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Recent trends in power system reliability and implications for evaluating future investments in resiliency

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ABSTRACT

This study examines the relationship between annual changes in electricity reliability reported by a large cross-section of U.S. electricity distribution utilities over a period of 13 years and a broad set of potential explanatory variables, including weather and utility characteristics. We find statistically significant correlations between the average number of power interruptions experienced annually and above average wind speeds, precipitation, lightning strikes, and a measure of population density: customers per line mile. We also find significant relationships between the average number of minutes of power interruptions experienced and above average wind speeds, precipitation, cooling degree-days, and one strategy used to mitigate the impacts of severe weather: the amount of underground transmission and distribution line miles. Perhaps most importantly, we find a significant time trend of increasing annual average number of minutes of power interruptions over time—especially when interruptions associated with extreme weather are included. The research method described in this analysis can provide a basis for future efforts to project long-term trends in reliability and the associated benefits of strategies to improve grid resiliency to severe weather—both in the U.S. and abroad.

1. Introduction

In the U.S. and abroad, recent catastrophic weather events; existing and prospective government energy and environmental policies; and growing investments in smart grid technologies have drawn renewed attention to ensure the reliability of the electric power system [6,42]. Over the past 15 years, the most well-publicized efforts to assess trends in electric power system reliability have focused only on a subset of all power interruption events [3,8] —namely, the very largest events, which trigger immediate emergency reporting to federal agencies and industry regulators. Anecdotally, these events are believed to represent no more than 10% of the power interruptions experienced annually by electricity consumers. Moreover, a review of these emergency reports has identified shortcomings in relying upon these data as accurate sources for assessing trends, even for the reliability events they target [16].

Recent work has begun to address these limitations by examining trends in reliability data collected annually by electricity distribution companies [13,14]. In principle, all power interruptions experienced by electricity customers, regardless of size, are recorded by the distribution utility. Moreover, distribution utilities have a long history of recording this information, often in response to mandates from state public utility commissions [12]. Thus, studies that rely on reliability data collected by distribution utilities can, in principle, provide a more complete basis upon which to assess trends or changes in reliability over time.

Eto et al. [13,14] was one of the first known studies to apply econometric methods to account for utility-specific differences among electricity reliability reports. This study found that the annual average amount of time and frequency customers are without power had been increasing from 2000 to 2009. In other words, reported reliability was getting worse. However, the Eto et al. [13,14] paper was not able to identify statistically significant factors that were correlated with these trends. The authors suggested that "future studies should examine correlations with more disaggregated measures of weather variability (e.g., lightning strikes and severe storms), other utility characteristics (e.g., the number of rural versus urban customers, the extent to which distribution lines are overhead versus underground), and utility spending on transmission and distribution maintenance and upgrades, including advanced ("smart grid") technologies" [13,14].

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Ahvehag and Söder [2] describe a reliability model that correlate two severe weather metrics (lightning, wind speed) to distribution system failure rates (SAIFI) and restoration times (SAIDI) in Sweden. The aforementioned authors found that the "stochasticity in weather has a great impact on the variance in the reliability indices" [2]; p. 910). However, the Ahvehag and Söder [2] study does not consider other factors, which may contribute to reliability including utility spending and the presence of outage management systems—among other things.

This paper seeks to extend the Eto et al. [13,14] and Ahvehag and Söder [2] analyses along exactly these lines. This paper attempts to identify statistically significant factors, including various aspects of "abnormal weather", but also other utility characteristics, using up to 13 years of information on power interruptions for a large cross-section of U.S. electricity distribution utilities. These utilities, taken together, represent approximately 70% of both total U.S. electricity sales and customers. We also consider the possibility that utility operations and maintenance spending may impact reliability and that weather and reliability have a non-linear relationship. Following Hoen et al. [25]; we employ a sequential modeling approach to ensure model (1) performance; (2) parsimony; and (3) coefficient stability is achieved prior to interpretation.

In this work, we seek to answer the following questions:

Are warmer/cooler, wetter/drier, and/or windier than average years correlated with changes in the annual average number of minutes and/or frequency of power interruptions?

Are the number of customers, annual sales of electricity, share of underground lines, or the presence of outage management systems (OMS) correlated with changes in the annual average number of minutes and/or frequency of power interruptions? Is previous year T&D operations and maintenance (O&M) spending correlated with changes in the annual average number of minutes and/or frequency of power interruptions in the following year?

Are there trends in the annual average number of minutes and/or frequency of power interruptions over time, which we cannot explain by considering the above factors?

Answers to these questions have important implications for efforts to project long-term trends in reliability and the associated benefits of strategies to improve grid resiliency to severe weather—both in the U.S. and abroad.

2. Causes of power outages and data used in this study

2.1. Reported causes of power outages

Utilities in the U.S. publicly report a number of causes associated with increased frequency and duration of outages. This section reviews causes of reliability events as reported by a subset of the U.S. electric utilities evaluated in the broader econometric analysis. The following utility reliability reports were consulted to determine the causes of past reliability events: Florida Public Utilities Company [17]; Rocky Mountain Power [41]; Interstate Power and Light Company [27]; Jersey Central Power & Light [28]; Madison Gas and Electric Company [32]; Pacific Gas & Electric Company [38]; Portland General Electric [39]; PSE&G Services Corporation [40] and AEP Southwestern [1]. Table 1 provides information on the range of categories used by a selected number of utilities introduced above. Weather, equipment failure, human error, vegetation, other/unknown, and wildlife are factors which typically affect the frequency and duration of power interruptions. These causes, which have been documented by the utilities, informed the choice of explanatory variables used in this model of power system reliability.

2.2. Electricity reliability metrics considered in this study

The measures of electricity reliability used in this study are the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI).

SAIDI represents the total minutes that electricity customers, on average, are without power over the course of a year. Equation (1) shows that annual SAIDI for a utility is calculated by summing all annual minutes of customer interruption and dividing this number by the total number of customers served. In this equation, the total number of minutes of each interruption event in a given year is represented by Time_t, the number of customers affected by all interruptions in a given is Affected_t, and the total number of customers served by the utility in a given year is Customers_t.

$$SAIDI_t = \frac{\sum Time_t \times Affected_t}{Customers_t} \tag{1}$$

SAIFI represents the number of times that electricity customers, on average, experiences power interruptions over the course of a year. Equation (2) shows that annual SAIFI for a utility is calculated by summing all annual customer interruptions and dividing this number by the total number of customers served. In this equation, the number of customers affected by an event is Affected_t and the total number of customers served by the utility in a given year is Customers_t.

$$SAIFI_t = \frac{\sum Affected_t}{Customers_t} \tag{2}$$

Some utilities report these metrics with the inclusion of what are known as "major events", which represent times during the year when the utility is subjected to significant, yet generally infrequent stresses, often due to severe weather. The number of major events experienced by a utility in any given year can vary considerably, yet because they are large events they have a disproportionate effect on reported reliability. In order to facilitate year-to-year comparisons of utility reliability performance, SAIDI and SAIFI are often reported without inclusion of the interruptions associated with major events. For more information on major events and how the IEEE defines major events days as well as more information on reliability metrics please refer to the IEEE guideline [26]. Our analysis considered each of the four distinct ways of reporting reliability performance separately. That is, we conducted separate analyses of: (1) SAIDI without major events; (2) SAIDI with major events; (3) SAIFI without major events; and (4) SAIFI with major events.

The primary source for utility-reported reliability performance information was state utility regulatory commissions, because many require the utilities they regulate (generally speaking, these are investor-owned utilities) to report these data, and these commissions typically make this information publicly available [12].[1] In order to collect data on utilities not under the jurisdiction of state utility commissions (e.g., municipal utilities and cooperatives) or when the commissions either do not require or make these data publicly available, we also obtained reliability performance data via online press releases, reports posted by the utility or through direct contact with the utility.

Ultimately, we collected reliability data for 195 different utilities, representing both 70% of total U.S. electricity sales and total U.S. electricity customers. Of these, 152 of the utilities are investor-owned utilities and 43 are either municipals or electricity cooperatives. Fig. 1 shows the geographic coverage of the utilities we

[1] Previous work by Eto and LaCommare reviewed state utility commission reporting practices across the U.S. [12].