Methodology to Calibrate Fragility Curves Using Limited Real-World Data

Fernando Bereta dos Reis*, Patrick Royer*, Vishvas Hiren Chalishazar*, Sarah Davis*, Marcelo Elizondo*, Jeffery Dagle*, Alexandre Nassif†, Andrija Sadikovic†, Elli Ntakou†, Olga Soto†,Shay Bahramirad†
*Energy & Environment Directorate, Pacific Northwest National Laboratory, Richland, WA 99354, USA
† LUMA Energy L.L.C., San Juan, PR 00936, USA

Abstract

With increasing human dependence on electricity and increasing energy demand, electrical infrastructure has emerged to be one of the most critical services. On the other hand, climate-change driven extreme events progressively increase in frequency and intensity. This is one of the main reasons for making the power grid more resilient to extreme events during which uninterrupted power supply is crucial in keeping the consequences of the extreme event limited. The first step towards making the power grid more resilient is to evaluate the probabilities of failure for all assets at risk from the extreme events. Thus, this paper presents the a methodology to calibrate fragility curves. The strength of the proposed approach is its ability to calibrate the fragility curves utilizing limited data, which is the most common constraint in carrying out such analyses. This paper describes the calibration of transmission tower fragility curves for Puerto Rico utilizing only damage reports for hurricane Maria. That, combined with Puerto Rico's wind modeling & geographic information system, this study also calibrates fragility curves for transmission towers made with four different construction materials.

Index Terms

Resilience, Fragility Curves, Transmission, Extreme Events, Hurricanes

I. Introduction

Designing a resilient power system has become imperative in the face of increasing intensity and frequency of the extreme events. Every element of the power system, such as transmission and distribution support structures, transmission and distribution conductors, substation equipment, centralized and distributed generators, and even loads are vulnerable to a variety of hazards. To increase the overall resilience of the entire grid, it is important to: first identify these vulnerabilities; second evaluate the probability of failures (fragility) over a range of excitation measures stemming from the type of extreme event and; third mitigate asset fragility making relevant system assets robust thus reducing their probability of failure (hardening the assets). The fundamentals of asset fragility, vulnerability and risk is described in detail by Keith Porter in [1].

A summary presented in [2] lists the different high impact low probability (HILP) hazards threatening the power system are Seismic, Hurricane, Tornado, Geomagnetic storm, High-altitude electromagnetic pulse, ice storms, cyber-attack, physical attack, etc. While planning and preparing for such HILP events, the most cost-effective strategy is to upgrade/retrofit the assets which are most vulnerable as well as most consequential when lost/damaged [3]. Fragility curves are used to assess these most vulnerable assets and also to compare the effectiveness of different retrofitting strategies for these assets. For a single asset experiencing a single hazard there can be multiple causes of failure and thus multiple fragility curves. For different causes of failure the restoration time for that asset can be significantly different. Thus, fragility curves can also inform the restoration time calculation to facilitate the evaluation of overall consequences to the power grid. The studies evaluating power system consequences (such as

The authors would like thank the Federal Emergency Management Agency (FEMA) and the U.S. Department of Energy (DOE) for funding this study. This study was conducted at Pacific Northwest National Laboratory, which is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC05-76RL01830.
Corresponding author: fernando.beretadosreis@pnnl.gov

the loss of load, energy not served, etc.) for different HILP events: 1) Augment power system models (or use more detailed node-breaker version of the models), so that asset fragilities can be translated to power system contingencies [4], and 2) Utilize asset fragility curves that are either developed by modeling structural integrity of assets using tools like Structural Analysis Program (SAP2000) [3], or developed using real world data based academic models such as log-normal functions [5]. However, the availability of real world data for infrastructure damage and fragility is often very limited for such HILP extreme events.

The fragility curves for a hurricane hazard for different types of generation given the hazard's peak gust wind speed are presented and utilized in [6] and for transmission electrical conductors relative to: a) sustained wind speed, b) relation to the conductor type, and c) the distance of support structures is presented in [7]. To that end, this paper presents the methodology to calibrate fragility curves. The strength of the proposed approach is its ability to calibrate the fragility curves utilizing limited data, which is the most common constraint in carrying out such analyses. This paper describes the calibration of transmission tower fragility curves for Puerto Rico utilizing only damage reports for hurricane Maria. That combined with the Puerto Rico's wind modeling & geographic information system, this study also calibrates four transmission tower fragility curves based on their construction material. The remainder of this paper is organized as follows: Section II presents the overview of tower fragility curves for wind. Section III describes how the maximum wind speed for every tower from historical hurricane events is estimated. Section IV presents the proposed calibration of fragility curves. Section V describes the resulting calibrated transmission towers fragility curves. Section VI provides concluding remarks on the proposed calibration of transmission tower fragility curves for gust wind speed.

II. Transmission Tower Fragility Curve

There are two main hazards for power systems in hurricane events are wind and flood. Different wind speed measurements are used for different elements/assets. The fragility of conductors of the transmission line is commonly not utilized as stated by the authors that have developed fragility curves of conductor [7]. Reference [8] states that due to design requirements (i.e., civil engineering design requirements) the fragility of the transmission line under wind loading is mainly determined by the failures of support structures (i.e., towers). Flood hazard for power systems refers to the inundation – defined as the depth of water above local land elevation. Other parameters associated with flood are rainfall, speed of the water (i.e., increase in water speed on rivers), and debris on the water but those are commonly utilized for bridges and other structures. The combined utilization of wind and flooding for transmission and distribution lines is presented in [9]. However, the combination of hazards is not commonly utilized. In summary, substations are mainly subject to inundation depth and transmission towers to wind speed. There are four approaches for obtaining the fragility curves [10].

1) Judgmental method – It is not limited by data or models, being a fast method to implement. Utilizing expert knowledge to determine the fragility. Thus, it is difficult to validate and is based on the biases or past experience of the experts.
2) Empirical method – It utilizes statistical data from controlled experiments or from actual extreme events. It is useful and flexible if data is available. The availability of data can be scarce and experiments can be expensive.
3) Analytical method – It is based on physical models that can be validated and verified, enhancing transparency. It is easier to extrapolate results to new situations. It facilitates a distinction between aleatory and epistemic uncertainty and is based on simplifications and assumptions. Require the availability of data for the models.
4) Hybrid method – It is utilized to overcome the limitations of any individual approach but have the same disadvantages of the combination of approaches. A common combination is the Empirical and Analytical methods, thus, the analytical model is fitted based on data to overcome the differences from the model to actual events.

The designs of transmission lines have a well-founded desire to exercise some control over the sequence of failure for the different line components [11]. Fig. 1 presents the different line components. The cables are especially important under extreme events given that failure puts critical demands on the failure containing capabilities of the support structures. The isolators have a larger mechanical loading than the cables. Foundation of towers have the tower as the mechanical loading. By design, the transmission towers are expected to fail before the other elements.

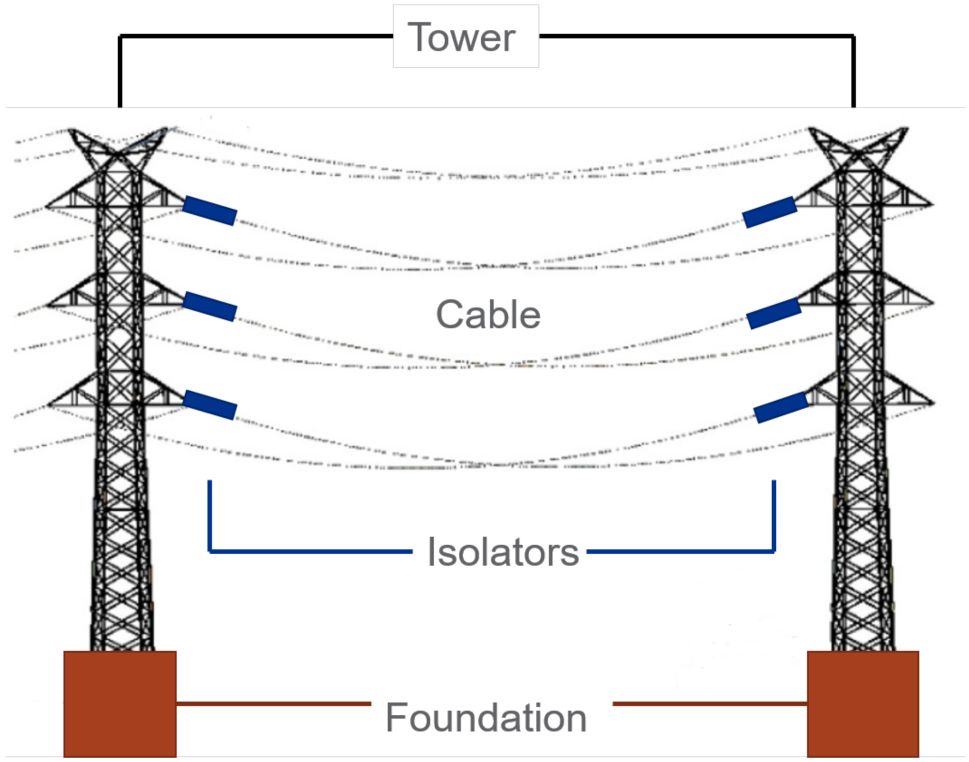

Fig. 1. Mechanical loading transmission lines civil engineering designed. Failure containment. Image adapted from [12].

This paper considers the fragility of towers as independent as in [13]. This assumption is supported by [14] where the reliability of the elements of transmission lines were evaluated in the field. A transmission line was equipped with multiple sensors to evaluate mechanical stresses. The stresses were created using explosive charges on the cables and towers and the stresses on the nearby towers were evaluated. The evaluation supports the independent consideration of tower failures.

The failure probability of transmission towers is associated with the 3-second averaged wind speed commonly referred to as wind gust [6], [15]–[17]. The failure rate model for towers was developed with the data from ten years of named storms that reached the Texas coast, and is presented in [16]. Fig. 2 describes the failure rate of existing towers that have a wind load requirement of 105 mph in accordance with the National Electrical Safety Code (NESC) before 2008. Fig. 3 illustrates the failure rate of the towers after 2008. After 2008, NESC incorporated the American Society of Civil Engineers 7-98 standards – "Minimum Design Loads for Buildings and Other Structures" [18], which has "extreme" wind and ice loading requirements. Thus, the towers designed with the updated standards have wind load requirement of 130 mph. The equation describing the failure rate (λ) in relation to the wind gust (w) from Fig. 2 and 3 is,

$$\lambda(w) = \alpha e^{\delta w}. \tag{1}$$

where, α and δ are the curve fitting parameters. These parameters for the curve fitting are presented in Table I.

Reference [6] converted the failure rate from [16] to failure probability utilizing the Poisson random sampling. The authors sample a Poisson distribution with the failure rate to obtain the probability of damage. To avoid using a random sample, the probability of the Poisson distribution is calculated,

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!}. \tag{2}$$

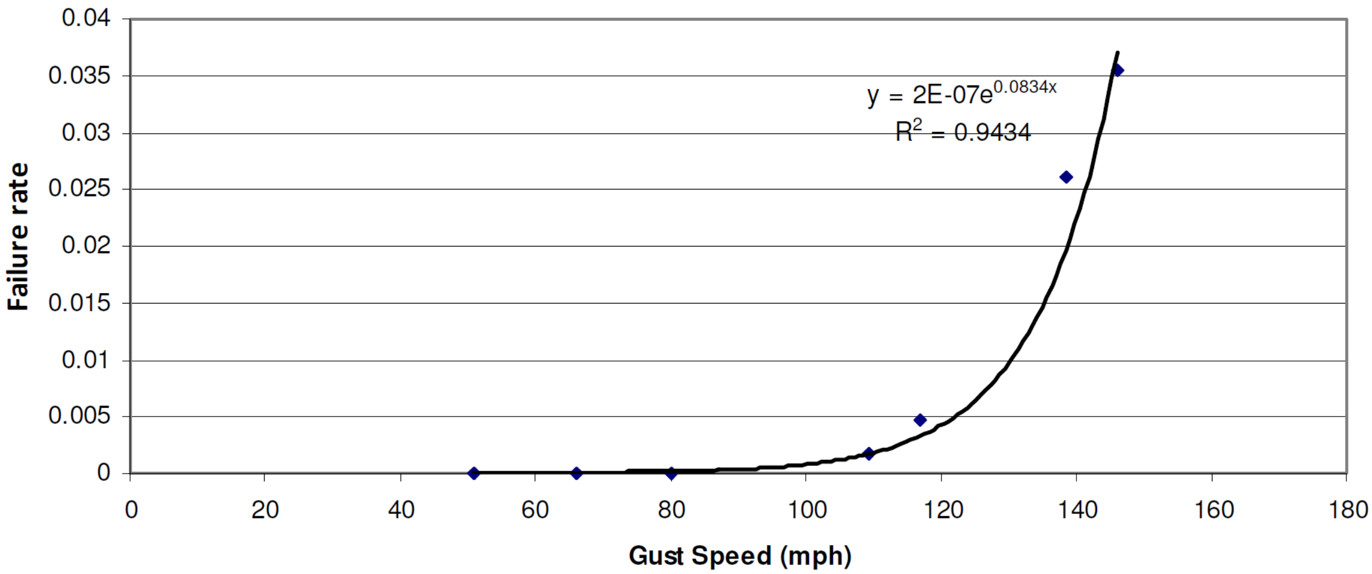

Fig. 2. Failure rate of towers designed with a wind loading of 105 mph (i.e., existing towers). Image extracted from [16].

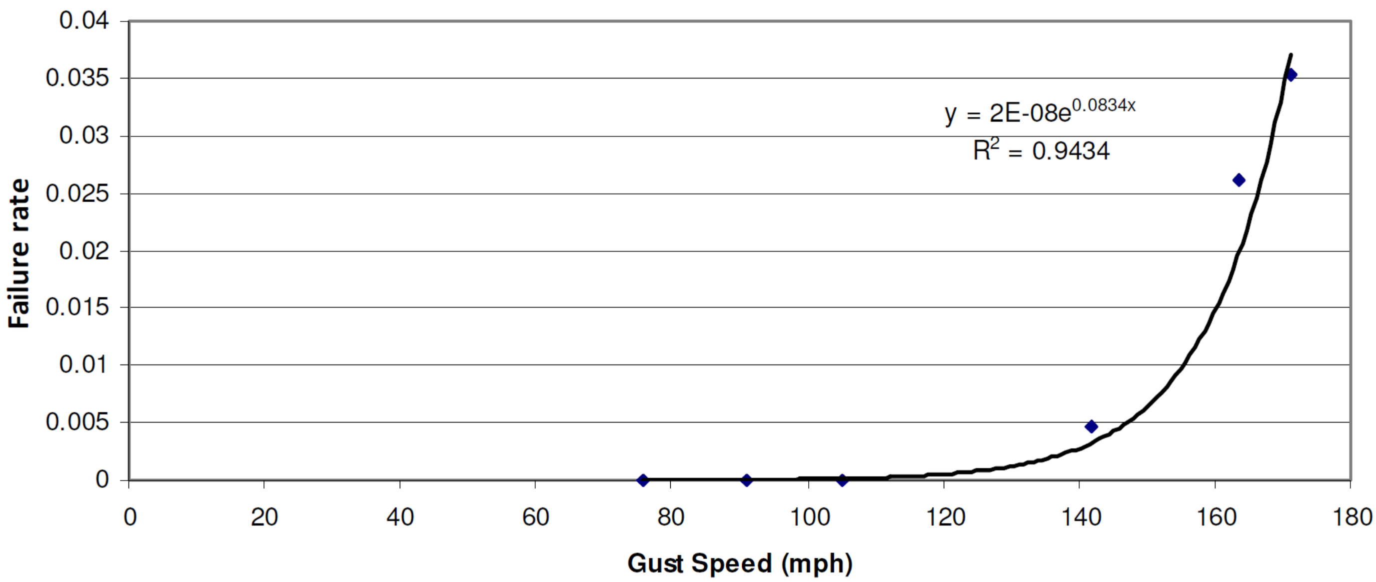

Fig. 3. Failure rate of towers designed with a wind loading of 130 mph (i.e., hardened tower). Image extracted from [16].

TABLE I
FAILURE RATE CURVE FITTING COEFFICIENTS FOR EXISTING AND HARDENED TOWERS.

Tower wind loading requirement (mph)	α	δ
105	2×10^{-7}	0.0834
130	2×10^{-8}	0.0834

The failures with one or more occurrences are of interest. Thus, the Poisson probabilities of interest are all $P(k)$ except for $k = 0$. Since k is non-negative integer numbers, the Poisson probabilities of interest are calculated,

$$P(k \geq 1) = 1 - P(k = 0) = 1 - e^{-\lambda}. \tag{3}$$

The tower failure rate from [16] are converted to failure probability using (3). Fig. 4 presents the fragility curve for both existing & hardened transmission towers for wind gust speed in mph & m/s. Note that the towers designed with a wind loading requirement of 105 mph and are more likely to fail at lower wind speeds than the tower designed for the wind loading of 130 mph. This is expected given that the updated considerations of transmission tower standards require the structures to be able to withstand stronger winds. Which in turn increases the survivability of the towers to the physical stresses of hurricane winds.

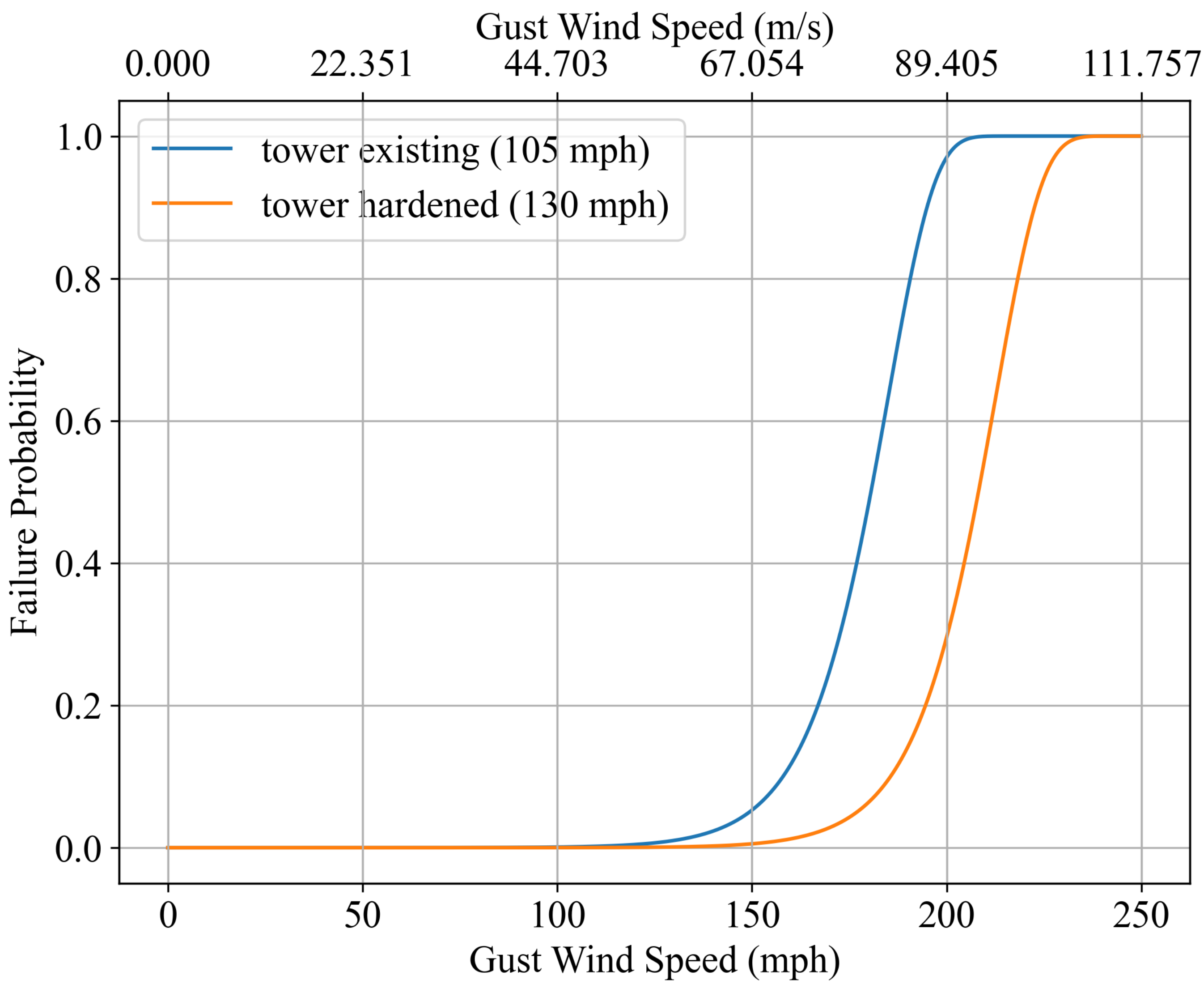

Fig. 4. The fragility curve for the towers designed with 105 mph, and 130 mph from the Fig. 2 and Fig. 3 respective tower failure rate.

III. Hurricane Wind Modeling

The wind speed intensity can be estimated utilizing historical hurricane data. Historical hurricane wind information is available from the National Hurricane Center [19]. Fig. 5 presents the Hurricane Maria path and wind intensity at each location. Geographic information system (GIS) is used to map the wind speed data to tower locations.

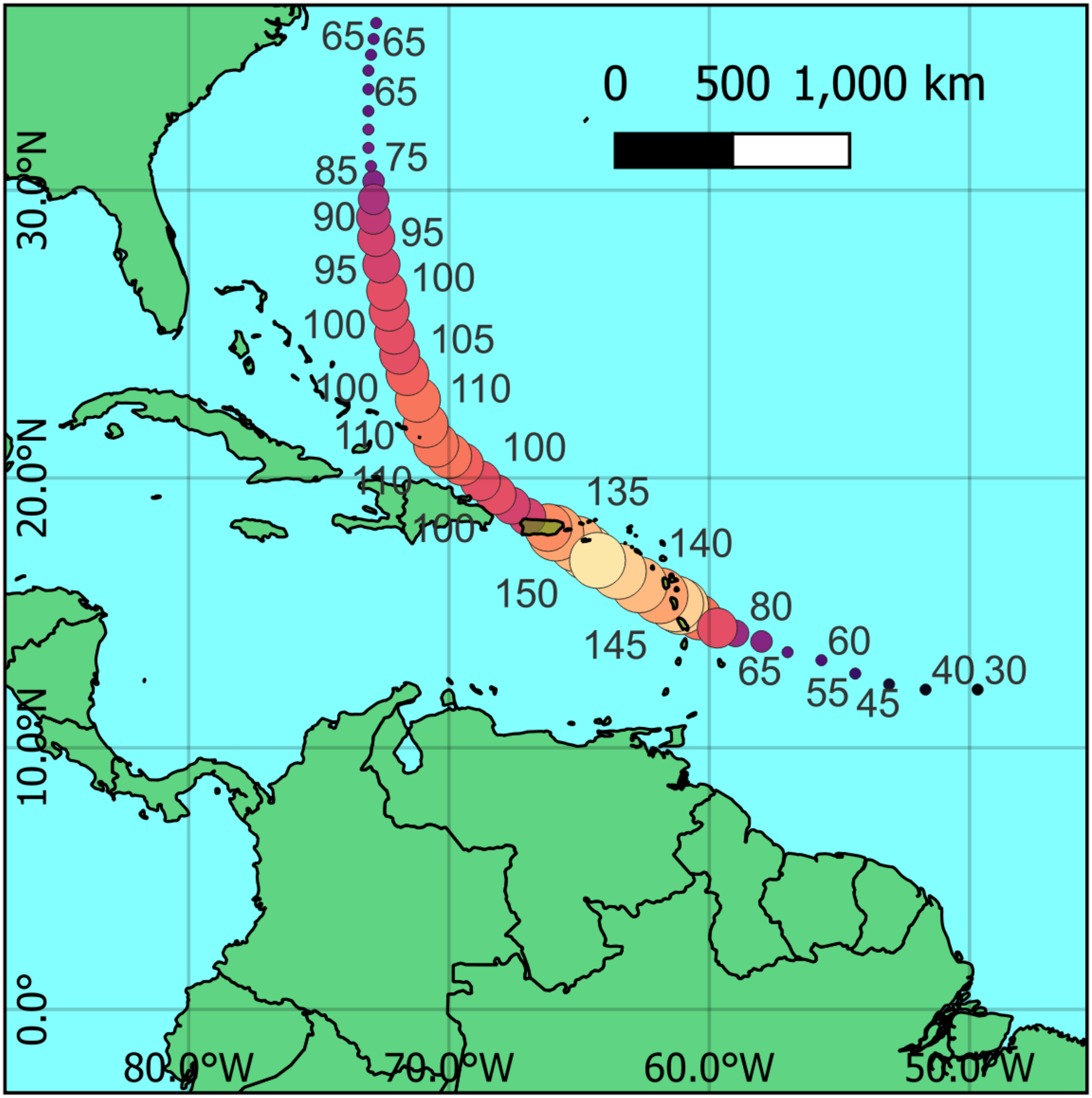

Fig. 5. GIS map of hurricane Maria's trajectory and its wind speeds.

To map the wind speed data to tower locations is necessary to interpolate values from the available wind data to the extent of the study area. The wind swaths represent the footprint in which wind speeds of a certain bin are expected to occur, for example 64 knots, 50 knots, and 30 knots. Fig. 6 illustrates the wind swaths for Hurricane Maria over Puerto Rico. It is assumed that wind speed intensity within each swath is at least equal to or lesser than the wind speed intensity for that swath. Second and third order equations, depending on the number of coincident swaths - were used to develop linear interpolation between center point measurement of wind speed, and the outer edge of each wind swath. An interpolation is used to generate 1 X 1 meter resolution wind data.

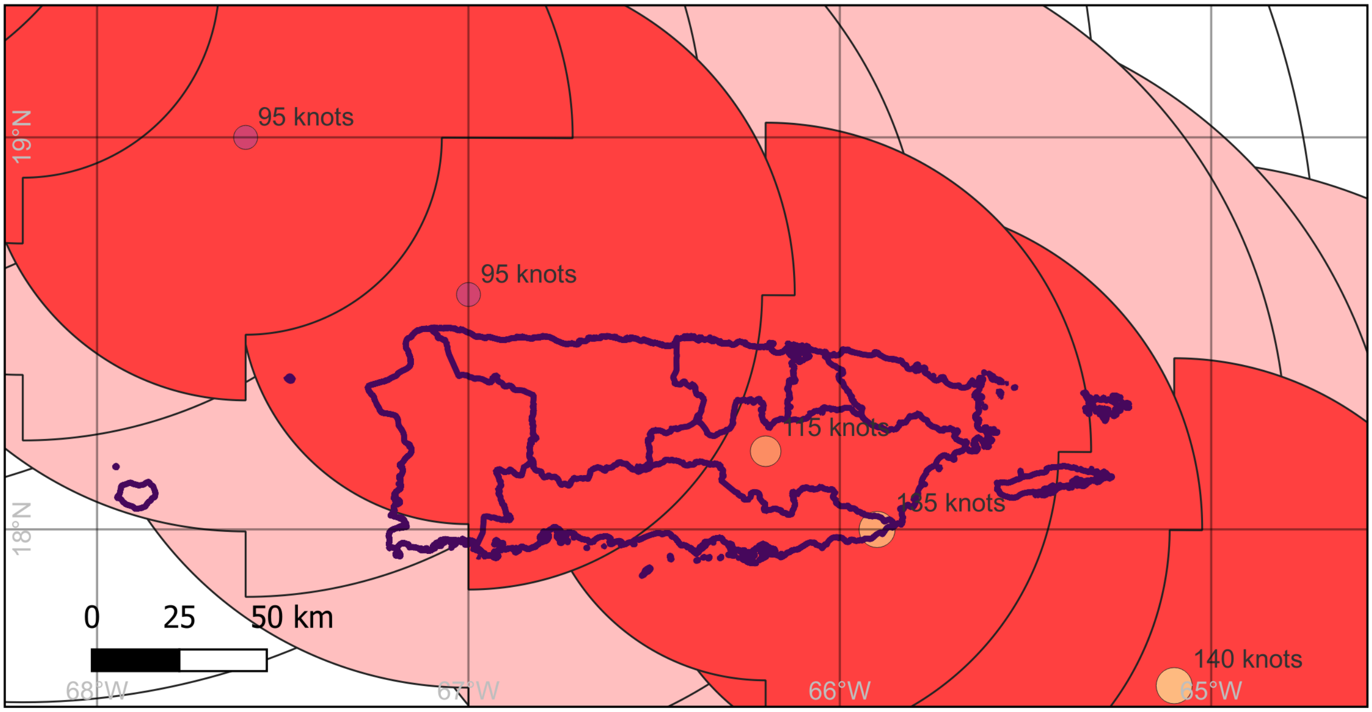

Fig. 6. Hurricane Maria wind swaths over Puerto Rico.

The interpolated wind speed is averaged over one minute. To convert the wind speed from one minute average to three second average wind speed (i.e., wind gust) is not trivial but can be approximated. This conversion of wind speed to wind gust was done using the area terrain roughness, which is dependent on the surrounding terrain difference and the elevation around every tower. Using GIS information of the terrain around every tower, the wind gust factor was computed as presented in [16].

IV. Calibrating Fragility Curves

The calibration of transmission tower fragility curves could be performed with different approaches. For example, using the tower design standards, and historical damage reports. The objective of calibrating fragility curves is to better represent the system under study. As presented in Section I, the fragility curves are the starting point for multiple studies of HILP events. The accurate representation of the element's ability to survive HILP events will impact resilience planning and thus in the end affect the actual system status and response capabilities. Independent of the type of study: 1) Monte-Carlo simulation to evaluate the power system resilience, 2) Cost-benefit evaluation of upgrades, 3) Planning for an HILP event, etc. all studies use fragility curves [20].

Reference [16] utilized the empirical method with detailed damage reports from multiple events over the course the ten years. Their study had complete knowledge of the tower population, towers that failed, and their wind design rating also considering the changes that naturally happen through time. Such abundance of data is not common given the challenging and/or dire circumstances the HILP events impose on the region. Given such challenges, the approach presented in this paper does not create a completely new fragility curve, but it calibrates an existing one by using one detailed damage report.

If the fragility curve is known, the intensity of weather parameter for every asset is associated with their respective failure probability. Historical data from events like hurricane Maria, which had numerous element failures, can be utilized to calibrate fragility curves. The event is required to have cause failures of the elements being calibrated in order to be utilized. With the combination of the intensity of weather parameter for every asset and with the associated damage report the calibration of one fragility curve parameter Ψ can be performed. The three-step interactive procedure describes the calibration of fragility curves, is presented below:

1) With the intensity of weather parameter for every asset compute the individual failure probability.
2) Having the failure probability for every asset compute the number of expected asset failure.
3) Compare the number of asset expected to fail with the known number of asset that actually failed.
   a) If the comparison in Step 3 is above the tolerance, the fragility curve coefficient Ψ is updated and returned to Step 1. The coefficient Ψ is increased or decreased depending on the previous curve having overestimated or underestimated the number of asset failures.
   b) If the comparison in Step 3 is below the tolerance, the asset fragility curve coefficient Ψ has already been calibrated and the interactive procedure has concluded.

The interactive procedure for calibrating one parameter of the fragility curves utilizing damage report results in a calibrated empirical fragility curve.

V. Results

The calibration of transmission tower fragility curve is performed with damage report for hurricane Maria. The intensity of the event resulted in numerous transmission towers that failed (not considering smaller damages that did not lead to tower failure). From the damage report it was evident that the tower construction material (i.e., wood, steel, aluminium, and concrete) had a significant impact on probability of failure of the tower. To that end, the transmission tower fragility curves are calibrated for all different tower material.

Considering that the δ coefficient for tower failure rate (1) is a constant. The α coefficient can be calibrated as in Section IV. In order to calibrate the transmission tower wind gust fragility curve, the maximum wind gust for every tower must be known. The maximum wind gust is extracted from a historical event as described in Section III. The calibration procedure from Section IV is performed for every tower material. The resulting calibrated tower fragility curve are presented in Fig. 7.

The failure rate coefficients for existing towers is presented in Table II. The wind loading for towers with different materials is estimated based on the known design standards used for constructing the towers. The failure rate of the existing and hardened towers at their respective loading requirement is 0.00127 and 0.00102, respectively. The estimated wind loading of towers is an integer value chosen with the range of possible wind values that result in a failure rate between 0.00127 and 0.00102. Computing the wind loading with the knowledge of the failure rate is performed using (4).

$$w = \frac{ln\left(\frac{\lambda}{\alpha}\right)}{\delta}. \tag{4}$$

TABLE II
CALIBRATED FAILURE RATE COEFFICIENTS FOR TRANSMISSION TOWERS OF DIFFERENT MATERIALS.

Material	Tower estimated wind loading requirement (mph)	α	δ
Wood	80	1.39×10^{-6}	0.0834
Steel	104	1.83×10^{-7}	0.0834
Aluminium	105	1.73×10^{-7}	0.0834
Concrete	112	9.44×10^{-8}	0.0834

VI. Conclusion

The presented methodology for calibration of fragility curves using limited real-world data is capable of tuning generic fragility curves to a specific region with their own characteristics. The proposed approach requires the modeling of the intensity of the weather parameter in the fragility curve for an HILP event, and the knowledge of the number of elements that failed from the damage report. The presented method is utilized for the calibration of transmission towers based on their material, however, the calibration can be based on other characteristics of failure (e.g., structure design standards) depending on the available data. The calibration was performed considering the main island of Puerto Rico and tested on the towers that failed in each area.

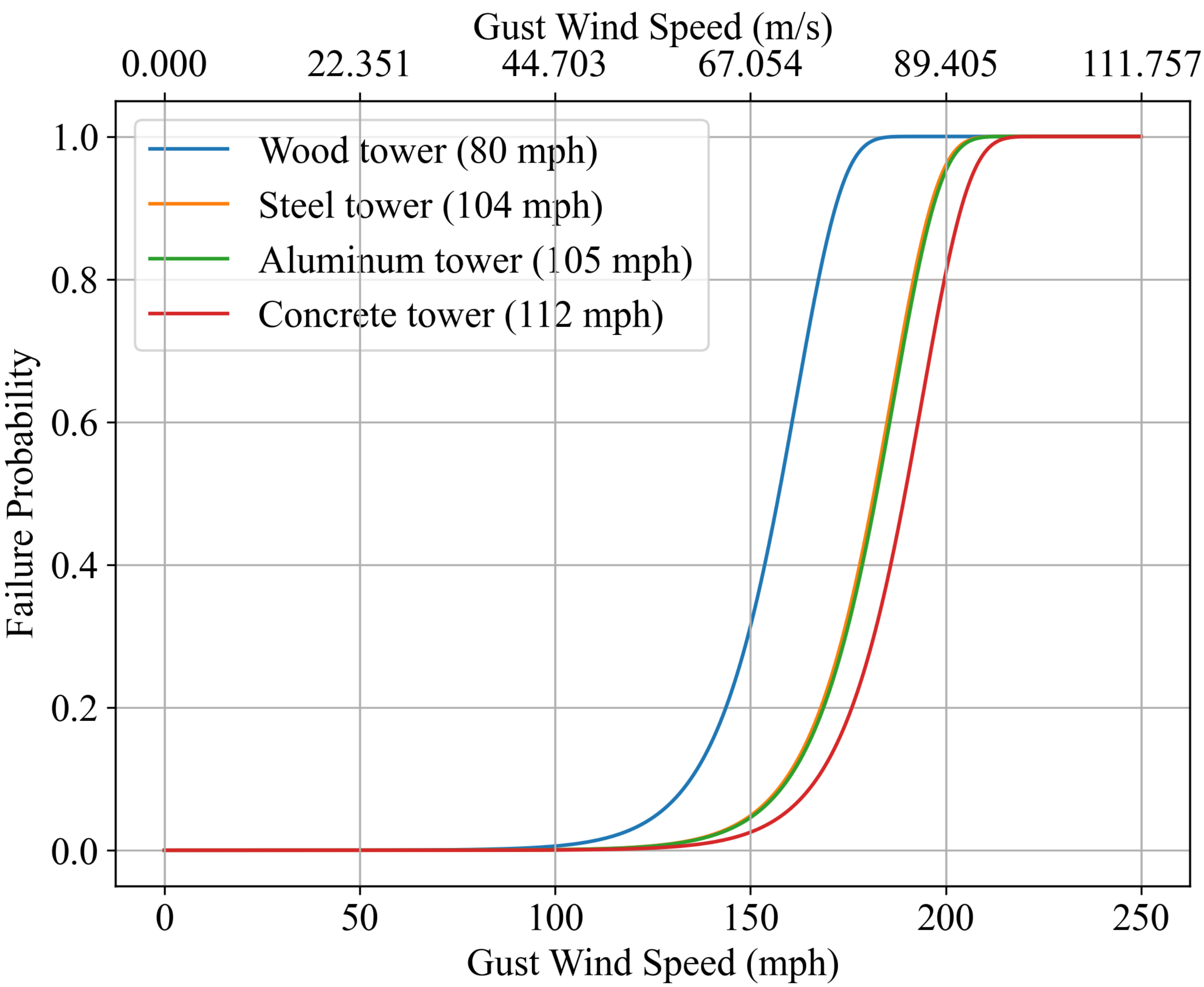

Fig. 7. Calibrated fragility curves for the towers made with different materials. Wind loading for towers with different materials is calculated based on the known design standards used for constructing the towers.

REFERENCES

[1] K. Porter, "A beginner's guide to fragility, vulnerability, and risk," *Encyclopedia of earthquake engineering*, vol. 2015, pp. 235–260, 2015.

[2] A. Veeramany, S. D. Unwin, G. A. Coles, J. E. Dagle, D. W. Millard, J. Yao, C. S. Glantz, and S. N. Gourisetti, "Framework for modeling high-impact, low-frequency power grid events to support risk-informed decisions," *International Journal of Disaster Risk Reduction*, vol. 18, pp. 125–137, 2016.

[3] V. Chalishazar, T. Brekken, D. Johnson, K. Yu, J. Newell, K. Chin, R. Weik, E. Dierickx, M. Craven, M. Sauter, A. Olennikov, J. Galaway, and A. Radil, "Connecting risk and resilience for a power system using the portland hills fault case study," *Processes*, vol. 8, no. 10: 1200, 2020.

[4] V. Chalishazar, B. Johnson, E. Cotilla-Sanchez, and T. K. A. Brekken, "Augmenting the traditional bus-branch model for seismic resilience analysis," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 1133–1137.

[5] B. Johnson, V. Chalishazar, E. Cotilla-Sanchez, and T. K. A. Brekken, "A Monte Carlo methodology for earthquake impact analysis on the electrical grid," *Electric Power Systems Research*, vol. 184, p. 106332, Jul. 2020.

[6] E. B. Watson and A. H. Etemadi, "Modeling Electrical Grid Resilience Under Hurricane Wind Conditions With Increased Solar and Wind Power Generation," *IEEE Transactions on Power Systems*, vol. 35, no. 2, pp. 929–937, 2020.

[7] L. Ma, P. Bocchini, and V. Christou, “Fragility models of electrical conductors in power transmission networks subjected to hurricanes,” *Structural Safety*, vol. 82, no. September 2019, p. 101890, 2020.
[8] M. Ouyang and L. Dueñas-Osorio, “Multi-dimensional hurricane resilience assessment of electric power systems,” *Structural Safety*, vol. 48, pp. 15–24, 2014.
[9] D. A. Reed, C. J. Friedland, S. Wang, and C. C. Massarra, “Multi-hazard system-level logit fragility functions,” *Engineering Structures*, vol. 122, pp. 14–23, 2016.
[10] M. T. Schultz, B. P. Gouldby, J. D. Simm, and J. L. Wibowo, “Beyond the Factor of Safety : Developing Fragility Curves to Characterize System Reliability-US Army Corps of Engineers,” no. July, p. 51, 2010.
[11] C. J. Wong and M. D. Miller, *Guidelines for electrical transmission line structural loading*. American Society of Civil Engineers, 2009.
[12] J. Xue, F. Mohammadi, X. Li, M. Sahraei-Ardakani, G. Ou, and Z. Pu, “Impact of transmission tower-line interaction to the bulk power system during hurricane,” *Reliability Engineering and System Safety*, vol. 203, no. June, 2020.
[13] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, and P. Mancarella, “Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures,” *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3747–3757, 2017.
[14] P. Vincent, C. Huet, M. Charbonneau, P. Guilbault, M. Lapointe, and D. Banville, “Testing and Numerical Simulation of Overhead Transmission Line Dynamics under Component Failure Conditions,” *Conférence Internationale des Grands Réseaux Électr*, pp. 1–8, 2004.
[15] P. J. Vickery and P. F. Skerlj, “Hurricane Gust Factors Revisited,” *Journal of Structural Engineering*, vol. 131, no. 5, pp. 825–832, 2005.
[16] Quanta Technology, “Cost-Benefit Analysis of the Deployment of Utility Infrastructure Upgrades and Storm Hardening Programs,” *Satellite Communications*, vol. 3021, pp. 1–108, 2009.
[17] R. Cwece, D. Bernard, Y. Krien, F. Leone, T. Candela, M. Péroche, E. Biabiany, G. Arnaud, A. Belmadani, P. Palany, and N. Zahibo, “A 30 m scale modeling of extreme gusts during Hurricane Irma (2017) landfall on very small mountainous islands in the Lesser Antilles,” *Natural Hazards and Earth System Sciences*, vol. 21, no. 1, pp. 129–145, 2021.
[18] ASCE, “Minimum design loads for buildings and other structures.” American Society of Civil Engineers, 1998.
[19] “Historical Hurricane Tracks.” [Online]. Available: https://coast.noaa.gov/hurricanes/#map=4/32/-80 [Accessed 17 Nov. 2021].
[20] V. H. Chalishazar, “Evaluating the Seismic Risk and Resilience of an Electrical Power System,” Thesis, 2019.