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A multi-hazard approach to assess severe weather-induced major power outage risks in the U.S.

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ABSTRACT

Severe weather-induced power outages affect millions of people and cost billions of dollars of economic losses each year. The National Association of Regulatory Utility Commissioners have recently highlighted the importance of building electricity sector's resilience, and thereby enhancing service-security and long-term economic benefits. In this paper, we propose a multi-hazard approach to characterize the key predictors of severe weather-induced sustained power outages. We developed a *two-stage hybrid risk estimation model*, leveraging algorithmic data-mining techniques. We trained our risk models using publicly available information on historical major power outages, socio-economic data, state-level climatological observations, electricity consumption patterns and land-use data. Our results suggest that power outage risk is a function of various factors such as the type of natural hazard, expanse of overhead T&D systems, the extent of state-level rural versus urban areas, and potentially the levels of investments in operations/maintenance activities (e.g., tree-trimming, replacing old equipment, etc.). The proposed framework can help state regulatory commissions make risk-informed resilience investment decisions.

1. Introduction and background

The U.S. electric power infrastructure is a highly complex and geographically extended socio-technical system, with varying degrees of connectivity and redundancy. The reliability and resilience of the electric power infrastructure system is a major concern worldwide, since our modern society is strongly dependent on adequate supply and delivery of electricity for its proper functioning. Due to the large-scale interdependencies between the electric sector and all other critical infrastructure systems in the U.S., disruption in this sector can adversely affect our national security, socio-economic conditions, public health, and the environment. The current U.S. electric power infrastructure is aging, and suffering from chronic under-investments. The existing capacity expansion plans in the electricity sector are not keeping pace with the society's rising demand [1]. On the other hand, under climate change, the frequency and/or intensity of extreme weather and climate events are increasing in many regions of the world [2–12]. Extreme weather and climate events are among the primary causes of infrastructure damage causing large-scale cascading power outages, or shifts in the end-use electricity demands leading to supply inadequacy risks in the United States [12–19]. In fact, the weather and climate related outages have substantially increased over the past two decades [20]. Extreme hydro-climatological hazards such as storms, floods, wildfires, droughts, and heatwaves are imminent risks that can result in cascading outages, either due to physical damage or deviated electricity demand [19,17,21,22]. The extreme-weather induced impacts on the electric power infrastructure can be so severe that service restoration to ex-ante disaster condition might take weeks, months or sometimes even years [23,24]. A recent report by Climate Central (2014) indicated that higher frequency and intensity of severe weather and climate events under climate change will likely increase large-scale power outage risks in the U.S., that can affect millions of people, and cost the economy billions of dollars each year [20].

The large-scale blackouts, such as, (i) the Southwest Blackout in 2011 that left 2.7 million people without power for around 12 h; (ii) the Derecho in 2012 that impacted 4.2 million people across 11 states, and (iii) Super storm Sandy in 2012 that impacted more than 8.5 million people across several northeastern states (e.g., MD, DE, NJ, NY, CT, MA, RI), particularly highlight the extent to which the urban communities are vulnerable to electric power service interruptions [25,26]. Over the

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Nomenclature

Abbreviations

BART	Bayesian Additive Regression Trees
CPI	Consumer Price Index
FERC	Federal Energy Regulatory Commission
FRCC	Florida Reliability Coordinating Council
GWHr	Gigawatt-hour
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
NPCC	Northeast Power Coordinating Council
PDP	Partial Dependence Plot
RF	Random Forest
SPP	Southwest Power Pool, Inc.
SVM	Support Vector Machines
TRE	Texas Reliability Entity
U.S.	United States
USD	United States Dollar ($)
WECC	Western Electricity Coordinating Council

period of 2003–2012, weather-related outages have cost the U.S. economy an inflation-adjusted annual average of $20 billion to $55 billion [27]. The U.S. has experienced 219 billion-dollar severe weather and climate disasters since 1980, total cost of which exceeded $1.5 trillion (as of 2017) [25]. The year 2017 ranked first in terms of witnessing sixteen number of billion-dollar disasters in the U.S. (Fig. 1) [25].

Given the vulnerability of the grid, analyzing and minimizing the severe weather-induced power outage risks and thereby enhancing the resilience of the electric power sector is of utmost importance [28]. However, the federal and state-level risk and reliability metrics/standards for both electricity transmission and distribution (T&D) systems do not internalize the impacts of extreme events on electric power service and have no effective mechanisms for assessing/regulating the levels of preparedness and response during such events [29]. Moreover, while significant research progress has been made in the areas of infrastructure risk and resilience impacted by natural hazards—leveraging different approaches such as simulation, optimization, network theory or empirical analysis—several gaps exist in the body of knowledge and the state-of-the-art practice. Most of the previous research studies have focused on analyzing the impact of a specific type of extreme event on the power infrastructure systems. For example, the performance of electric power systems during and after the impacts of various specific types of storms and hurricanes, and restoration planning in post disaster scenarios have been extensively studied [13,14,30–46]. Researchers have also assessed the impacts of earthquakes on the electric power system in various previous studies [37,47–62]. The impacts of other specific types of severe-weather events such as, thunderstorms, heavy wind and rain storms on the electricity distribution systems have also been assessed [27,63–66]. However, ‘threat-specific’ risk modeling, which is prevalent in today’s society, often overlooks the broader perspectives of multi-hazard risk assessments and can lead to silo’ ed solutions, duplicated efforts and at times, shortsighted mitigation strategies that may render the system more fragile to a wider suite of hazards [67,68]. In most cases, policy review and impact assessments are conducted after a major blackout event. But, monolithic approaches leveraged to study infrastructure risk to a specific type of natural hazard can obscure analysis of longer time-trends and state-level vulnerability patterns; and can lead to myopic policy incentives and suboptimal investment decisions [68].

To address these shortcomings associated with ‘hazard-specific’ risk analysis, we leveraged a data-driven, multi-hazard approach to assess major outage risks in the continental U.S. Using a data-driven hybrid risk modeling approach, we assessed the historical trends and identified the key predictors of the major power outages. Based on the exploratory analysis of nationwide power outage data (explained in Section 2.2), we were motivated to identify the key predictors of single-state, severe-weather triggered major power outages. To that end, we leveraged a two-stage hybrid risk estimation model to: a) predict the intensity of power outages and, b) characterize the underlying risk factors associated with the electricity supply disruptions from the end-user perspective. Although our approach is generalizable to all types of outages of

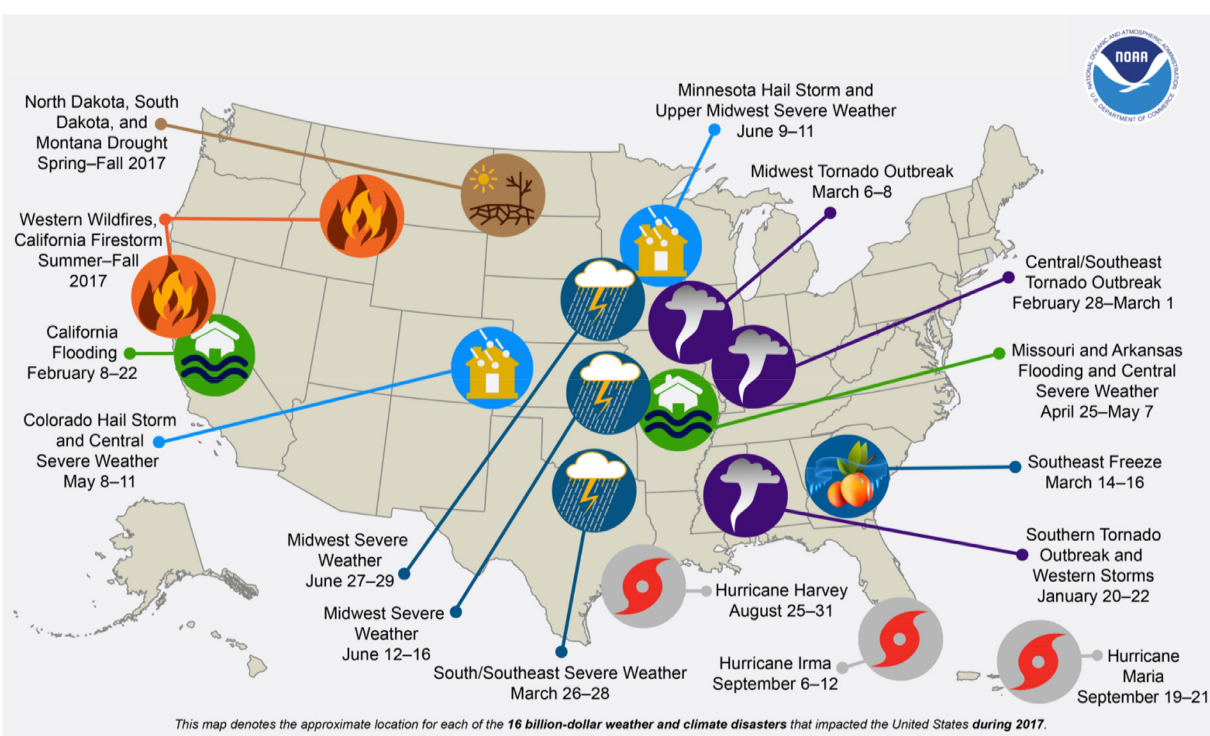

Fig. 1. U.S. 2017 billion-dollar weather and climate disasters [25].