto Rico, started powering Bayamón and Monacillos on Sept. 25th on a limited basis as reported on Sept. 28th, 2018 in [19] and San Juan by mid-October with a 50MW temporary unit. The San Juan plant also started operating in October, although in a limited way due to stability problems. Ecoelectrica and AES, private power plants come online weeks later to help to recover the system. Additionally, PREPA granted a $ 4.7 million contract to repair some units of the Palo Seco power plant. System interconnection began by connecting Mayagüez with Costa Sur (for black start) followed by the connection to Cambalache in Arecibo twenty days after Hurricane Maria struck, with only four 230 kV lines in service. These are the lines from Manatí to Costa Sur and Costa Sur to Mayagüez.

Figure 10 shows the restoration process of the transmission lines, substations and approximate service restoration percentage with respect to the estimated percentage of customers with electricity based on data from [18]. The fact that these curves are not monotonically increasing or decreasing is explained in most cases by seasonal variations in power demand and lines that failed after they were brought back to service. Such occurrence is usually caused by weakened vegetation from the hurricane that eventually fall on the line or by human errors. Another cause for loss of load in Puerto Rico during the restoration process was operating failures in PREPA's main power plants, such as in Cambalache, San Juan and Palo Seco. In Fig. 10, the island is considered as a whole in order to be able to compare its values with those in [18] and [20]. In these works, past hurricane outage statistics are calculated with respect to counties or parishes. In the case of Puerto Rico, its area of just over 3,500 mi^2 is equivalent to the combined land area of Broward and Miami-Dade counties in Florida or comparable to most of Louisiana's Gulf Coast parishes, such as Plaquemines. Dividing the island in smaller areas would alter this comparison because outage progression of such smaller areas is then influenced much more by operational and particular grid design characteristics, such as individual transmission lines paths or specific locations of power plants.

Locations of power plants played an important role in influencing faster restoration in their neighboring areas because, as indicated, service restoration started with the formation of electrical islands, which explains why Fig. 10 shows some limited service restored before the first transmission lines and substation services were restored and why substation restoration led transmission service recovery. Restoration generally progressed from the west to the east of the island. Service restoration for many municipalities was very slow. For example, after 35 days 44 municipalities had no grid connections and after 84 days, 9 municipalities had still absolutely no connection to the grid. As Fig. 11 shows based on data no longer publicly available provided by the U.S. Army Corps of Engineers, six months after Maria, the Caguas Region in the center and Eastern part of the island still had 27% of the PREPA clients without power.

Some restoration strategies, such as the use of mobile transformers in San Juan, were also commonly observed after a hurricane struck the continental U.S. in the past. Yet, such strategies were applied in Puerto Rico on a more limited basis due to fewer available material and human resources compared to past hurricanes in the U.S. Contributing factors to such more limited resource availability in Puerto Rico includes pre-existing legal and economic issues that affected contracting and shipping resources to the island. The fact that Puerto Rico is an island also severely affected resource availability that, for example, limited the deployment of mutual assistance restoration crews that could have been contracted despite the legal and economic limitations. Such availability of resources from outside a disaster area is very important because local human resources are themselves usually also affected by the disaster making their work restoring power much more difficult. The complicated island orography and thick vegetation further aggravate the situation. Still, it was reported that "the six weeks delay in requesting mutual aid assistance hampered recovery efforts and raised questions as to Puerto Rico's authorities overall management of the recovery effort" [21] suggesting that political barriers also contributed to the slow restoration process.

Other restoration strategies were not commonly observed in past hurricanes in the continental U.S. For example, temporary transmission poles, like those in Fig. 8, were widely used in Puerto Rico. Although the use of diesel generators connected to the utility side of a mains supply have been observed in the past (e.g., Galveston and the Bolivar Peninsula after Hurricane Ike), such solution was more widely deployed by the USACE in Puerto Rico, in Maunabo, Patillas and Yabucoa. Use of local means of power generation with small gasoline and diesel back-up generators was the most widely used approach by PREPA's customers to power their facilities and homes. Installation of new residential PV systems with batteries surged. This bottom-up solution may act as a catalytic solution to eventually have microgrids implemented as a permanent solution for improving the island's power resilience.

V. RESILIENCE EVALUATION

Figure 10 can be used to calculate Puerto Rico's electric power system resilience based on metrics presented in [20]. Since the outage data provided in [19] until January 3rd, 2018 was not indicated with respect to the total number of customers but, instead, it was calculated with respect to the peak load, the percentage of customers without service in Fig. 10 had to be estimated from the percentage of peak load information. Typically, the fewer, larger and more critical loads are restored before the far more numerous smaller and less critical residential loads. Hence, outage data specified with respect to the peak load is usually less than that indicated with respect to the total number of customers. This is also demonstrated by these data set. On January 3rd, 2018 when outage data was first indicated both with respect to peak load and total number of customers, the former was 12.40 percentage points higher than the latter. In order to take a conservative estimation, half of this difference is considered for estimating the outage data from the time Hurricane Maria made landfall to the end of 2017. Additionally, although for the first few weeks outage data were published on a daily basis, during the last months reports were issued every few days up to a week. Thus, missing data was estimated with a linear interpolation considering the data points in [19].

In [20] resilience, R, is calculated as

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

where N is the total number of customers (equal to 1,569,796 [19] for Puerto Rico, which is lower than the combination of Broward and Miami-Dade counties in Florida or Harris County in Texas), $T_{D,i}$ is the total outage duration for customer "i" and T_e is the total event duration. In [20] T_e is considered as the period from when first outages started until restoration was completed. When this same assumption is considered based on the 196 days for the data shown in Fig. 10, the total downtime in (1) is of 3,316 million of customer-hours, which is similar to values reported in [23]. This total downtime value evaluated over the 196 days of data in Fig. 10 results in a value for R equal to 0.55, which is lower than the values reported in [20]. Yet, although selecting T_e as indicated may provide a suitable assessment of resilience in most other cases, it may not completely represent Puerto Rico's grid resilience. For example, as pointed out in [24], almost a third of the total customer-hours of downtime was due to the last 200,000 customers that were connected to PREPA's grid starting on day 156.

To place Puerto Rico's grid resilience metric into context, power outage data shown in Fig. 10 is compared to those from hurricanes that affected the continental U.S. from 2004 to 2011 based on the local intensity indexes in [18]. During Maria, Puerto Rico was under at least tropical storm winds for 24 hours. Weather data also suggests that an average of 120 mph winds is a conservative estimate of the average highest sustained winds observed in the island. Additionally, the area variable A in [18] is considered here equal to 1 because all of the island sustained at least tropical storm winds. Likewise, H in [18] is taken equal to 1 due to storm surge and flooding information for the island. Based on these values, the calculations indicated in [18] yield a local tropical cyclone intensity index (LTCII) for maximum outage incidence, $LTCII_{MOI}$, of 2,520.45 and an LTCII for 95% restoration time, $LTCII_{Tr95}$, of 37.82. With these values, the expected maximum outage incidence is of 99.5 % (matching actual performance) and the expected time required to restore service to 95% of the customers is approximately 20.5 days. The average deviation of this dataset with respect to the regression curve of the 95% restoration time vs. $LTCII_{Tr95}$ is of 1.8 days although it is possible to observe that almost all of the points do not deviate by more than 10 days from the 95% restoration time regression curve. Such deviations are normal because, as explained in [18] restoration times are significantly influenced by human decisions and processes. Hence, an alternative approach is to consider T_e in (1) equal to the expected 95 % restoration time from [18]. Hence, when T_e is taken equal to 20.5 days, Puerto Rico's Hurricane Maria grid resilience equals 0.045. Such extremely low value is expected because it took 192 days to restore service to 95% of PREPA's customers, whereas in none of the previous hurricanes that affected the continental U.S. power outages extended for more than a few weeks (e.g., about two months in some flooded areas in New Orleans due to the time it took for the flooded waters to recede or be pumped away after Hurricane Katrina).

VI. LESSONS AND POSSIBLE SOLUTIONS

Hurricane Maria confirmed that traditional power grids are relatively fragile systems that may not be able to provide resilience levels required by their users [20]. Damage to transmission lines and difficulties for repairing those lines due to Puerto Rico's mountainous topography, was one of the main factors that led to the island's long power outage. Such influence of transmission lines performance on electric outages after a natural disaster is relatively uncommon because in most past disasters long power outages originate on the distribution part of the grid. The effects of transmission lines loss of service on the overall PREPA's grid performance after Hurricane Maria highlights the value of microgrids to improve power supply resilience because microgrids avoids the use of transmission lines. Yet, in order for microgrids to be effective, they need to be well planned and designed by using diverse local power sources and use energy storage [25].

A suitable bottom up solution at the individual household level includes microgrids powered by solar PV plus battery systems. Recently installed PV and batteries microgrids in Las Piedras and Toro Negro may be the first of such projects representing an alternative for improved power supply resilience. A current estimate cost for an installed off-grid solar PV system with peak capacity of 2 kW is $6,000 USD Added lead acid battery system with 10 kWh of storage capacity increase costs by $1,000 USD. Considering that the expected rates from PREPA are going to increase 20% to $0.30/kWh in the next two years [2], off-grid solar PV systems become a economically viable for many more people. Such economic suitability is particularly important for the many rural communities, which commonly experience longer outage restoration times than those in urban settings. Renewable energy sources provide an alternative to power sources that depend on a lifeline because renewable energy sources tend to be self-sufficient. However, design of renewable energy sources, such as PV or wind generators, need to be improved in order to avoid having those systems damaged as it was described in Section III.

Local energy storage is important particularly if a microgrid uses more conventional power sources that require the use of some fuel, such as natural gas or diesel fuel, because having a local storage of such fuel mitigates the potential loss of the lifeline. Thus, local energy storage mitigates resilience reduction due to lifeline dependencies [26]. In the particular case of Puerto Rico, storing fuel locally is important because roads could be blocked by debris or landslides as it happened during Maria. In addition to proper planning, microgrids need to also be well operated. Knowledge of a safe operating area (SOA) of the microgrid is important in determining its level of resilience [25], [27], suggesting the need for further research to ensure that the system stays within the SOA when disasters appear.

Puerto Rico's economic situation, PREPA's financial conditions and the island's electric energy environment are other main factors that led to the extensive and long power outage that affected the island after Hurricane Maria. Puerto Rico's grid is an example of resilience issues found in conventional power grids in which social, economic and technical aspects are all integrated. Moreover, the effects of Hurricane Maria on PREPA's grid strongly suggests that electric power grids have a dependence on economic services [28] that reduces electric power grids resilience.

Conventional power grids are built based on a framework that requires that most community members to be connected to a same grid so that those who can afford paying for the infrastructure and its operation can support those with more limited economic resources. As a result, all users receive a similar quality of service. Microgrids provide an alternative to this paradigm in which different users (or communities) could receive a differentiated quality of service, such as improved resilience. However, this higher resilience may likely imply a higher cost due to the need for local distributed energy resources and distributed maintenance needs. As a result, microgrids could achieve higher resilience at, likely, a higher cost. It is reasonable to expect that this higher cost could be paid by those users with more economic resources, which, without government intervention would likely become early microgrid adopters. Hence, conventional power grid operators may likely see a load reduction in areas with more economic resources creating a disruptive situation in which the conventional grid infrastructure and operation becomes increasingly supported by communities with less economic resources. On the other hand, if low and medium income communities are provided with the appropriate mechanisms to acquire a minimum of rooftop solar PV + battery system, this disruptive situation could be alleviated. However, PREPA must face the reality that grid defection (as indicated, a contributing factor to PREPA's past issues) is going to be part of the future projections in the very short term as rooftop solar PV + battery residential systems are already reaching grid parity and rate hikes to $0.30/kWh are possible.

Hurricane María also showed the importance of humans in the restoration process. The U.S. Department of Energy established the need for a comprehensive Energy Assurance Planning together with mutual assistance projects. As it was demonstrated in the past, it is important to have well defined restoration and logistical processes and plans, including pre-established contracts for transporting material and human resources, and having sufficient spares. Such processes and plans are particularly important for Puerto Rico because of its natural isolated location. Performing regular maintenance, such as vegetation trimming programs, is also very important, as it is upgrading the grid. In the case of Puerto Rico, grid upgrades need to be implemented at all of the grid portions but, particularly, at the generation side in order to reduce the use of high-cost fossil fuel-based power generation units. Yet, the cost of these solutions may worsen PREPA's finances, which, in turn, may worsen resilience as discussed in the previous paragraph. Hence, a critical question to answer in the case of PREPA's grid is how and who could pay for these measures. Certainly, significant incentives need to be provided in order to attract investors willing to risk capital in these measures in a difficult economic and financial environment. However, for PREPA's customers and Puerto Rico's taxpayers, generating these incentives may likely imply an additional negative impact to their economic situation. Hence, obtaining the resources for covering the costs of improvements and the incentives to attract investors seem to be a very difficult question to answer.

VII. CONCLUSIONS

Hurricane Maria caused a complete power outage in Puerto Rico, which was expected because of the hurricane strength. Yet, Hurricane María damages cannot explain alone the duration of such outage. Another reason for the long outage was the extreme damage suffered by power transmission lines that was difficult to repair because of the mountainous terrain where those lines are located. Distribution infrastructure suffered more damage than in past similar events making restoration longer. When compared to hurricanes that affected the continental U.S., it was possible to observe less human and material resources available for the restoration process. A six weeks delay in requesting mutual aid assistance demonstrated that the challenges are not only technical but also political. PREPA's difficult economic and financial situation was also an important contributing factor of the long power outage, because lack of economic and financial resources led to an aged infrastructure and reduced maintenance activities in the years before Hurricane Maria affected the area. As a result, PREPA's grid resilience was very low.

Improving Puerto Rico's electric power grid resilience requires both technical, economical, financial and political solutions. Microgrids have been identified as a potential technical solution but research is still required in order to make microgrids a more widespread solution easy to apply in practical cases. In the same way that resilience studies of infrastructure systems, such as communication networks require the study of their dependence on power grids, this paper shows that power grids resilience studies should also consider their dependence on economic and political social systems. That is, a novel component of this paper is to show from a descriptive approach that resilience studies should not be considered exclusively a technical problem but they are also an economic and organizational and management problem. It has also been shown that because of PREPA's financial and management problems, it is possible to argue that the disaster that affected Puerto Rico's grid was a combined human and natural disaster which started years before Hurricane Maria made landfall on the island and, in which, this hurricane was the last disruption stage of the disaster. Arguably, it is difficult to find economic, financial and political solutions that are applicable to Puerto Rico's particular context. In the short term, the bottom-up approach to build decentralized resiliency from individual solar home systems, to microgrids, and all the way to the main grid needs to be explored as a potential option because a relatively high penetration rate could enable a variety of options for microgrid development that enhance the robustness of community resilience while also provides economies of scales. Hence, significant research is required in order to identify more resilient economic and financial conditions that would increase the ability of the people in Puerto Rico to maintain electric power to survive and withstand events similar to Hurricane Maria. Although beyond the scope of this paper, it is important to mention the social challenges related to re-designing electric infrastructures for resilience due to the economic implications that such new grid would have. Through its descriptive approach this paper layout the foundations for technical, economic and social questions that need to be studied in order to improve power systems resilience.

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REFERENCES

[1] R. J. Pasch, A. B. Penny, and R. Berg, "Hurricane Maria," Nat. Ocean. Atmos. Admin. (NOAA), Silver Spring, MD, USA, Tech. Rep. AL152017, Apr. 2018.

[2] *Puerto Rico Electric Power Authority Fiscal Plan*, Puerto Rico Electric Power Authority, San Juan, Puerto Rico, Apr. 2017.

[3] State Data Center of Puerto Rico, *Estimados Anuales Poblacionales de LOS Municipios Desde 1950*. Accessed: Feb. 10, 2019. [Online]. Available: https://censo.estadisticas.pr/EstimadosPoblacionales

[4] E. O'Neill-Carrillo, "Una Nueva AEE: Energía Eléctrica para la sociedad Puertorriqueña del Siglo XXI," Tech. Rep., 2010. [Online]. Available: iteas.uprm.edu/docs/Resumen_Una_Nueva_AEE_8_dic_fci.pdf

[5] A. Skibell. (2016). *PUERTO RICO: How a stubborn utility and aging grid added to island's woes–Monday, May 2, 2016–www.eenews.net*. E&E News Reporter. Accessed: Aug. 17, 2018. [Online]. Available: https://www.eenews.net/stories/1060036577/

[6] E. O. Carrillo. (2012). *Vientos Huracanados en la AEE*. Sin Comillas. Accessed: Aug. 17, 2018. [Online]. Available: http://sincomillas.com/vientos-huracanados-en-la-aee/

[7] L. A. Aviles. "La Comisión de energía de puerto rico y la autoridad de EnergÃa eléctrica: Hacia un modelo colaborativo de regulación tarifaria," *UPR Bus. Law J.*, vol. 7, no. 2, p. 310, 2016.

[8] A. Kwasinski, "Effects of hurricane maria on renewable energy systems in puerto rico," in *Proc. IEEE ICRERA*, Oct. 2018, pp. 383–390.

[9] U.S. Energy Information Administration. (Sept. 21, 2017). *Puerto Rico Profile*. Accessed: May 25, 2018. [Online]. Available: https://www.eia.gov/state/print.php?sid=RQ

[10] "Fortieth annual report on the electric property of the puerto rico electric power authority," Puerto Rico Electr. Power Authority, San Juan, Puerto Rico, Tech. Rep. CEPR-AP-2015-0001, Jun. 2013.

[11] D. Ferris, "Heavyweights offer sweeping changes to Puerto Rico's grid," E&E News, Tech. Rep., Dec. 2017. Accessed: Feb. 26, 2019. [Online]. Available: https://www.eenews.net/stories/1060068733/

[12] *Update on Help for Hurricane-Ravaged Puerto Rico and Virgin Islands*, American Public Power Association, Washington, DC, USA, Sep. 2017.

[13] J. Gonzalez, "Informe revela el deplorable estado de la infraestructura en Puerto Rico," El Nuevo Dia, Guaynabo, Puerto Rico, Nov. 2017.

[14] "Minimum design loads for buildings and other structures," Standard ASCE/SEI 7-10, American Society of Civil Engineers, 2010.

[15] J. Anderson, "Puerto Rico needs 50,000 utility poles, 6,500 miles of cable," Amer. Public Power Assoc., Washington, DC, USA, Tech. Rep., Oct. 2017. Accessed: Feb. 26, 2019. [Online]. Available: https://www.publicpower.org/periodical/article/puertorico-needs-50000-utility-poles-6500-miles-cable

[16] W. Howell, "Workforce issues Hurricanes Gustav and Ike," in *Proc. Nat. Hurricane Conf.*, Austin, TX, USA, Apr. 2009.

[17] R. Wernsing, "Reliability and Resiliency in New Jersey," in *Proc. IEEE PES General Meeting*, Washington, DC, USA, Jul. 2014. [Online]. Available: https://www.ieee-pes.org/presentations/gm2014/IEEE2014-EnergyStrongRWWv3.pdf

[18] V. Krishnamurthy and A. Kwasinski, "Characterization of power system outages caused by hurricanes through localized intensity indices," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2013, pp. 1–5.
[19] Department of Energy. *Hurricanes Nate, Maria, Irma, and Harvey Situation Reports | Department of Energy*. Accessed: Aug. 17, 2018.[Online]. Available: https://www.energy.gov/ceser/downloads/hurricanes-nate-maria-irma-and-harvey-situation-reports
[20] A. Kwasinski, "Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level," *Energies*, vol. 9, no. 2, p. 93, 2016.
[21] "Energy resilience solutions for the puerto rico grid; final report," Dept. Energy, Washington, DC, USA, Jun. 2018. [Online]. Available: https://www.osti.gov/biblio/1463124-energy-resilience-solutions-puerto-rico-grid-final-report-june
[22] "Overhead electric distribution standards: Poles," Jacksonville Electric Authority, Jacksonville, FL, USA, Tech. Rep., Oct. 2010. [Online]. Available: https://www.jea.com/engineering_and_construction/electric_reference_materials/overhead_electric_distri bution_standards/
[23] T. Houser and P. Masters, *The World's Second Largest Blackout*. Rodhium Group, New York, NY, USA, 2018.
[24] M. Castro-Sitiriche, Y. Cintrón-Sotomayor, and J. Gómez-Torres, "The longest power blackout in history and energy poverty," in *Proc. 8th Int. Conf. Appropriate Technol.*, Porto-Novo, Benin, Nov. 2018, pp. 36–48.
[25] A. Kwasinski, V. Krishnamurthy, J. Song, and R. Sharma, "Availability evaluation of micro-grids for resistant power supply during natural disasters," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2007–2018, Dec. 2012.
[26] A. Kwasinski, "Numerical evaluation of communication networks resilience with a focus on power supply performance during natural disasters," in *Proc. INTELEC*, Osaka, Japan, Oct. 2015, pp. 1–7.
[27] V. Krishnamurthy and A. Kwasinski, "Characterization of power system outages caused by hurricanes through localized intensity indices," in *Proc. IEEE Power Energy Soc. General Meeting*, Jul. 2013, pp. 1–5.
[28] A. Kwasinski and V. Krishnamurthy, "Generalized integrated framework for modeling communications and electric power infrastructure resilience," in *Proc. INTELEC*, Gold Coast, QLD, Australia, Oct. 2017, pp. 1–8.

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