Simulation of Grid Hardening Impacts on Puerto Rico Hurricane Recovery

Meng Zhao, Rabayet Sadnan, Patrick Maloney, Alexandre B. Nassif, Kishan Prudhvi Guddanti,
Fernando Bereta dos Reis, Marcelo Elizondo, Patrick Royer, Vishvas Chalishazar,
Veronika Rabl, Estefania Alfaro-Mejia, Daniel Haughton, Taisha Rosa-Ramirez, Oscar Garzon Rivera
(meng.zhao; rabayet.sadnan; patrick.maloney; alexandre.nassif, kishan.g,
fernando.beretadosreis, marcelo.elizondo, patrick.royer, vishvas.chalishazar) @pnnl.gov
Pacific Northwest National Laboratory, Richland, WA, USA.
(veronika.rabl, estefania.alfaromejia, daniel.haughton, taisha.rosa, oscar.garzon) @lumapr.com
LUMA Energy, San Juan, PR, USA.

***Abstract*—The Puerto Rican power grid has faced significant power system outages with recent hurricanes such as Maria in 2017 and Fiona in 2022, which resulted in emergency declarations with long recovery times. In response, the United States Federal Emergency Management Administration (FEMA) has obligated significant monetary funds to establish a new baseline containing hardened assets. While these targeted funds were determined based on field inspections conducted by FEMA and the Puerto Rico Electric Power Authority (PREPA), the impact to be realized as a result of these improvements was not predicted or quantified. The work in this paper proposes a framework for quantifying this resilience enhancement. To do so, it predicts transmission and distribution damages using the Electric Grid Resilience Assessment System (EGRASS), and then leverages Recovery Simulator Analysis (RSA), a DC optimal power flow-based optimization tool, to simulate recovery times. RSA simultaneously optimizes the recovery of transmission, subtransmission, and distribution feeders while modeling non-black start cranking power requirements and critical load recovery priority. This framework allows us to conclude that the post-investment grid recovers from a Hurricane Maria-like event 13% faster than the current grid (pre-investments), reflecting a substantial improvement in overall system resilience.**

***Index Terms*—black-start generators, direct-current optimal power flow, power system recovery, linear programming**

I. Introduction

Historically, the islands of the Caribbean, such as Puerto Rico, have experienced significant hurricane activity, with two of the more recent damaging hurricanes being Hurricane Maria in 2017 and Hurricane Fiona in 2022. Hurricane Maria, often regarded as the most devastating Hurricane to impact Puerto Rico, resulted in a loss of electrical service to some customers in excess of 11 months [1]. In response to recent hurricanes in Puerto Rico, a significant amount of resources have been invested in understanding how Puerto Rico's grid can be hardened to future storms and in upgrading Puerto Rico's electric power infrastructure.

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Studies from National Labs that have focused on hardening the Puerto Rico's power grid include [2] and [3]. In [2], the authors evaluate how Puerto Rico can meet its goal of 100 % renewable energy, while [3] analyzes system vulnerabilities as well as their likelihood to occur. These studies have helped develop software analysis tools to assist in future resilience studies of the grid such as Electrical Grid Resilience and Assessment System (EGRASS) [4] for geo-spatial analysis and outage simulation, Recovery Simulator and Analysis (RSA) [5] for recovery time estimates and simulation, and Grid Utility Asset Vulnerability Assessment (GUAVA) [6] for critical component analysis.

In addition to expert studies and tools to augment decision making generated by US National Labs, the transmission and generation utilities in Puerto Rico (LUMA and Genera) have submitted plans to enhance reliability and resilience. These include the FEMA 5-Year Plan [7] for years 2025-2029 that focuses on creating a more resilient power system in accordance with Act 17 [8], LUMA's recent Integrated resource plan (IRP) [9], and LUMA and Genera's stabilization plans [10], [11], [12]. Of particular interest to FEMA is the assessment of projects proposed under Section 406 of the Stafford Disaster Relief and Emergency Assistance Act, also referred to as Hazard Mitigation, which funds protective measures that reduce or eliminate the threat of future similar damages to a disaster-damaged element or facility [13].

The study of resilience, analyzed in the context of hurricanes in Puerto Rico in the studies above, has frequently been broken into several categories which include anticipating, adapting, surviving, recovering, and sustaining [14]. The focus of the work in this paper is on recovery as well as how recovery simulations can be used to quantify the benefits of planning efforts aimed at enhancing grid survival and adaptability. With regard to recovery simulation, significant work has been performed. [15] developed a stochastic recovery-oriented power grid investment planning model which integrates preventive hardening measures and responsive backup generator (BG) support to mitigate the impact of disasters and facilitate efficient rehabilitation. [16] proposed a novel mixed-integer linear

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programming model that prescribes the most effective usage of mobile-substation resources to enhance the resilience of a power transmission system against a particular, widespread flood event. [17] developed a tool called System Restoration Navigator that uses generic restoration milestones to guide the restoration process. In [18], a transmission restoration on-line decision support system (TRDSS) tool was developed to evaluate the economics and security of restoration plans. In [19], a top down recovery strategy focusing on the transmission backbone first is devised within a bi-level optimization problem. Those efforts provide foundation to resilience planning, but there is a need to include practical recovery aspects and adapt to real systems.

More recently, Pacific Northwest National Laboratory (PNNL) has introduced a tool called Recovery Simulation and Analysis (RSA) [5] for simulating recovery and has evaluated its performance on hurricane-style events on the Puerto Rican electric power grid. In [20], RSA was used to simulate the recovery of a single hurricane instance on the Puerto Rican electric power grid and included explicit modeling of non-black start generation units and their associated cranking power requirements. In [21], RSA evaluated many hurricane instances with different outages profiles using a Monte Carlo style simulation. Alao in [22], the RSA capability was extended to model individual feeder loads and their associated customers as well as evaluating the difference in recovery when maximizing load served versus maximizing customer restoration.

The contribution of this work includes:

1) The extension of the RSA to include all of the features developed in [20], and [21], and [22] simultaneously which had previously been untested. This includes transmission and sub-transmission recovery, non-black start unit cranking power requirements, feeder recovery, and a maximizing customers objective. Furthermore, this work simulates hurricane recovery across 100 hurricane outage instances developed by EGRASS for each scenario unlike [20]. Additionally, it models critical feeders to better incentivize load that should be recovered first.
2) The comparison of recovery times between present day Puerto Rican grid and a hardened future grid.

The rest of the this paper is organized as follows: Section II briefly describes RSA formulations, Section III introduces the system model scenarios, Section IV provides the simulation results and the conclusions are summarized in Section V.

II. RSA Setup and Formulation

RSA is an optimization model that maximizes customers served by co-optimizing the recovery of generation, transmission lines and feeders under generator cranking power and labor budget constraints (work-crew-days, or WCDs). The WCDs represent the combined multiplication of the number of work crews and the days required for those crews to perform recovery tasks, forming the labor budget for restoration efforts. The model efficiently balances short-term and long-term grid recovery strategies.

A. Variable Definitions

The model uses indices t (time periods), b (buses), g (generators), a (arcs/lines), y (line IDs), z (feeder IDs), u (generator IDs), and w (load IDs). Key sets include $\mathcal{T}$ (time periods), $\mathcal{B}$ (buses), $\mathcal{Y}$ (lines), $\mathcal{G}$ (generators, with subsets $\mathcal{G}^R$ for renewable and $\mathcal{G}^T$ for traditional generators), $\mathcal{A}$ (arcs, with subsets $\mathcal{A}^D$ for damaged and $\mathcal{A}^{ND}$ for non-damaged lines), and $\mathcal{Z}$ (feeders). Parameters include demand $D_{t,b,w}$, generation limits $P_{g_{b,u}}^{min/max}$, line capacity $F_{a,y}^{min/max}$, line reactance $X_{a_{b,b'},y}$, recovery time budget $RB_{TS,t}^{num}$; feeder characteristics, such as $FL_{b,z}$ (feeder load for bus b, feeder z), $FRT_{b,z}$ (feeder recovery time at bus b, feeder z), and $C_{b,z}$ (feeder criticality scaling factor), and renewable capacity factors $C_{t,g_{b,u}}$. Decision variables include energy not served $ens_{t,b}$, load lift $ll_{t,b}$, power flows $f_{a,y,t}$, generation outputs $p_{t,g_{b,u}}$, voltage angles $\theta_{t,b}$, time expended recovering feeders $frt_{t,b,z}$, line status $s_{t,a,y}$ (binary), generator status $\eta_{t,g,u}$ (binary), and cranking power indicators $a_{b,t}$ for non-black start units.

B. Objective Function

The objective that maximizes customers served across the system is defined by (1). To address the multi-objective nature of the optimization caused by differing units for load and clients on feeders, a scaling factor "ϵ" is introduced to align the magnitudes of these terms in the objective function. Also, $TL_{t,b}$ denotes aggregated transmission load (see (1a)).

$$\max \sum_{t,b}(TL_{t,b} - ens_{t,b} - ll_{t,b}) + \sum_{\substack{t,b,z:\\ FRT_{b,z}>0}} \epsilon \cdot C_{b,z} \cdot \frac{frt_{t,b,z}}{FRT_{b,z}} \cdot N_{b,z} \quad (1)$$

$$TL_{t,b} = \sum_{z:FRT_{b,z}=0} FL_{b,z} + \sum_{w:\sum_z FL_{b,z}=0} D_{t,b,w} \quad (1a)$$

C. Constraints

The constraints are composed of power balance, generator, transmission system, and feeder models. The power flow equation is modeled as (2). The first summation term after the equality sign in (2), represents the amount of feeder load recovered for feeders that are damaged.

$$\begin{gathered}\sum_{g \in G} p_{t,g} + ens_{t,b} + \sum_{a_{b',b}} f_{a,t} - \sum_{a_{b,b'}} f_{a,t} = \\ \sum_{z:FRT_{b,z}>0} \frac{frt_{t,b,z}}{FRT_{b,z}} \cdot FL_{b,z} + TL_{t,b} \quad \forall t \in \mathcal{T}, \forall b \in \mathcal{B}\end{gathered} \quad (2)$$

The generator constraints are modeled as (3). Limits for the generators with black start (represented by set BS) capabilities and non-black start capabilities (represented by set BS^C) are defined in (3a) and (3b), respectively. Equations (3c)-(3e) models the generator status monotonicity, non-black start unit cranking power requirement, and non-dispatchable generation limits.

$$P_{g_{b,u}}^{min} \leq p_{t,g_{b,u}} \leq P_{g_{b,u}}^{max} \quad \forall t \in \mathcal{T}, \forall g \in G^T \cap BS \quad (3a)$$

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$$-0.1 \cdot P^{max}_{g_{b,u}} \cdot (1-\eta_{t,g_{b,u}}) + \eta_{t,g_{b,u}} \cdot P^{min}_{g_{b,u}} \leq p_{t,g_{b,u}} \leq -0.1 \cdot P^{max}_{g_{b,u}} \cdot (1-\eta_{t,g_{b,u}}) + \eta_{t,g_{b,u}} \cdot P^{max}_{g_{b,u}} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^T \cap BS^c \tag{3b}$$

$$\eta_{t,g_{b,u}} \geq \eta_{t',g_{b,u}} \quad \forall t > t', \forall g_{b,u} \tag{3c}$$

$$a_{b,t} = \frac{\sum_{a(b',b),y} f_{a_{b',b},y,t} - \sum_{a(b,b'),y} f_{a_{b,b'},y,t}}{0.1 \cdot P^{max}_{g_{b,u}}} \quad \forall t > 0, \forall b \text{ s.t. } \exists g_{b,u} \in \mathcal{G}^T \cap BS^c \tag{3d}$$

$$P^{min}_{g_{b,u}} \leq p_{t,g_{b,u}} \leq C_{t,g_{b,u}} \cdot P^{max}_{g_{b,u}} \quad \forall t \in \mathcal{T}, \forall g \in \mathcal{G}^R \tag{3e}$$

The transmission line models are defined by equation (4) $\forall t \in \mathcal{T}, \forall y \in \mathcal{Y}$. Ohm's law for the non-damaged and damaged lines are defined in (4a) and (4b), respectively. Where M is a large number which should be large enough such that when $s_{t,a,y} = 0$, (4b) is non-binding. Additionally, the limits for the non-damaged and damaged lines are defined as (4c) and (4d), respectively. The line status monotonicity, that ensures recovered lines remain recovered for the rest of the recovery horizon is modeled by (4e), and the limit on the allowed number of lines recovered at each stage of the recovery is modeled by (4f).

$$X_{a_{b,b'},y} \cdot f_{t,a_{b,b'},y} = \theta_{t,b} - \theta_{t,b'} \quad \forall a \in \mathcal{A}^{ND} \tag{4a}$$

$$-M(1-s_{t,a,y}) \leq X_{a_{b,b'},y} \cdot f_{t,a_{b,b'},y} - (\theta_{t,b} - \theta_{t,b'}) \leq M(1-s_{t,a,y}) \quad \forall a \in \mathcal{A}^D \tag{4b}$$

$$F^{min}_{a,y} \leq f_{t,a,y} \leq F^{max}_{a,y} \quad \forall a \in \mathcal{A}^{ND} \tag{4c}$$

$$s_{t,a,y} \cdot F^{min}_{a,y} \leq f_{t,a,y} \leq s_{t,a,y} \cdot F^{max}_{a,y} \quad \forall a \in \mathcal{A}^D \tag{4d}$$

$$s_{t,a,y} \geq s_{t',a,y} \quad \forall t > t' \text{ for line } a \text{ with ID } y \tag{4e}$$

$$\sum_{a \in \mathcal{A}^D, y \in Y} s_{t,a,y} \leq RB^{num}_{TS,t} \tag{4f}$$

The feeders are defined by equation (5). The total number of WCDs expended on recovery each feeder is bounded by the forecasted WCDs recovery time in (5a), the number of customers that can be recovered is bounded by the total customers existing at each feeder in (5b), the relationship between customers recovered and time expended on recovery is modeled as (5c) (customers are fully recovered when recovery effort equals forecasted recovery effort), and finally, the allowed labor in WCDs on feeder recovery per time step is modeled as (5d). Here, a recovery budget, $RB^{num}_{F,t}$ for feeders is implemented for each timestep t of the recovery.

$$0 \leq frt_{t,b,z} \leq FRT_{b,z} \tag{5a}$$

$$0 \leq n_{t,b,z} \leq N_{b,z} \tag{5b}$$

$$\frac{frt_{t,b,z}}{FRT_{b,z}} = \frac{n_{t,b,z}}{N_{b,z}} \tag{5c}$$

$$\sum_{b,z:FRT_{b,z}>0} frt_{t,b,z} \leq RB^{num}_{F,t} \quad \forall t \in \mathcal{T}, \forall b \in \mathcal{B}, \forall z \in \mathcal{Z} \tag{5d}$$

The equations described by (2)-(5) are used to construct the constraints for the recovery optimization problem with objective function defined by (1). For more details, please refer to [5] where the full model formulation is provided.

III. Recovery Simulation Setup

Recovery simulator and analysis simulates the recovery of grid assets. Using DC powerflow and linear programming techniques, it simultaneously co-optimizes the recovery of transmission, load, and non-black start units to maximize customer recovery.

A. Recovery scenarios

The proposed recovery model is validated on several realistic representations of Puerto Rico transmission network, capturing the power system under both present and projected future conditions. Apart from the base case as the current status of the Puerto Rico system, these conditions consider two state-of-the-art microgrids being installed in Vieques and Culebra islands [23], [24] with 16.2MW total generation capability as a sensitivity case. Furthermore, a second sensitivity case encompases four submarine cables that are part of LUMA's resilience plans.

These investments are integrated in current and future PR systems under three main classes:

1) Current (CUT) Case-Base: Puerto Rico System in its present state.
2) Current Case-Submarine/Microgrid: Puerto Rico System in its present state with 4 new submarine/underground cables or/and 2 new microgrids.
3) Future (FUT) Case-Resilience: Puerto Rico System in its upgraded state includes hardened transmission towers and feeders that can better withstand high wind speeds, thereby reducing failure frequency, along with additional investments in generation and transmission infrastructure.

B. Hurricane Instances

This paper simulates the grid recovery following the simulated Hurricane Maria events. 100 Monte Carlo instances of Hurricane Maria are developed by EGRASS, which is a cloud-based application that is used to interface and visualize the data between several resilience-based power systems applications [21]. Within EGRASS, the impact of wind speeds on transmission/feeder assets is evaluated using fragility curves. The hurricane instances are developed by simulating probabilities associated with (1) hurricane intensity (2) asset failure for each hurricane instance [25].

About the transmission/feeder fragility assessments in EGRASS, only complete asset failures are modeled. Minor component (e.g., crossarm, insulator) failures are not modeled. From the EGRASS prediction, the probability of transmission failure is about 8% and feeder failure is around 7%. For the

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hardened assets in FUT case, 16.5% of towers and 7% of feeders are reinforced in EGRASS model.

IV. Results and Discussion

To better understand how the recovery model performs, six simulations are conducted based on the three classes introduced above. These tests are conducted on Intel(R) Xeon(R) Gold 6442Y (2.6GHz) and a 32GB RAM. The six scenarios are defined as:

1) CUT base case
2) CUT based case with microgrids only
3) CUT based case with submarine only
4) CUT based case with microgrids and submarine
5) FUT base case
6) FUT base case with microgrids and submarine

Among these scenarios, only part of the generators in CUT cases have the black-start capability; all the generators in FUT cases are black-start units.

In the CUT base case, there are 1410 buses, 42 generators with 19 of them have black-start capability, 904 load buses and 1550 transmission lines; in the FUT base case, 1527 buses are included, 72 generators with all of them are black-start units, 874 load buses and 1726 transmission lines. All the cases consist of 323 feeder representation of the Puerto Rico's electric infrastructure and a total of about 1.34M customers.

As mentioned in Section III, the recovery simulation of each scenario is conducted based on 100 instances of Hurricane Maria, TABLE I shows the predicted tower / pole damage data of CUT and FUT cases from EGRASS.

TABLE I: Predicted Damage from EGRASS.

Region	Tower / Pole Count	Predicted Tower / Pole Failures (CUT)	Predicted Tower / Pole Failures (FUT)
Arecibo	7066 / 75611	354 / 4041	283 / 3826
Bayamon	5044 / 50168	284 / 3786	260 / 2734
Caguas	7938 / 74226	1909 / 9776	1595 / 8356
Mayaguez	6502 / 70231	57 / 1885	39 / 1586
Ponce	10352 / 73219	714 / 5379	667 / 5210
San Juan	7627 / 73422	588 / 5928	507 / 5335
Total	44529 / 416877	3906 / 30795	3351 / 27047

Understanding how recovery evolves under different operational or resource conditions is critical for evaluating the recovery performance and resilience of the system. Two metrics are utilized for the evaluation:

1) **Average Customer Recovery Evaluation**: The customer recovery rate measures the proportion of customers restored after a disruption, providing an essential metric for evaluating the system resilience. Fig. 1 presents the evolution of average customer recovery percentage over WCDs across 100 scenarios.

   Among the six cases as shown in Fig. 1, Case 6 shows the fastest and most consistent recovery. As the system becomes more developed—from CUT cases to FUT cases, the recovery process accelerates markedly. The most advanced configuration (Case 6) achieves a 90% recovery level with less WCDs, which is 13% faster than the baseline case (Case 1). This consistent improvement demonstrates that system feature enhancements substantially strengthen overall resilience and expedite recovery following disruption.

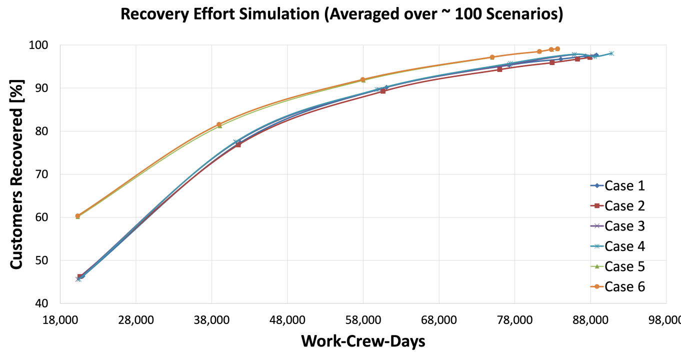

Fig. 1: Average Customer Recovery Trend.

2) **System Recovery Evaluation**: In addition to analyzing customer recovery trends, system restoration efficiency was further evaluated the total repair effort required to recover at least 90% of the total system customers. A lower WCDs value indicates a more efficient restoration process, as fewer cumulative crew resources are needed to achieve complete recovery.

   TABLE II represents the average WCDs across 100 scenarios, capturing the time step t at which each scenario first meets or exceeds the 90% customer recovery threshold. This provides a scenario-averaged metric of restoration effort. In contrast, Fig. 1 illustrates the aggregated recovery trajectories for each system configuration, from which the timing of 90% recovery can be identified by interpolating between points.

   The results show a clear decline as WCDs decrease progressively from Case 1 to Case 6, implying that systems with additional infrastructure investment and hardening are recovering faster because their is less repair effort needed. The most hardened configuration (Case 6) reduces the total WCDs by nearly 11% compared with the base case, demonstrating significant gains in restoration efficiency and overall system resilience.

TABLE II: System Recovery Effort.

Scenario	Feeder WCDs	Line WCDs	Total WCDs
Case 1	46860	21417	68277
Case 2	44872	20736	65608
Case 3	48262	20752	69014
Case 4	48352	20596	68948
Case 5	44667	17389	62056
Case 6	44108	16968	61076

V. Conclusions

In this work, RSA is used to evaluate several present day and potential future configurations of the Puerto Rico electric power grid which includes hardened transmission

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towers, increased hydroelectric capacity, microgrids, and underground/submarine transmission lines. The simulations in this paper demonstrate a clear improvement in recovery speed through decreases in labor (WCDs) requirements needed to recover 90% or more customers. Specifically, the total WCDs required for 90% customer recovery declined substantially from Case 1 to Case 6, indicating enhanced operational efficiency and reduced restoration effort due to system enhancements.

Overall, these findings highlight the strong link between grid hardening and system resilience. The combination of EGRASS to simulate system outages for hurricane speeds combined with RSA to capture recovery time provides a powerful tool for evaluating the efficacy of grid hardening investment in terms of labor efforts to recovery grid assets. Future work will extend this framework to include additional uncertainty sources, interdependent infrastructure systems, greater distribution granularity, and optimization of resource deployment strategies to further enhance recovery planning and decision support.

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