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Component Assessment of the Electric Transmission Grid to Hurricanes

Zachary D. Schumann[1] and Christopher M. Chini[1,2]

[1]Department of Systems Engineering and Management, Air Force Institute of Technology, Wright-Patterson AFB, OH, USA, [2]Earth Systems Predictability & Resilience Group, Pacific Northwest National Laboratory, Richland, WA, USA

Key Points:

- Component-level characteristics of the electric transmission, such as tower type and location, are important for modeling
- The tower types across the region has varying levels of vulnerability to hurricanes
- Robustness efforts to increase structural integrity of transmission towers would reduce overall system vulnerability

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. M. Chini,
christopher.chini@pnnl.gov

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Author Contributions:

Conceptualization: Christopher M. Chini
Data curation: Zachary D. Schumann
Formal analysis: Zachary D. Schumann
Funding acquisition: Christopher M. Chini
Investigation: Zachary D. Schumann
Methodology: Zachary D. Schumann
Project Administration: Christopher M. Chini
Software: Zachary D. Schumann
Supervision: Christopher M. Chini
Validation: Zachary D. Schumann

Abstract

The increased frequency and intensity of extreme weather events from climate change necessitates understanding impacts on critical infrastructure, particularly electrical transmission grids. One of the foundational concepts of a grid's resilience is its robustness to extreme weather events, such as hurricanes. Resilience of the electric grid to high wind speeds is predicated upon the location and physical characteristics of the system components. Previous modeling assessments of electric grid failure were done at the systems level with assumptions on location and type of specific components. To facilitate more explicit adaptation metrics, accurate component-level information is needed. In this study, we build and utilize a data set of location, physical characteristics, and age of transmission structures for nine counties in the Florida Panhandle. These component characteristics were then simulated for failure under a variety of scenarios using fragility curves. Eight hurricanes were modeled using Hazus from the Federal Emergency Management Administration and the resulting impact to the network was assessed. The network was generated using the transmission lines and towers, showing increasing impacts to network efficiency with larger storms. Although modern transmission structures are built under the more stringent extreme wind loading construction standards, the prevalence of older, wooden transmission structures throughout the region poses a substantial risk to reliable electricity transmission during tropical cyclone events from the Gulf of Mexico.

Plain Language Summary

Coastal infrastructure is increasingly vulnerable to extreme weather events. A critical infrastructure, such as electric transmission grids, must be robust and resilient to increasing intensity events to continue to provide an appropriate level of service to its customers. However, there are limited data on the component-level assets of the transmission grid. Therefore, there are significant uncertainties in models and how they can be used in disaster preparedness and response scenarios. In this study, we build a high-resolution transmission grid data set for nine counties in the Florida Panhandle. We then simulate eight different hurricane scenarios and detail how vulnerable the transmission grid is to hurricanes.

1. Introduction

Climate change has profound implications to the electricity sector with respect to demand, generation, transmission, and distribution. Proactive and reactive adaptation measures to anthropogenic climate change are driving the single largest transformation of the transmission and distribution grid since its inception at the beginning of the nineteenth century (Chalamala et al., 2022). The impacts of climate change on the existing bulk power system are numerous and compounding, including temperature accelerated degradation, increased variability in demand, and climate-induced migration. Increases in both mean temperature and thermal variability accelerate asset degradation and derate line transmission capacity (Fant et al., 2020). Transmission transformers often having a replacement lead time from 12—18 months, making them one of the grid's most vulnerable components (NASEM, 2017; US-Canada Power System Outage Task Force, 2006). The rate of breakdown increases exponentially with temperature, placing an already aging fleet of transformers at risk of accelerated degradation (Brown, 2009). Increased variability requires winter capacity to remain constant as prolonged cold snaps caused from more frequent breakdowns of the polar vortex are possible. Additionally, all these mechanisms in concert will drive yet-to-be-determined climate migrations (Shaw et al., 2020). These factors, among others, create unique challenges for a critical infrastructure system. In this study, we specifically focus on storm intensity, the physical infrastructure assets of the transmission grid, and their relationship to the regional network and population it supports.

Visualization: Zachary D. Schumann, Christopher M. Chini
Writing – original draft: Zachary D. Schumann
Writing – review & editing: Zachary D. Schumann, Christopher M. Chini

Although reliability metrics quantifying the frequency and duration of momentary and sustained outages are mature and commonly accepted throughout the electricity sector, there are generally no standardized resilience metrics currently in use (Chiu et al., 2020; NASEM, 2017). The lack of resilience metrics is a result of only a few historically large-area, long-duration outages occurring to guide future investments. Many resilience metrics have been proposed through research and academia and remain immature (Willis & Loa, 2015). The Grid Modernization Laboratory Consortium, a strategic partnership between the U.S. Department of Energy and 13 National Laboratories, have proposed a matrix of direct and indirect resilience measures related to electric and critical electric service disruptions, community functionality and direct and indirect monetary metrics (Watson et al., 2015). Some researchers have approached resilience and robustness of electrical networks using topological indicators derived from graph theory (Winkler et al., 2010). Metrics such as efficiency (Bompard et al., 2012; Kim et al., 2017) and meshedness (Winkler et al., 2010) have been used to characterize the performance of the electrical grid under different damage scenarios.

Hurricanes are common disruptions to power system operations along the Gulf and Atlantic Coasts. As the mean temperature of the atmosphere and surface of the sea increases from the effects of climate change, hurricanes are expected to increase in intensity (Kossin et al., 2007; NASEM, 2017). Moreover, the occurrence of 1-billion-dollar hurricane events is increasing in frequency. In 2021 alone, there were 4 of the 59 recorded billion-dollar hurricane impacts since 1980, totaling $82.5B (Smith, 2020). The severity of the economic impacts resonating from transmission outages caused by hurricane damage underscores a need to understand, quantify, and enhance power grid resilience subjected to such threats. The ability to accurately estimate the damages caused by such events is a foundational predecessor to an effective resilience strategy.

The inherent infrequency of high impact low probability disruptions such as hurricanes makes it difficult to adjudicate the effectiveness of resilience investments through empirical observation. For this reason, accurate damage simulations provide a means by which a transmission network's response to a hurricane can be estimated. Within the existing literature of the topic, there are two primary approaches to estimating a grid's response to a perturbation: statistical models and fragility-based models. Although statistical models provide successful implementation and accurate estimates at a spatial unit scale, for example, zip code or census tract, they do not provide accurate results at a component level (Zhai et al., 2021). While fragility analyses provide component-level failure resolution, they often require exhaustive data collection techniques as much of the information required is often not publicly available. As a result, fragility analyses of transmission networks to wind damage often approximate the grid topology and structure with various test-bus cases provided by the Institute of Electrical and Electronics Engineers (IEEE). For example, Mahzarnia et al. (2020) modeled the resilience of a transmission system based on fragility curves of transmission lines to a hurricane across an IEEE 24-bus test system comprised of 34 lines and 12 generating units. The study area was divided into eight different climatic zones which would experience different weather conditions during the Monte Carlo based damage simulation. Additionally, Scherb et al. (2019) modeled a fragility-based wind load simulation of the Nordic transmission grid across Denmark, Norway, Sweden, and Finland. Other analyses have investigated the transmission network for Great Britain (Panteli et al., 2015, 2016), or the state of Texas, using transmission outage predictions to model security-constrained optimal power flows (Javanbakht & Mohagheghi, 2014).

Ouyang and Duenas-Osorio (2014) modeled the transmission network of Harris County, TX, and simulated transmission tower damage using wind field data simulated by Hazus. Hazus is a software program developed for the Federal Emergency Management Agency (FEMA) to model earthquake (Kircher et al., 2006; Neighbors et al., 2013), flooding (Banks et al., 2015; Schauer et al., 2002), tsunami (Burns et al., 2021), and hurricane damage (Pei et al., 2014; Vickery, Lin, et al., 2006). However, the location of transmission towers in the Harris County study, a critical failure component of transmission lines, was approximated based on the utility's report of average structures per line mile on each transmission line. Therefore, there is a need to be more spatially explicit regarding location and type of transmission tower. Additionally, Ji et al. (2016) identified inherent vulnerabilities of electrical systems using outage data from Super Storm Sandy, highlighting the need for robust data sets to evaluate and prepare for disaster scenarios in the electric transmission grid.

The location and physical characteristics of transmission structures are critical in accurately modeling hurricane-induced wind damage on the network. Different locations experience different wind speeds based on probabilistic hurricane simulations. Wood, steel, concrete, and aluminum lattice and guyed mast structures have different failure loadings resulting from wind speeds. Each of these transmission structure materials experience a varying rate of deterioration in terms of resistive moment to wind loading because of their age. Additionally, design standards governing the construction material and wind load ratings of transmission structures, have evolved to account for the impacts of extreme winds. The 2007 version of the National Electrical Safety Code (NESC) incorporated "extreme wind and ice" loading criteria for utility structures and adopted standards for wind loading from ASCE 7-98, *Minimum Design Loads for Buildings and Other Structures*. However, there are potentially inequities in the robustness of these towers across a region.

There is a knowledge gap in the granularity and availability of component-level data for fragility-based model simulations and subsequent analysis. Therefore, the objective of this research is threefold: (a) build a spatially explicit component-level data set including physical characteristics and (b) simulate multiple hurricanes on the transmission grid in the Florida Panhandle, and (c) assess the failure impacts on network structure. The results address two questions: (a) What are the benefits of modeling a transmission grid's response to hurricanes at a spatially accurate component level? (b) Can age, physical characteristics and location of transmission structures subjected to multiple hurricane simulations quantify a grid's robustness in terms of failure rates at various wind speeds?

2. Methods

In this study, we explore the western Florida Panhandle, a nine-county area that has historically been subject to intense hurricanes, requiring three primary lines of effort. First, the location, age, and physical properties of each transmission structure within nine counties in the Florida Panhandle (Escambia, Santa Rosa, Okaloosa, Walton, Holmes, Washington, Bay, Jackson, and Calhoun Counties) are cataloged. Transmission structures were also located for lines extending into this region of interest from their substation of origin located in an adjacent county or state. Section 2.1 describes the process of building and validating the transmission data set including lines, towers, and substations. Section 2.2 describes the modeling of fragility for the transmission towers against multiple storm scenarios. Fragility curves for each transmission structure were applied to account for the robustness (material) and deterioration (age) of each transmission structure. Second, 3-s peak gust wind speeds (mph), generated in Hazus—the same model used to develop design wind speeds in ASCE-7-98 and ASCE-7-02 (Vickery, Lin, et al., 2006; Vickery, Skerlj, et al., 2006), were applied to each transmission structure within the region of interest.

2.1. Data Collection

A significant contribution of this research is a descriptive data set of components of the transmission network in the western Florida Panhandle. This research compiled spatial information and relevant descriptive details about 260 substations, taps, risers, and dead ends; 18,363 transmission structures; and 360 transmission lines across nine counties. Information was aggregated from a variety of sources including, the Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD, 2019, 2022a, 2022b) for transmission lines and substations, Gulf Power Company's (GPCO) Federal Energy Regulatory Commission (FERC) Form 1 submissions from 1977 to 2020, GPCO Ten-Year Site Plans (TYSPs) from 1999 to 2019, and GPCO Distribution Reliability Reports (DRRs) from 2012 to 2020. All the information is open access, but it is often embedded in a not accessible or intuitive format. Geospatial data files for substations and transmission line locations are available on HIFLD's website (HIFLD, 2019; HIFLD, 2022a). All data from GPCO are available on Florida Public Service Commission's (FPSC) website under utility regulation (FPSC, 2000). Each of the following sections details the collection process and validation method for each component. Additionally, each data set is available for future research through Zenodo (Schumann & Chini, 2023).

2.1.1. Substations

Geospatial data files for substation structures were first imported from HIFLD. GPCO nomenclature was then applied to each substation within the region of interest by use of the GPCO Service Territory map supplied on the company's 2019 TYSP submission (GPCO, 2019a). This, in turn, enabled joining GPCO FERC Form 1 Section 426 *Substations* data to the geospatial data file (FPSC, 2000). The information includes primary, secondary, and tertiary substation voltage, disposition of the substation, the number and capacity of substation transformers in Megavolt-Amperes (MVA) and if GPCO maintains a spare transformer for replacement given a potential failure.

Additionally, in GPCO's 2017 & 2018 filings to the FPSC (GPCO, 2018, 2019b), the substation name was attributed to distribution feeder identification. Using these attributions, we correlated substation of origin with the number of customers served on overhead and underground lateral lines, the number and length of laterals, total length of the feeder circuit, customer interruptions, and customer minutes of interruptions, load growth, peak load, and total number of connected customers on each feeder. Although spatial details for distribution feeders, laterals, and associated supporting structures and conductors were not available, feeder exit location is spatially identified via distribution or transmission substation of origin within the substation data set. The collected substation data were validated against the various GPCO filings. The data details the fields within the substation layer file and from where each field was collected (Schumann & Chini, 2023).

2.1.2. Transmission Lines

A geospatial data file for transmission lines was first imported from HIFLD. Line voltage and owner were verified with GPCO's 2019 TYSP service territory map (GPCO, 2019a). The nomenclature of origin and destination substations was then corrected to match the substation data set and verified against the GPCO service territory map (GPCO, 2019a). Transmission line attributes were collected from GPCO's annual FERC Form 1 submissions from 1977 to 2020, specifically Section 422 (FPSC, 2000). The rectifying of nomenclature allowed the following information to be attributed to the geospatial data file for each transmission line in the region of interest: voltage, owner, the year the line entered service, length of the line, size, material and configuration of the conductors, supporting structure physical makeup, average spacing per line mile, and the cost of the land and construction including poles, fixtures, conductors and devices.

Transmission line segments, bearing the same data fields as the parent transmission line data set, were then created between each transmission structure. The geometric length of each segment was calculated, attributing a span length to each segment of transmission line within the region. Additionally, land use categories for the State of Florida were uploaded as a layer file from the Florida Department of Environmental Protection Geospatial Open Data (Florida Department of Environmental Protection, 2017), to provide additional context of the spatial characteristics for the grid.

2.1.3. Transmission Towers

The overall features of each transmission line presented the approximate age of the structures as well as the anticipated construction material. However, the HIFLD data did not contain specific transmission structure locations. The lack of data necessitated manual location and identification of each transmission structure within the region of interest. This process was completed in three steps: location identification, categorization of material and structure, and validation of selection.

First, the geospatial data file of transmission lines was uploaded into Google Earth. Aerial imagery for each line over its entire length was then analyzed manually. Location was identified by drawing a polygon within Google Earth around the transmission structure. This data and aerial imagery was accessed from May to September 2022. Next, the observed material type was then inspected by observing the tower from street view, where possible, to confirm whether the tower was made of aluminum or steel, concrete (PCC) or wood. Additionally, guyed mast structures were identified as they present superior wind loading characteristics to typical aluminum lattice transmission structures (Gani et al., 2010).

The anticipated structure type from GPCO FERC Form 1 Sections 422 & 424 (FPSC, 2000) was validated against the observed structure from aerial imagery analysis within Google Earth. Each discrepancy was reanalyzed and visually confirmed within Google Earth and a final structure disposition was attributed to each of the 18,363 transmission structures within the study region.

2.2. Disaster Simulation

To demonstrate the utility of the component-level data, we perform simulations of eight different storms across the region against transmission structure failure. Damage simulations were conducted on each of the located transmission towers using generation of wind fields from Hazus tropical cyclone simulations, application of material and age-specific fragility curves, and probabilistic damage simulation by means of a Monte Carlo Simulation of 10,000 iterations.

2.2.1. Hazus

Hazus is a geospatial analysis tool developed by the FEMA to simulate and estimate damage from high-intensity, low-probability events such as hurricanes, floods, tsunamis, and earthquakes. This research specifically utilizes

Table 1

Although the Maximum Windspeed of the 200-Year Storm is the Highest of the Scenarios, the Magnitude of the Impacted Area of the 1,000-Year Storm Makes It Extremely Disruptive to the Regional Transmission Grid

Tropical cyclone simulation	Category (wind speed)	Max wind speed (mph)
10-year storm	2	101
20-year storm	3	117
50-year storm	4	131
100-year storm	4	135
200-year storm	4	155
500-year storm	4	143
1,000-year storm	4	143
Hurricane Michael	4	141

Note. Hurricane Michael made landfall as a Category 5 hurricane in 2018; however, the Hazus recreation used a Category 4 storm.

the hurricane wind field projections within Hazus 5.1 Hurricane Model (HM) for the nine counties of the Florida Panhandle. The wind field is comprised of the maximum 3-s peak wind gust for various probabilistic and historical hurricane scenarios measured at census-tract resolution. Further details on Hazus are provided in Text S1 in Supporting Information S1.

This research utilized Hazus HM to develop eight different hurricane scenarios for the damage simulation. The 10-, 20-, 50-, 100-, 200-, 500-, and 1,000-year return period tropical cyclone events for the nine-county area were modeled through Hazus probabilistic hurricane simulations. For these probabilistic scenarios, Hazus estimated the aforementioned design storms from a 100,000-year ensemble of storm scenarios. Finally, the historic 3-s peak gust speeds recorded from Hurricane Michael (2018) were translated into a wind field for applicational use in the Monte Carlo-based damage simulation.

As shown in Table 1, the strongest wind speeds emanate from the 200-Year Storm. However, this storm is smaller in impact than the 500- and 1,000-Year Storms, relative to the region, whose tracks fall across a much broader swath of the region of study. We recognize significant uncertainty in wind speed during a tropical cyclone event and use the different scenarios to illustrate the probabilistic failure of the components. Further description is included in limitations within the discussion section.

2.2.2. Fragility Curves

Fragility curves represent a probability density function describing the conditional probability of failure of an individual system component based on a parameter of hazard loading (Han et al., 2014). In the case of transmission support structures, fragility curves describe the probability of tower buckling, collapse or failure given a specific wind speed. Much of the existing literature on fragility-based models of transmission grid response to hurricanes or severe wind events classify transmission structures into two categories in terms of underlying fragility curves: base and robust (Ouyang & Duenas-Osorio, 2014; Panteli et al., 2015, 2016; Panteli & Mancarella, 2015). There is also a diverse range of fragility curves resulting from dynamic structural modeling (Du & Hajjar, 2022; Ma et al., 2021) and nonlinear static analysis based on Latin hypercube sampling techniques (Cai & Wan, 2021). Although there is no separate fragility curve for guyed mast transmission structures, their divergence in design characteristics suggest differing dynamic wind loading behavior to that of self-supporting lattice structures (Gani et al., 2010).

There is sparse literature on wooden, steel, and concrete transmission structures. However, there is ample documentation on wooden utility pole performance based on wind speeds (Shafieezadeh et al., 2013) and incorporating historical data to perform posterior correction (Han et al., 2014). Additionally, research of wooden utility poles has considered strength deterioration resulting from Southern Pine degradation at the ground line due to thick, un-dead sap wood (Salman & Li, 2016; b; Shafieezadeh et al., 2013). Age deterioration was also shown to impact the strength of a pristine Class 1 pole nearly to that of a pristine Class 4 pole after 75 years of age (Teoh et al., 2019). Pole rupture and foundation failure was also modeled for different pole ages and foundations of Class 3, 4, and 5 poles (Darestani et al., 2022) and generalized fragility curves were generated for various design strength parameters of wooden utility poles (Braik, 2019).

As a result, separate fragility curves were selected for lattice towers (Panteli et al., 2015) and guyed masts (Du & Hajjar, 2022), as shown in Figure S5 in Supporting Information S1. In both cases, age deterioration was not considered due to a lack of available information discussing strength attenuation of such structures. Wooden H-Frame and monopole structures were assigned fragility curves based on their age (Braik, 2019) using the 20-, 40- and 60-year curves, as shown in Figure S1 in Supporting Information S1. Concrete 2-pole, H-Frame, single-pole as well as steel H-Frame and single-pole structures constructed more than 10 years ago were also assigned fragility curves from Braik (2019) based on the same age categorization as wooden poles. These fragility curves are shown in Figures S2 and S3 in Supporting Information S1, respectively.

As previously mentioned, extreme wind loading considerations were added in the 2007 version of the NESC, upgrading the Grade B wind loading standard of 105– 130 mph for transmission structures over 18 m (ASCE

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Table 2
The Overwhelming Majority of Critical Transmission and Generation Substation Transformers Do Not Have a Spare, Making Them Some of the Most Critical Components in the Regional Transmission Grid

	Generation substations	Transmission substations	Distribution substations
Count	12	20	88
Capacity (MVA)	2,872	6,419	3,937
# Transformers	23	31	147
# Spare transformers	2	3	13
Peak load (MVA)	–	–	1,514.20
Spare capacity (MVA)	460	937	542
Spare peak load (MVA)	–	–	291.2
# Customers connected	–	–	431,800
# Customers connected to spare	–	–	35,364

7-98) (Brown, 2009). Additionally, an initiative put forth by the Florida Public Service Commission for electric system hardening, began after the 2004–2005 hurricane season (FPSC, 2007). Therefore, a hardened fragility curve (Panteli et al., 2016) was applied to concrete or steel transmission structures constructed 10 years ago or less, as shown in Figure S4 in Supporting Information S1. Hardened transmission structures (Figure S5 in Supporting Information S1) have shorter spans, can have extended-length steel bracing driven below the groundline, storm guying or push braces and consist of upgraded materials (Brown, 2009).

2.2.3. Validation of Fragility Curve Selection

To validate the analysis, we compare the failure rates for each wind speed of the transmission structures within the region of interest to the failure rates from Quanta Technology's report to the Public Utility Commission of Texas in 2009 (Brown, 2009). For this report, Quanta collected transmission structure failure rate information from TX electric utilities assessing hurricane impacts from the 10 previous years. They used this data to generate failure rate curves for existing transmission structures and hardened structures having the properties mentioned previously. ASCE 7-10 and Rule 250 of the NESC requires similar wind loading design for transmission structures within 50 miles of the Gulf Coast of TX as it does in the Florida Panhandle. As a result, the failure rate curves produced in this report were chosen as a calibration check for accuracy of selected fragility curves for the transmission line supporting structures. We acknowledge this data source is relatively outdated (2009), but we were unable to find a more recent quantitative assessment of failure rate against wind speed for transmission towers.

2.3. Analysis of Failure Across the Network

Failure of the network was evaluating using a Monte Carlo simulation with component failure estimated using a four-parameter Weibull fit of the fragility curves. See Text S2 in Supporting Information S1 for more details. Using the expected failures from the fragility a Monte Carlo simulation was conducted for each of the eight storm scenarios. We performed two analyses of the failure profiles to evaluate the performance of the network and demonstrate the importance of understanding component-level modeling.

The existing transmission network was converted into a topological graph model using transmission towers as nodes and the transmission lines as links. A failure of a transmission tower in the Monte Carlo simulation was assumed to remove the node from network and, subsequently, removing its two incident line segments. Following failure of the network, the resultant changes in global efficiency and meshedness were tracked to understand the storm scenarios impact on the overall topology of the network. These metrics are consistent with previous efforts to evaluate electrical network resiliency using topological indicators (Kim et al., 2017; Winkler et al., 2010).

3. Results

3.1. Data Set Description and Validation

3.1.1. Substations

Within the nine counties of the Florida Panhandle, there are 195 substations, 57 taps, 6 risers, and 2 dead ends. Of these substations, 130 are owned and operated by GPCO: 88 distribution, 20 transmission, and 12 generation substations. Furthermore, 13 distribution, 3 transmission and 2 GPCO generation substations have spare transformers within organic bench stock, as reported by the company's FERC Form 1 filing. In other words, GPCO has 1,939 MVA of spare transformer capacity on hand, backing up 35,634 customers connected to these substations out of a total of 431,800 customers for the whole service area.

Table 2 describes a stark vulnerability of the regional transmission grid: there are very few spare transformers within organic bench stock with which expedient repairs can be made during a disruption to substations. This vulnerability is common to transmission networks and has prompted the National Academy of Science,

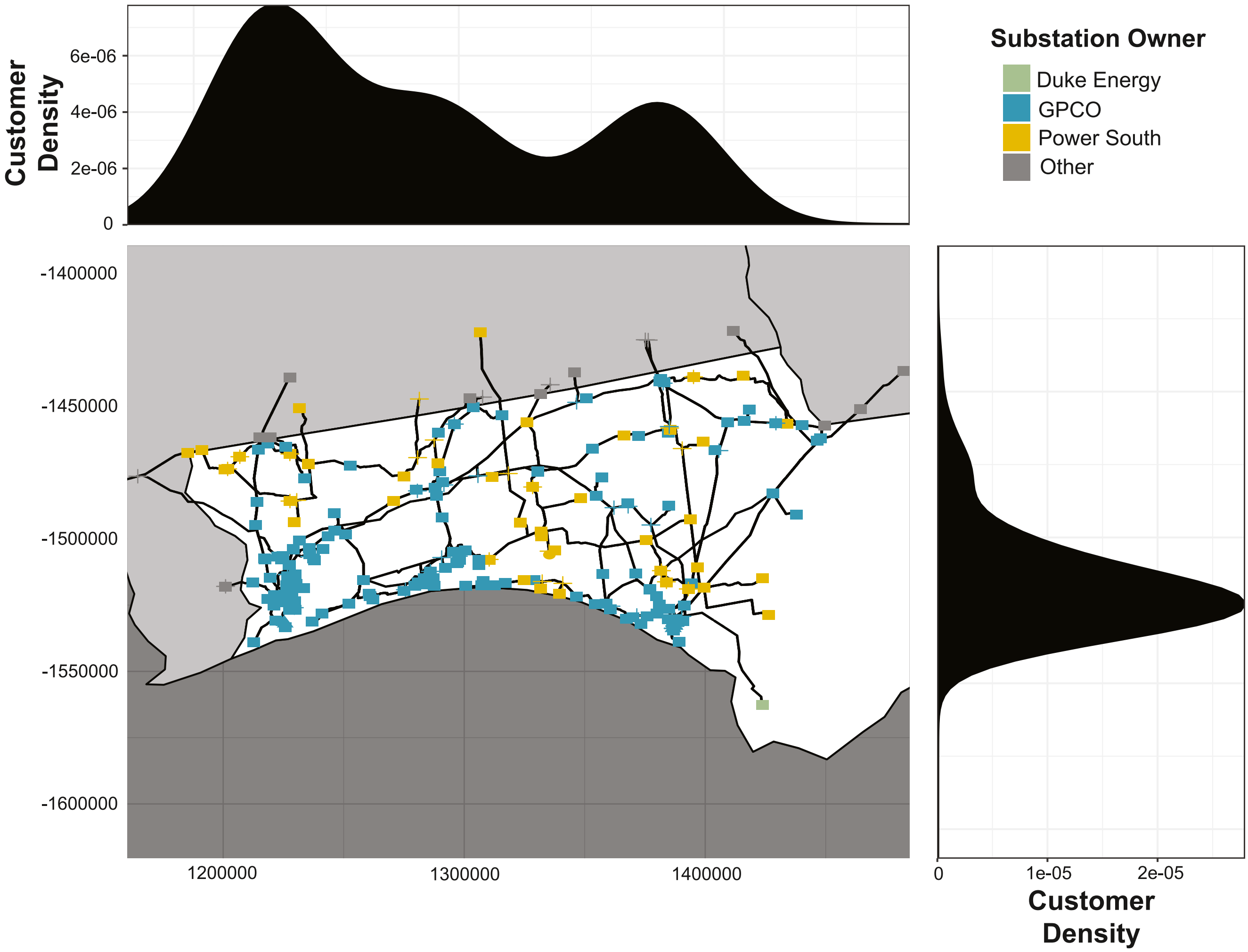

Figure 1. Gulf Power Company (GPCO) customers are primarily served from distribution substations along the coast, with a majority around population centers in Pensacola in the western counties. Although the northern substations are further from storm surge and coastal flooding risks, they serve substantially fewer customers.

Engineering and Medicine to recommend that the US Department of Energy launch a program to manufacture and deploy transformer sets that can be pre-positioned around the country (NASEM, 2017). For additional context, Table S2 in Supporting Information S1 shows substations within GPCO's inventory which fall within various storm surge zones.

Distribution reliability reports describe attributes of the distribution grid as they pertain to industry-accepted reliability metrics such as sustained average interruption duration index, momentary average interruption frequency index, and customer average interruption duration index as prescribed by IEEE Standard 1366. These metrics are normally only attributed to the distribution feeders and associated laterals, making them impossible to geospatially identify on the map with the information from HIFLD data sets. However, the 2017 and 2018 GPCO DRRs (GPCO, 2018, 2019b) attributed each feeder identification number with a substation of origin from each of the 82 distribution substations within the GPCO service territory. This information was then used to glean insightful information from the GPCO distribution grid and spatially determine feeder origin location within the data set. This information also enabled a geospatial GPCO customer distribution as depicted in Figure 1.

After disaggregating the feeder and distribution data per substation, there are 308 feeder lines in the area with 61% of the distribution feeders loop-fed, enabling back-feeding and presenting additional redundancy and line reliability during fault location, isolation and service restoration activities. There are 7,748 line-miles of feeder with 5,810 mi (75%) overhead and 1,938 mi (25%) underground. Table S3 in Supporting Information S1 shows the detailed breakdown of lateral lines tied to distribution substations.

Table 3
Although Many of the Transmission Support Structures Owned and Maintained by Gulf Power Company Are Hardened and Resilient Against Extreme Winds of Tropical Cyclone Events, 44% of the Inventory Is Wooden and Presents a Stark Vulnerability

	Structure type	Count	Total
Wood	H-frame	6,252	8,102
	Single pole (SP)	1,850	
Concrete (PCC)	H-frame	1,115	7,464
	Single pole (SP)	6,249	
	Two-pole (2P)	100	
Steel	H-frame	488	1,253
	Single pole (SP)	765	
Lattice	Self-supporting	522	1,532
	Guyed mast	1,010	

3.1.2. Transmission Lines

As mentioned in the methodology, the accuracy of the transmission tower age and material makeup came from accurately matching GPCO FERC Form 1 (FPSC, 2000) to HIFLD geospatial data (HIFLD, 2019, 2022a, 2022b). A breakdown of the voltages in the Form 1 submission against the transmission lines calculated in this study is shown in Table S4 in Supporting Information S1. Additionally, these transmission lines were compared visually to maps from GPCO. Figure S6 in Supporting Information S1 shows the layout and breakdown of different voltage lines and their associated substations across the region. A breakdown of the transmission lines, their material, and their size is important to evaluate resilience of transmission grids to heat events as aluminum conductor steel supported conductors are much more thermally efficient, resulting in reduced sag during high power flow conditions and greatly reducing the risk of inadvertent ground faults from sagging lines contacting vegetation below the conductors—one of the primary culprits of the Great North American Blackout of 2003 (US-Canada Power System Outage Task Force, 2006). Our estimation of line length has less than a 10% error rate across all line voltages when compared to GPCO filings. Much of the variation can be attributed to uncertain demarcations of GPCO boundaries.

3.1.3. Transmission Towers

Finally, the study cataloged 18,363 transmission support structures. Table 3 highlights the numerical breakdown of tower material within the region of study. Although there is an abundance of steel and concrete transmission support structures, 44% of the total number of structures are made of wood, a significant vulnerability in a humid climate next to the coast with a propensity for extreme wind events.

Hardened transmission towers are those which have been built under the more stringent wind loading design criteria of the 2007 NESC which requires the structure to withstand 130 mph 3-s wind gusts as opposed to Grade B construction designed to withstand 105 mph gusts. Existing transmission structures can also be hardened by installing push braces, installing more frequent dead-end structures along the line, lateral storm guying, fiber glass wraps near the ground line for wooden transmission towers and decreasing the span length of the conductors by installing more transmission towers.

Figure 2 shows the East-West and North-South spatial distribution of wooden transmission support structures is relatively homogenous. The East-West distribution of PCC and hardened transmission towers, on the other hand, is bimodal, peaking around the two major power generation plants in the Florida Panhandle: Crist and Smith (Figure S6 in Supporting Information S1). The guyed mast structures typically follow 230 kV transmission corridors, connecting the small network of critical transmission substations within the region.

3.2. Tropical Cyclone Simulations and Validation

The Monte Carlo simulation presented failure rates of individual towers for each of the 8 tropical cyclone simulations. Failure rates were aggregated by binned wind (whole number bin size) speeds for transmission structures and the results were validated against the failure rate curves produced by Quanta Technologies during their report on storm hardening techniques and cost-effectiveness for electric utilities along the Gulf Coast of Texas (Brown, 2009). In their report, Quanta delineated existing transmission structures as those constructed to 105 mph NESC Grade B wind loading requirements from hardened transmission structures designed to 130 mph wind loads mandated by the 2007 revision of the NESC and referencing wind loading design criteria found in ASCE 7-98. Figure 3 shows the predicted failures against the Quanta report with fitted four-parameter Weibull curves to evaluate trend.

The results of this research show more initial transmission tower failures during milder wind speeds than the data collected by Quanta Technologies (Romero & Hall, 2020). However, the expected failure rates become equal at 125 mph and the towers within the study region perform more robustly at higher wind speeds. This could be due to a higher density of transmission structure located nearer to the Gulf Coast, indicating a larger exposure of transmission

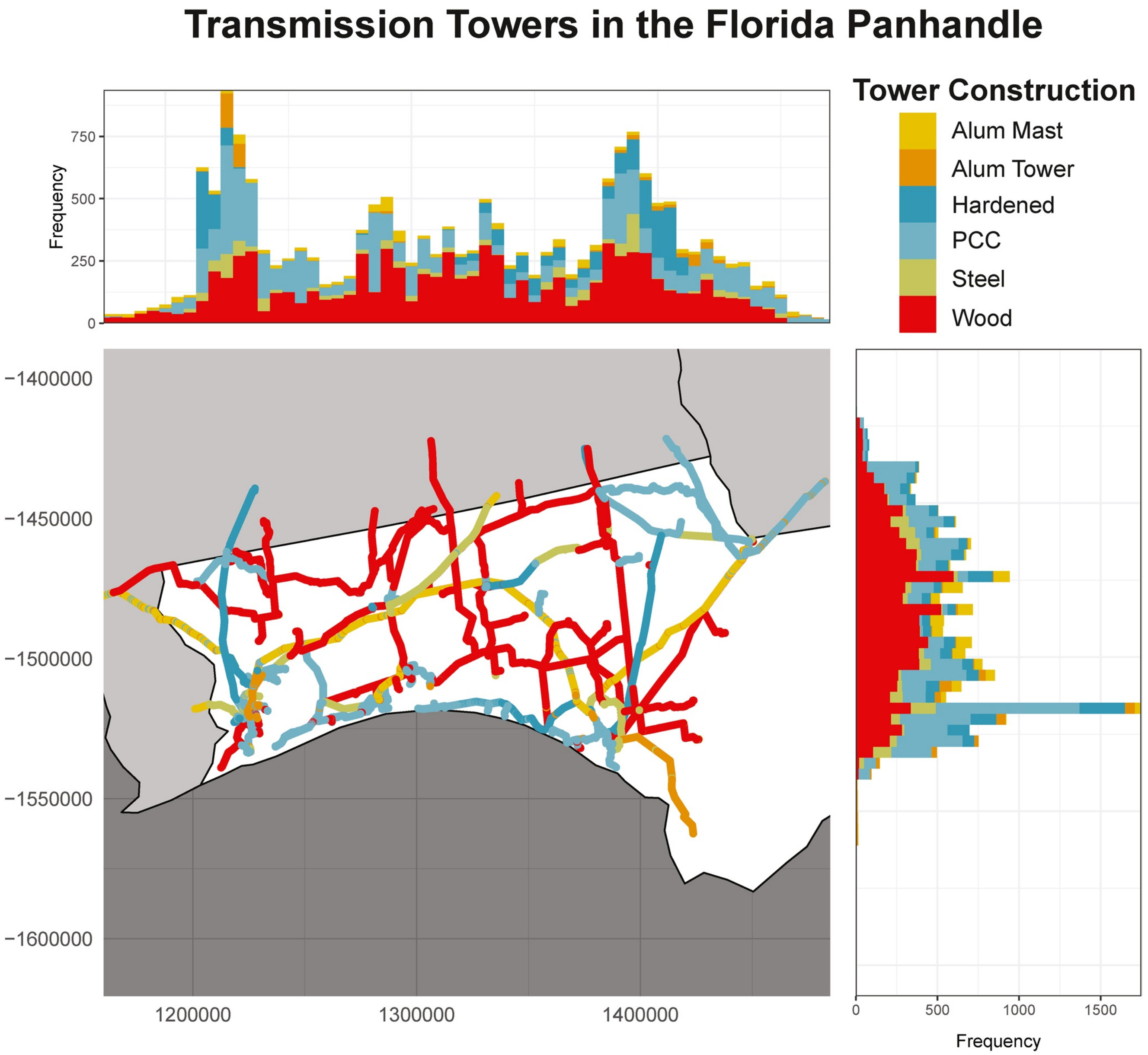

Figure 2. Although wooden transmission structures are uniformly distributed throughout the region, the majority of hardened transmission structures are located near the coast and the two primary Gulf Power Company generation stations: Crist and Smith.

structures to higher wind speeds at landfall and prior to storm attenuation over land. Historical investigation of GPCO transmission structure failures during past storms would have to take place to accurately calibrate this model and infer as to the sources of divergence between these results. However, the more gradual slope of the failure rate curve produced by this analysis seems to indicate a more diverse inventory of transmission tower structure types and materials than the steeper, more homogenous gust response of the data collected by Quanta Technologies.

The overall failure rate presented in Figure 4 falls reasonably within the bounds of hardened and non-hardened transmission structures located along the Gulf Coast of Texas (Brown, 2009). This historical validation against transmission structures of similar design wind loading and wind exposure to recorded storms presents reasonable levels of confidence in the damage simulation results. Unfortunately, we were unable to obtain more recent damage estimates for the area or validate failure rates using Hurricane Michael data due to availability. However, we estimate that the lifespan of transmission towers is such that the 2009 reported data are still valid.

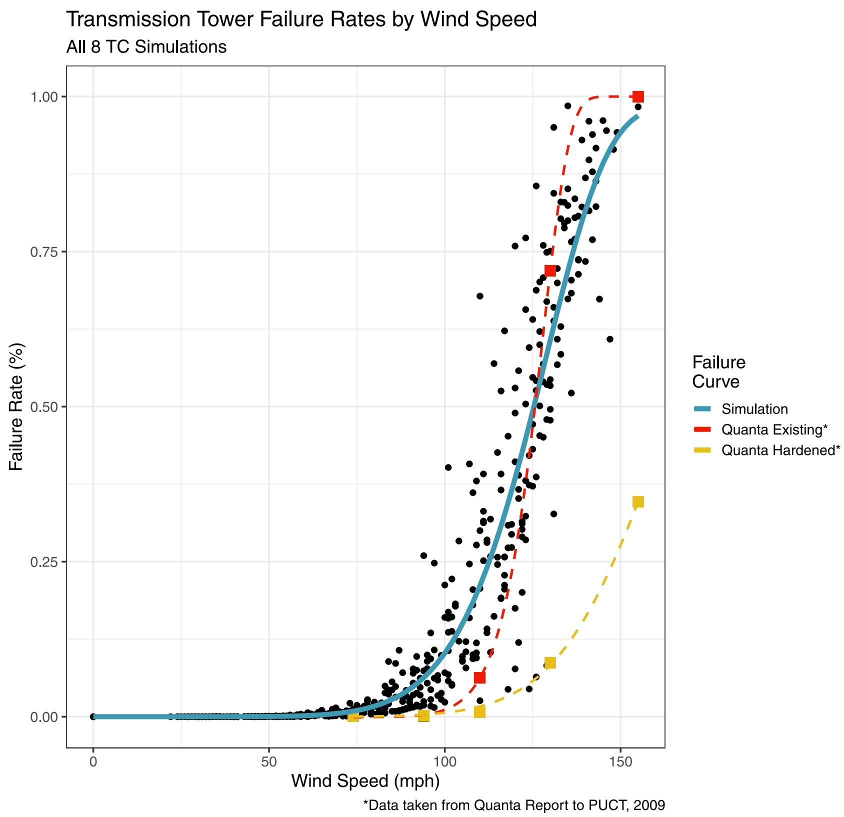

Figure 3. Transmission structures within the study region show less reliability at lower wind speeds and higher reliability at more extreme wind speeds than the transmission structures under investigation in Quanta Technology's report (Brown, 2009).

Following validation of the failure rate, Figure 4 highlights the dependence of transmission structure failures on geospatial characteristics of the storm tract as well as the peak wind speed. Four of the eight scenarios are shown in the figure with the remaining four scenarios in Supporting Information S1 (Figures S7–S14 in Supporting Information S1). The 200-Year Storm has the highest impact on hardened and concrete transmission structures. The tract for this storm brings extreme wind loads in immediate proximity to the Smith Lansing Power Generation Station. As shown in Figure 2, there is a high degree of hardened structures around this power production node. For these reasons, storms bearing characteristics of the 200-Year Storm ought to be planned for in depth, as they pose a very stark threat to the stability of the regional transmission grid during the disruption.

The 500-Year Storm impacts many of the transmission lines bifurcating the Eastern and Western GPCO service areas. This result is visible in the impact to self-supporting and guyed mast lattice structures. The wooden transmission towers throughout Eglin AFB and further North near the state boundary toward Pinckard, AL. The 20-Year Storm, on the other hand, is milder in overall transmission structure failures. However, the lattice towers connecting GPCO to Port St. Joe, similar to Hurricane Michael, can experience a degree of damage during such a storm scenario. The 230 kV transmission lines to Duke Energy Florida in Port St. Joe also serve as an intraregional power transfer line and could separate the GPCO transmission grid from additional power supply in the event of organic generation curtailment.

Table S5 in Supporting Information S1 outlines the transmission structures which have a failure rate greater than 75% across the simulation space (i.e., failed greater than 7,500 times in the 10,000 Monte Carlo Simulations). The 10-, 20- and 50-year storms have a relatively minor impact on the GPCO transmission grid. As the wind speed and storm radius both increases, we see greater impacts to the network. A component-level fragility analysis enables further exploration of transmission network exposure to tropical cyclone events and is critical in quantifying and describing resilience metrics as well as formulating optimal future investment strategies.

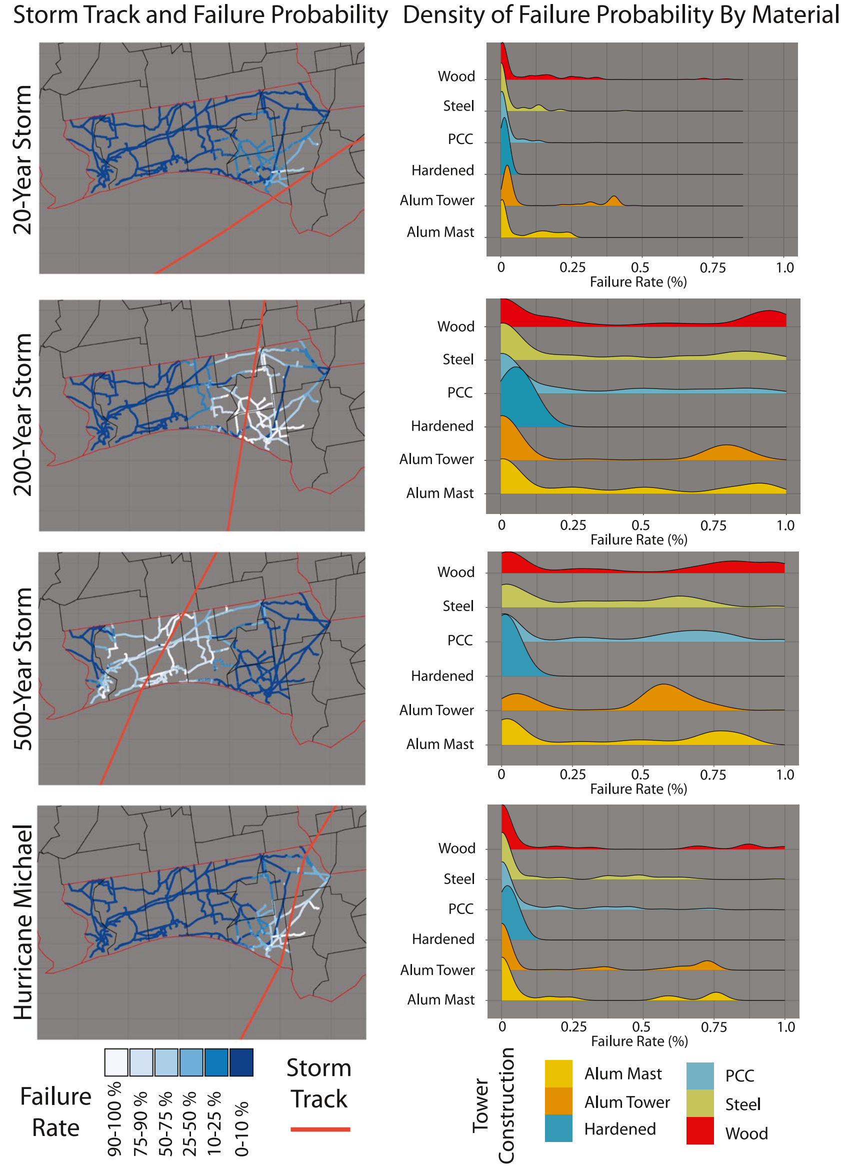

Figure 4. The 200-Year Storm is more destructive to hardened and PCC transmission structures as its path takes it within very close proximity to the Smith Lansing Power Generation Station.

3.3. Analysis of Failure and Inequities

To evaluate the resiliency of the network using its component-level failures, we assess the transmission network using topological metrics and social vulnerability correlations. First, using the perturbed network and two topological indices (efficiency and meshedness), we illustrate the relative impacts of the design storms against the network, Figure 5. Relative to the whole region, Hurricane Michael, which hit on the eastern edge of the region, has similar impacts to the grid as a 50-year design storm. In general, the change in both efficiency and meshedness increases with more intense storms. The exception to this trend is the 200-year design storm, which sees a lower change in meshedness than the 20-, 50-, and 100-year design storms. The evaluation of these topological metrics can be used to further illustrate the impacts of wind events on the topological structure of the network as a surrogate for performance. Robustness strategies for strengthening or replacing transmission towers could be incorporated into these metric assessments to show relative improvements to the grid.

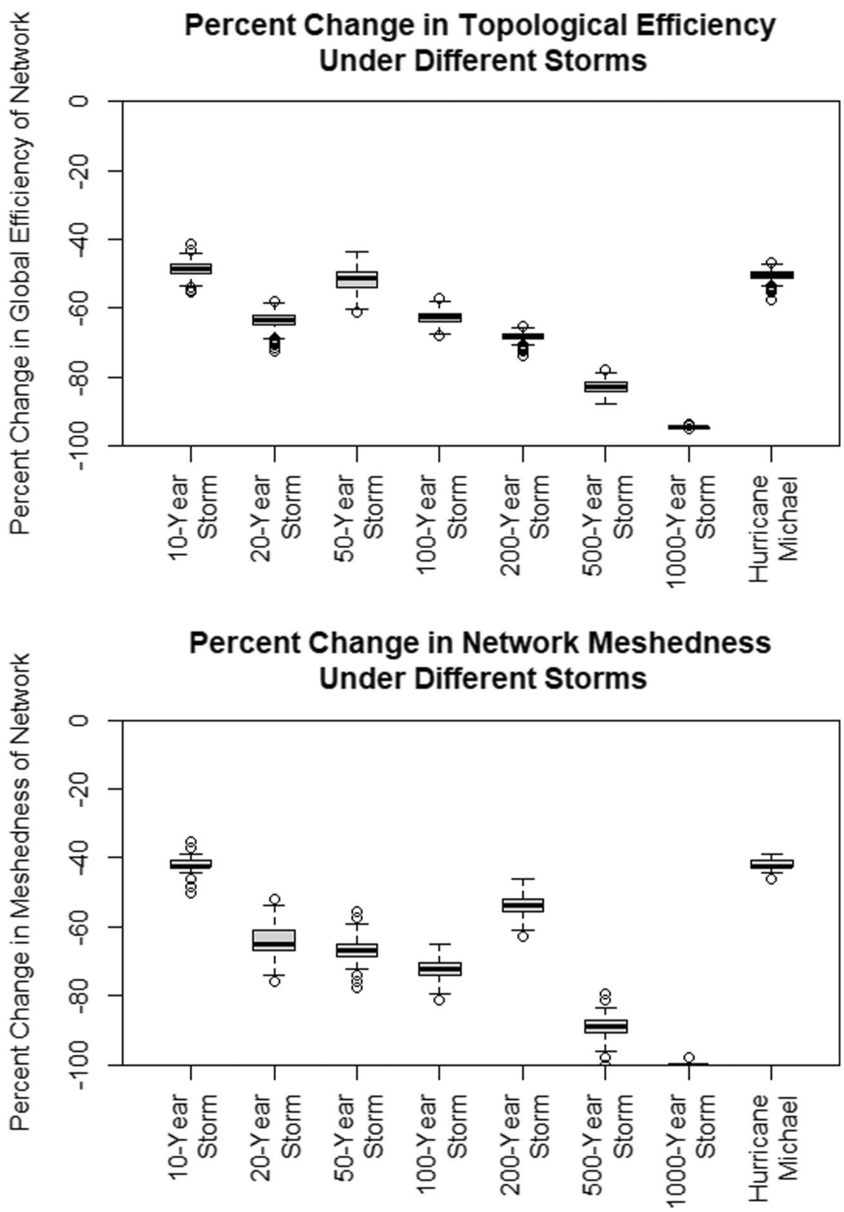

Figure 5. Efficiency and Meshedness experience changes associated with different storm return periods.

4. Discussion

The results of this research highlight current vulnerabilities of the Florida Panhandle transmission grid to wind damage during tropical cyclone events and presents a strategy for model calibration. Additionally, spatially accurate tower location provides actionable insight for targeted hardening and vegetation management programs designed to increase the grid's robustness in the face of threats posed by tropical cyclones.

4.1. Current Transmission Tower Vulnerabilities

Although modern, hardened transmission structures located along the coast offer enhanced robustness to tropical cyclone events, the preponderance of wooden transmission structures throughout the region presents a significant vulnerability. As mentioned previously, this vulnerability increases with time as it is exacerbated by the age-based deterioration of Southern Pine along the ground line of the tower (Salman & Li, 2016). Hardening transmission structures en masse may not, however, be a cost-effective solution to increasing the grid's robustness against wind damage from tropical cyclones. In their 2009 report on the cost-benefit analysis of utility infrastructure upgrades and storm hardening programs, Quanta Technologies calculated the average cost to "harden" a transmission structure from NESC Grade B to the extreme wind loading requirements of ASCE 7-98 at $60,000 per structure (Brown, 2009). This cost, translated to 8,102 wooden transmission structures equates to approximately $486 million for wooden structure upgrades, alone.

A more targeted approach has been prescribed to Florida investor-owned utilities (IOUs) after the 2004–2005 hurricane season (FPSC, 2007). Targeted hardening of transmission support structures includes strengthening those structures which are more likely to fail by means of fiber glass wraps, installation of a push brace below the ground line and extending to third-party attachments, storm guying, more frequent dead-end structures along lines to improve lateral tower support and decreasing span lengths. Additionally, a targeted approach could account for both vulnerability and consequence of failure while enhancing resiliency within the context of equity. The results of this research can offer insight to which lines and towers are optimal candidates for targeted hardening investments and provide a data set to be used in future studies for follow-on resilience analysis. However, the current study is limited by the lack of validation data to understand how the system performs under real-world stress such as Hurricane Michael.

4.2. Historical Storm Data for Model Calibration

The methodology put forth by this research also offers calibration techniques that can more accurately assess the robustness of transmission support structures against wind damage from tropical cyclones. However, this calibration would require more in-depth post storm data collection. Collecting these data may seem an impractical task during hectic post-disaster recovery and restoration efforts, but these types of data are important for assessments of vulnerability and updating of codes, which could yield powerful impacts. Spatial accounting of damaged and failed transmission towers, when coupled with historical hurricane simulations can provide a calibration space for the fragility curves for the different age and material classifications of transmission towers.

The primary focus after every major storm event or natural disaster is rapid recovery and restoration of services to customers in ranked order of criticality. Forensic analysis of the damages inflicted occurs only after restoration efforts have reached a satisfactory culmination. For this reason, forensic analysis of damages incurred to the transmission system are taken after the fact and limited to data from accounting and work management information systems (Brown, 2009).

Florida Public Service Commission (FPSC) regulation passed in 2008 mandates the "Big Five" Florida IOUs to account for transmission system assets using a geographical information system (FPSC, 2007). Tower identification nomenclature, inserted as a parameter for accounting purposes in the event of replacement, can be made to match the tower identification on GPCO and any IOU's database for the towers. With this information and the framework from this research, tower failure rates can be aggregated by type and age. The outcome will produce a set of tower failure rate curves which are, in turn, surrogates for accurate fragility curves of that specific tower type and age.

An accurate, calibrated model enables just-in-time damage estimates from projected tropical cyclones before they make landfall. Using the projected storm track and wind speed simulation function of Hazus allows transmission system operators to estimate component-level damage to the transmission grid based on projected wind speeds and known tower location, material type and age, enabling accurate and more expedient material acquisition and manpower request projections in the wake of a major storm event. Additionally, these estimates can be used as important information for repair crews, streamlining the planning process for repair locations and priorities.

4.3. Limitations

There are multiple, important limitations to the accuracy of this model. First and foremost, there is a lack of viable data to validate the simulated failures. This limitation is significant but is pervasive throughout the literature. We were unable to locate and reliable and robust data set cataloging failed transmission lines or towers in the aftermath of Hurricane Michael in 2018. These data would be incredibly valuable in validating the data set.

Additionally, Hazus-generated probabilistic tropical cyclone simulations are based on a stationary climate. Anthropogenic climate change is already shown to fundamentally challenge the assumptions of climate stationarity based on increasing global temperature and sea surface temperatures. Additionally, the non-stationarity of the climate has been shown to create an increasingly favorable dynamic and thermodynamic environment conducive to hurricane intensification along the US Atlantic coast (Balaguru et al., 2022). Software programs such as the Risk Analysis Framework for Tropical Cyclones (RAFT), currently in development by the Pacific Northwest National Laboratory, offer a means to estimate damages at future time horizons in a nonstationary climate. Using a hybrid model combining physics, statistics, and machine learning, the RAFT model is trained on observations and can accurately simulate salient hurricane features after accepting output from climate models, and can project hurricane risk into future timelines based on divergent greenhouse gas emission scenarios (Balaguru et al., 2021).

Second, there are numerous shortfalls to fragility curves based solely on dynamic structural analysis. Tangential towers will have a different gust response than its angle tower counterpart. Additionally, tower failures are likely influenced by adjacent spans between dual dead-end structure and guying schemes. Granular details of the transmission tower within a more robust database, when tied to failure occurrence from a work management database, can provide historically accurate calibration techniques to overcome inconsistencies in fragility curve selection and implementation.

The data collected regarding the age and material makeup of transmission structures throughout the region of interest is not a static data set. Targeted hardening practices already in progress change the makeup of the grid. In other words, as towers are replaced within the GPCO service territory, the accuracy of the data set used in this research wanes and becomes outdated. Accurate implementation of the model put forth by this research would require access to and continual updates from the owning and operating grid's database. While we preliminary validated the data against GPCO filings and a Quanta report from 2009, we recognize there are still some uncertainties in the data and further failure data sets from the region, particularly Hurricane Michael, would be beneficial in validating and calibrating the data and model further. These updated data would advance efforts to enhance the resilience of the transmission network.

4.4. Future Evaluations

The creation of the data set for the western Florida Panhandle has implications for future research. In this analysis we focus on transmission towers and line segments, reserving a comprehensive, integrated analysis of the data set including substations and generation for future work. Future work could also pair these damage estimates with logged outage data to validate impacts to customers for resilience evaluation (Carrington et al., 2021). A full system analysis would include flooding and wind hazards, addressing substation vulnerability and outages, which is beyond the scope of this investigation.

Alternatively, these component-level data could be paired with socioeconomic data to evaluate the equity in service and resilience efforts. Previous research has identified socioeconomic inequities associated with access and vulnerability of infrastructure, especially when considering intensifying damage events due to climate change (Boyle et al., 2022; Do et al., 2023; Roncancio & Nardocci, 2016). Therefore, in improving the resilience of a network, social vulnerability of the community needs to be considered in where to invest in rehabilitation and replacement of electric grid infrastructure. For example, the Center for Disease Control's (CDC) Agency for Toxic Substances and Disease Registry (CDC/ATSDR) maintains a social vulnerability indicator, defined as the potential negative effects on communities that are caused by external stresses, that is, natural, or human-cause disaster, or disease outbreaks, on human health ("CDC/ATSDR Social Vulnerability Index (SVI)", 2022). CDC/ATSDR social vulnerability indexes are based on four different themes across 15 variables from the United States Census Bureau's data to identify communities that might need assistance before, during, or after a disaster. These variables could be compared to failure rates and infrastructure characteristics at the census tract-level to evaluate equity in resilience efforts.

An initial comparison of failure rates against socioeconomic status shows a positive correlation across all storms with a significance level of 0.05. Regression statistics are provided in Table S6 in Supporting Information S1. Therefore, initial results indicate that communities with a high socioeconomic vulnerability are collocated with transmission infrastructure that is more susceptible to failure. Figure 6 shows three of the simulated storms and their failure rates correlated with social vulnerability spatially and on a scatter plot. Future work can expand upon these analyses to include other factors such as density of infrastructure and land-use to address inequities in robustness and resilience efforts of the infrastructure system.

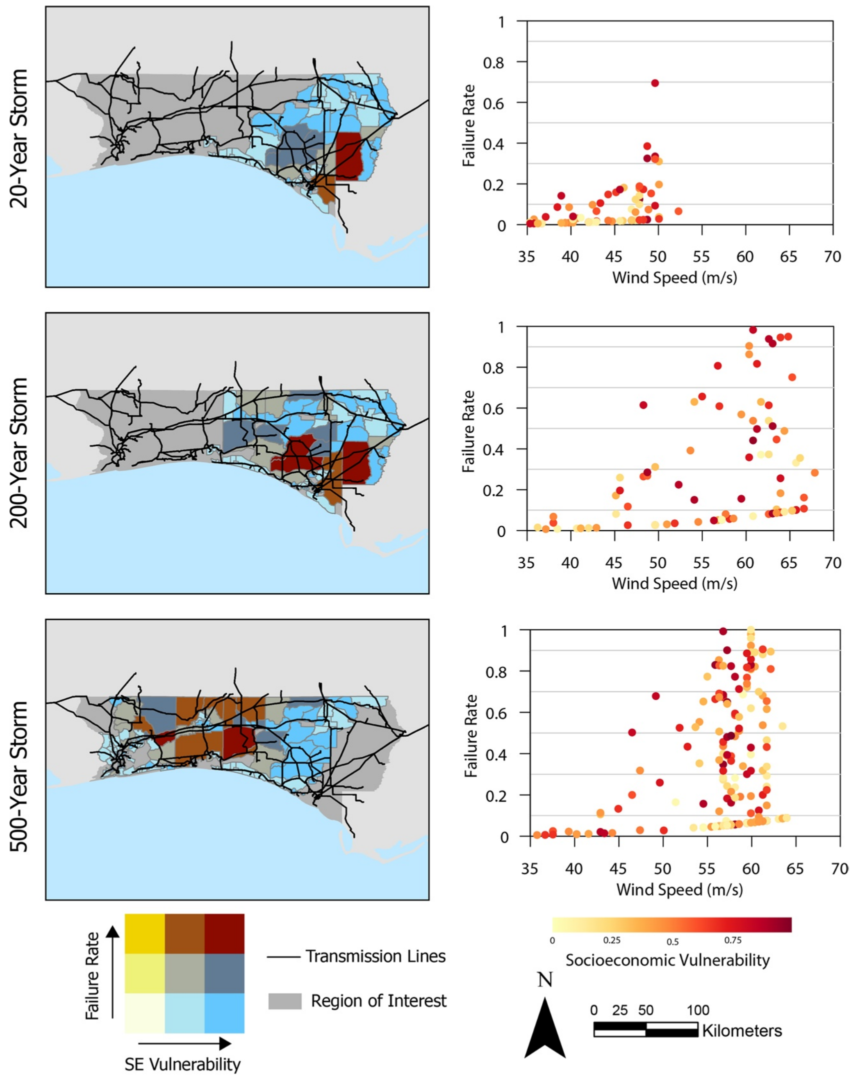

Figure 6. A larger socioeconomic vulnerability is associated with greater failure rates of transmission infrastructure.

5. Conclusions

Storm intensification driven by climate change makes the study of the resilience of electrical transmission networks paramount. The component-level fragility analysis of these networks is foundational to quantifying grid resilience and provides actionable insight to its enhancement. The data presented in this research can be used to make informed, optimal regional transmission planning decisions regarding robustness against extreme wind events. Additionally, this data presents the capability to link overall system performance to component degradation during disruptive tropical cyclone scenarios. Finally, the convergence of these results to other historical studies of transmission tower fragility to extreme winds make it a potentially powerful tool in estimating damage and pre-planning response and recovery operations for tropical cyclones within the service region.

Geospatially accurate, component-level data enable transmission grid planners to make informed decisions regarding investments in targeted hardening of the grid. Coupled with sound asset management principles, grid planners can use these results to prioritize hardening transmission exits from a primary generation station as well as towers highly vulnerable to wind loading. Transmission structures located along vital inter regional power transfer corridors, such as the connection to Duke Energy in Port St Joe can also be hardened to ensure adequate capacity in the event of generation curtailment. Storm guying, fiberglass wrap, push brace installation and third-party hardware management principles can be more effectively leveled across a portfolio of vulnerable transmission towers to efficiently increase overall grid robustness, which can be evaluated using topological metrics.

Finally, the data collected from this research also presents opportunities for future research regarding the resilience of transmission grids subjected to hurricanes including issues of equity of service and resilience in the region. The study identified over 18,000 transmission towers and nearly 200 substations across the western Florida Panhandle. These transmission towers are tied to important information including material, age, and right-of-way. Substations were identified with accompanying laterals and distribution customers to facilitate enhanced, component-level assessments of grid vulnerability and resilience. Component-level data are important in assessing system performance to a variety of disasters and the open-sourcing of these data creates important opportunities in the research space.

Data Availability Statement

The shapefiles of substations, transmission lines, and transmission towers created and simulated in the study are available at Schumann and Chini (2023).

FEMA's Hazus Program utilized in this study is a free GIS-based desktop application available for download (FEMA, 2022). Version 5.1 was used in this research.

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References

Balaguru, K., Foltz, G. R., Leung, L. R., Xu, W., Kim, D., Lopez, H., & West, R. (2022). Increasing hurricane intensification rate near the US Atlantic coast. *Geophysical Research Letters*, *49*(20), e2022GL099793. https://doi.org/10.1029/2022gl099793

Balaguru, K., Xu, W., Judi, D., & Leung, R. (2021). A risk analysis framework for tropical cyclones (RAFT). In *101st American Meteorological Society annual meeting*. AMS.

Banks, J. C., Camp, J. V., & Abkowitz, M. D. (2015). Scale and resolution considerations in the application of HAZUS-MH 2.1 to flood risk assessments. *Natural Hazards Review*, *16*(3), 04014025. https://doi.org/10.1061/(asce)nh.1527-6996.0000160

Bompard, E., Pons, E., & Wu, D. (2012). Extended topological metrics for the analysis of power grid vulnerability. *IEEE Systems Journal*, *6*(3), 481–487. https://doi.org/10.1109/jsyst.2012.2190688

Boyle, E., Inanlouganji, A., Carvalhaes, T., Jevtić, P., Pedrielli, G., & Reddy, T. A. (2022). Social vulnerability and power loss mitigation: A case study of Puerto Rico. *International Journal of Disaster Risk Reduction*, *82*, 103357. https://doi.org/10.1016/j.ijdrr.2022.103357

Braik, A. M. D. (2019). Reliability and cost analysis of power distribution systems subjected to Tornado hazard (Doctoral dissertation), Case Western Reserve University.

Brown, R. E. (2009). *Electric power distribution reliability* (2nd ed.). CRC Press.

Burns, P. O., Barbosa, A. R., Olsen, M. J., & Wang, H. (2021). Multihazard damage and loss assessment of bridges in a highway network subjected to earthquake and tsunami hazards. *Natural Hazards Review*, *22*(2), 05021002. https://doi.org/10.1061/(asce)nh.1527-6996.0000429

Cai, Y., & Wan, J. (2021). Wind-resistant capacity modeling for electric transmission line towers using kriging surrogates and its application to structural fragility. *Applied Sciences*, *11*(11), 4714. https://doi.org/10.3390/app11114714

Carrington, N. L. K., Dobson, I., & Wang, Z. (2021). Transmission grid outage statistics extracted from a web page logging outages in Northeast America. In *North American power symposium*.

CDC/ATSDR Social Vulnerability Index (SVI). (2022). Retrieved from https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

Chalamala, B., Paterson, M., Vournas, C., Van Hertem, D., Beerten, J., Lafitte, J., et al. (2022). *TR-93: Importance of T&D grid modernization to mitigate impacts from and adapt to climate change*. IEEE PES.

Chiu, B., Bose, A., Brown, S., Chalamala, B., Immerman, D., Khodaei, A., et al. (2020). *Resilience framework, methods, and metrics for the electricity sector*. Technical Report PES-TR83. IEEE Power & Energy Society.

Darestani, Y., Padgett, J., & Shafieezadeh, A. (2022). Parametrized wind–surge–wave fragility functions for wood utility poles. *Journal of Structural Engineering*, *148*(6), 04022057. https://doi.org/10.1061/(asce)st.1943-541x.0003319

Do, V., McBrien, H., Flores, N. M., Northrop, A. J., Schlegelmilch, J., Kiang, M. V., & Casey, J. A. (2023). Spatiotemporal distribution of power outages with climate events and social vulnerability in the USA. *Nature Communications*, *14*(1), 2470. https://doi.org/10.1038/s41467-023-38084-6

Du, X., & Hajjar, J. (2022). Electrical transmission and substation structures 2022: Innovating for critical global infrastructure. In *Hurricane fragility analysis of electrical transmission towers* (pp. 348–357). American Society of Civil Engineers.

Fant, C., Boehlert, B., Strzepek, K., Larsen, P., White, A., Gulati, S., et al. (2020). Climate change impacts and costs to US electricity transmission and distribution infrastructure. *Energy*, *195*, 116899. https://doi.org/10.1016/j.energy.2020.116899

FEMA (2022). Hazus hurricane model technical manual. Hazus 5.1. Retrieved from https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals

Florida Department of Environmental Protection (2017). *Statewide land use land cover*. Florida Department of Environmental Protection Geospatial Open Data. Retrieved from https://geodata.dep.state.fl.us/datasets/FDEP::statewide-land-use-land-cover/about

Florida Public Service Commission. (2007). Report on transmission system reliability and response to emergency contingency conditions in the State of Florida. Retrieved from https://www.psc.state.fl.us/infrastructure-storm-hardening

FPSC (2000). Annual reports for Gulf Power Company (EI804). Florida Public Service Commission Annual Utility Reports. Retrieved from https://www.psc.state.fl.us/company-annual-reports?Code=EI804&Name=Gulf%20Power%20Company

Gani, F., Legeron, F., & Ashby, M. (2010). Electrical transmission and substation structures 2009: Technology for the next generation. In *Dynamic wind analyses of transmission line structures* (pp. 1–12).

Gulf Power (GPCO). (2018). *Reliability and storm hardening initiatives report*. Florida Public Service Commission. Retrieved from https://www.psc.state.fl.us/distribution-reliability-reports

Gulf Power (GPCO). (2019a). *Gulf Power Company ten year site plan: For electric generating facilities and associated transmission lines*. Florida Public Service Commission. Retrieved from https://www.floridapsc.com/pscfiles/website-files/PDF/Utilities/Electricgas/TenYearSitePlans//2019/Gulf%20Power.pdf

Gulf Power (GPCO). (2019b). *Reliability and storm hardening initiatives report*. Florida Public Service Commission. Retrieved from https://www.psc.state.fl.us/distribution-reliability-reports

Han, S. R., Rosowsky, D., & Guikema, S. (2014). Integrating models and data to estimate the structural reliability of utility poles during hurricanes. *Risk Analysis*, *34*(6), 1079–1094. https://doi.org/10.1111/risa.12102

HIFLD. (2019). *Substations*. Homeland Infrastructure Foundation-Level Data. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::substations/about

HIFLD. (2022a). *Electric power transmission lines*. Homeland Infrastructure Foundation-Level Data. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::electric-power-transmission-lines/about

HIFLD. (2022b). *Generating units*. Homeland Infrastructure Foundation-Level Data (HIFLD). Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::generating-units/about

Javanbakht, P., & Mohagheghi, S. (2014). A risk-averse security-constrained optimal power flow for a power grid subject to hurricanes. *Electric Power Systems Research*, *116*, 408–418. https://doi.org/10.1016/j.epsr.2014.07.018

Ji, C., Wei, Y., Mei, H., Calzada, J., Carey, M., Church, S., et al. (2016). Large-scale data analysis of power grid resilience across multiple US service regions. *Nature Energy*, *1*(5), 1–8. https://doi.org/10.1038/nenergy.2016.52

Kim, D. H., Eisenberg, D. A., Chun, Y. H., & Park, J. (2017). Network topology and resilience analysis of South Korean power grid. *Physica A: Statistical Mechanics and Its Applications*, *465*, 13–24. https://doi.org/10.1016/j.physa.2016.08.002

Kircher, C. A., Whitman, R. V., & Holmes, W. T. (2006). HAZUS earthquake loss estimation methods. *Natural Hazards Review*, *7*(2), 45–59. https://doi.org/10.1061/(asce)1527-6988(2006)7:2(45)

Kossin, J. P., Knapp, K. R., Vimont, D. J., Murnane, R. J., & Harper, B. A. (2007). A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters*, *34*(4), L04815. https://doi.org/10.1029/2006gl028836

Ma, L., Khazaali, M., & Bocchini, P. (2021). Component-based fragility analysis of transmission towers subjected to hurricane wind load. *Engineering Structures*, *242*, 112586. https://doi.org/10.1016/j.engstruct.2021.112586

Mahzarnia, M., Moghaddam, M. P., Siano, P., & Haghifam, M. R. (2020). A comprehensive assessment of power system resilience to a hurricane using a two-stage analytical approach incorporating risk-based index. *Sustainable Energy Technologies and Assessments*, *42*, 100831. https://doi.org/10.1016/j.seta.2020.100831

National Academies of Sciences, Engineering, and Medicine (NASEM). (2017). *Enhancing the resilience of the nation's electricity system*. The National Academies Press.

Neighbors, C. J., Cochran, E. S., Caras, Y., & Noriega, G. R. (2013). Sensitivity analysis of FEMA HAZUS earthquake model: Case study from King County, Washington. *Natural Hazards Review*, *14*(2), 134–146. https://doi.org/10.1061/(asce)nh.1527-6996.0000089

Ouyang, M., & Duenas-Osorio, L. (2014). Multi-dimensional hurricane resilience assessment of electric power systems. *Structural Safety*, *48*, 15–24. https://doi.org/10.1016/j.strusafe.2014.01.001

Panteli, M., & Mancarella, P. (2015). Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. *IEEE Systems Journal*, *11*(3), 1733–1742. https://doi.org/10.1109/jsyst.2015.2389272

Panteli, M., Mancarella, P., Wilkinson, S., Dawson, R., & Pickering, C. (2015). Assessment of the resilience of transmission networks to extreme wind events. In *2015 IEEE Eindhoven PowerTech* (pp. 1–6). IEEE.

Panteli, M., Pickering, C., Wilkinson, S., Dawson, R., & Mancarella, P. (2016). Power system resilience to extreme weather: Fragility modeling, probabilistic impact assessment, and adaptation measures. *IEEE Transactions on Power Systems*, *32*(5), 3747–3757. https://doi.org/10.1109/tpwrs.2016.2641463

Pei, B., Pang, W., Testik, F., & Ravichandran, N. (2014). Structures congress 2014. In *Regional combined hurricane wind and flood loss estimation-A FEMA HAZUS-MH implementation* (pp. 1359–1370).

Romero, J., & Hall, A. D. (2020). *Resiliency of electric power systems*. Quanta Technology. Retrieved from https://quanta-technology.com/featured_publication/conference-posters-presentations/

Roncancio, D. J., & Nardocci, A. C. (2016). Social vulnerability to natural hazards in São Paulo, Brazil. *Natural Hazards*, *84*(2), 1367–1383. https://doi.org/10.1007/s11069-016-2491-x

Salman, A. M., & Li, Y. (2016). Age-dependent fragility and life-cycle cost analysis of wood and steel power distribution poles subjected to hurricanes. *Structure and Infrastructure Engineering*, *12*(8), 890–903. https://doi.org/10.1080/15732479.2015.1053949

Schauer, B. A., Scawthorn, C., Tertell, P., & Jones, C. (2002). The Hazus flood loss estimation model for characterizing coastal flood hazards and determining losses. *Solutions to Coastal Disasters*, *02*, 178–185.

Scherb, A., Garre, L., & Straub, D. (2019). Evaluating component importance and reliability of power transmission networks subject to windstorms: Methodology and application to the Nordic grid. *Reliability Engineering & System Safety*, *191*, 106517. https://doi.org/10.1016/j.ress.2019.106517

Schumann, & Chini (2023). Western Florida panhandle electric transmission grid substations, lines, and towers [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.7529261

Shafieezadeh, A., Onyewuchi, P. U., Begovic, M. M., & DesRoches, R. (2013). Advances in hurricane engineering: Learning from our past. In *Fragility assessment of wood poles in power distribution networks against extreme wind hazards* (pp. 851–861).

Shaw, A., Lustgarten, A., & Goldsmith, J. W. (2020). New climate map shows a transformed United States. *ProPublica*. Retrieved from https://projects.propublica.org/climate-migration/

Smith, A. B. (2020). *U.S. billion-dollar weather and climate disasters, 1980 - present* (NCEI Accession 0209268). NOAA National Centers for Environmental Information. Dataset.

Teoh, Y. E., Alipour, A., & Cancelli, A. (2019). Probabilistic performance assessment of power distribution infrastructure under wind events. *Engineering Structures*, *197*, 109199. https://doi.org/10.1016/j.engstruct.2019.05.041

US-Canada Power System Outage Task Force. (2006). *Final report on the implementation of the task force recommendations*. Natural Resources Canada and U.S. Department of Energy.

Vickery, P. J., Lin, J., Skerlj, P. F., Twisdale, L. A., Jr., & Huang, K. (2006). HAZUS-MH hurricane model methodology. I: Hurricane hazard, terrain, and wind load modeling. *Natural Hazards Review*, *7*(2), 82–93. https://doi.org/10.1061/(asce)1527-6988(2006)7:2(82)

Vickery, P. J., Skerlj, P. F., Lin, J., Twisdale, L. A., Jr., Young, M. A., & Lavelle, F. M. (2006). HAZUS-MH hurricane model methodology. II: Damage and loss estimation. *Natural Hazards Review*, *7*(2), 94–103. https://doi.org/10.1061/(asce)1527-6988(2006)7:2(94)

Watson, J.-P., Guttromson, R., Silva-Monroy, C., Jeffers, R., Jones, K., Ellison, J., et al. (2015). *Conceptual framework for developing resilience metrics for the electricity, oil, and gas sectors in the United States*. SAND 2014-18019. Sandia National Laboratories.

Willis, H. H., & Loa, K. (2015). *Measuring the resilience of energy distribution systems*. RAND Corporation. Retrieved from https://www.rand.org/pubs/research_reports/RR883.html

Winkler, J., Duenas-Osorio, L., Stein, R., & Subramanian, D. (2010). Performance assessment of topologically diverse power systems subjected to hurricane events. *Reliability Engineering & System Safety*, *95*(4), 323–336. https://doi.org/10.1016/j.ress.2009.11.002

Zhai, C., Chen, T. Y. J., White, A. G., & Guikema, S. D. (2021). Power outage prediction for natural hazards using synthetic power distribution systems. *Reliability Engineering & System Safety*, *208*, 107348. https://doi.org/10.1016/j.ress.2020.107348