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Environmental determinants of unscheduled residential outages in the electrical power distribution of Phoenix, Arizona

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ABSTRACT

The sustainability of power infrastructures depends on their reliability. One test of the reliability of an infrastructure is its ability to function reliably in extreme environmental conditions. Effective planning for reliable electrical systems requires knowledge of unscheduled outage sources, including environmental and social factors. Despite many studies on the vulnerability of infrastructure systems, the effect of interacting environmental and infrastructural conditions on the reliability of urban residential power distribution remains an understudied problem. We model electric interruptions using outage data between the years of 2002 and 2005 across Phoenix, Arizona. Consistent with perceptions of increased exposure, overhead power lines positively correlate with unscheduled outages indicating underground cables are more resistant to failure. In the presence of overhead lines, the interaction between birds and vegetation as well as proximity to nearest desert areas and lakes are positive driving factors explaining much of the variation in unscheduled outages. Closeness to the nearest arterial road and the interaction between housing square footage and temperature are also significantly positive. A spatial error model was found to provide the best fit to the data. Resultant findings are useful for understanding and improving electrical infrastructure reliability.

1. Introduction

Electrical power is a basic public service. The reliability of electrical power is important because many other infrastructures are directly dependent on it. Power interruptions may, for example, compromise transport and communications systems, and other emergency and security services [1]. Power interruptions are also inconvenient and costly to both commercial and residential consumers, precluding the use of lighting, computers, refrigerators, and HVAC systems among others [2]. A study of expected damage costs in the wake of the major blackout in the Northeastern U.S. and Canada in 2003 identified costs to three categories of consumers: residential, commercial and industrial, and what the authors termed 'wider infrastructure'—the ability of municipal, state and federal authorities to maintain essential public services [3]. The study concluded the costs incurred by residential users accounted for about $1.6 billion per year.

The reliability of power infrastructures is a measure of their capacity to function over the range of expected environmental conditions. Most existing studies of electrical reliability explore cascading blackouts at a national or regional scale. For example, Hines et al. [4] study regional blackouts in the U.S. using the Disturbance Analysis Working Group (DAWG) database from the North American Electrical Reliability Council (NERC) and investigate the different causes of regional blackouts. In this paper we consider a different problem: the role of interactions between distinct environmental and infrastructural conditions in determining the average reliability of the electric power distribution infrastructure. There are many studies on the vulnerability of infrastructures of this type [5,6]. However, the effect of interacting environmental and infrastructural conditions on the reliability of power distribution systems remains under-researched [7–9]. While the impact of individual environmental conditions such as animals, trees, sand/dust, lightning, earthquakes, hurricanes, and ice storms on power reliability has been well documented [10–19], interactions between them have not. Analysis of responses to individual events such as hurricanes provides some insight into the reliability of the electrical distribution system, but unless it controls for the effect of interactions between the event and other environmental conditions, the results may be misleading. In urban areas, for example, outages in residential power frequently occur because of interactions between biophysical, environmental and infrastructural conditions. Storm winds cause vegetation to come into contact with electrical

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distribution lines. Poles, vegetation, and water bodies attract birds that interfere with overhead lines through collision, nesting, excrement, and other activities and so on.

In this paper, we consider the factors that affect residential power reliability in the urban region of Phoenix, Arizona focusing on environmental conditions, the electric power distribution infrastructure, and interactions between the two. We model electric interruptions using outage data for the years 2002–2005 obtained from Arizona Power Supply (APS), a local utility. Estimations were conducted using least squares regression, generalized linear regression, and spatial regression. We consider all unscheduled incidents where voltage falls to zero. These include momentary outages that persist no longer than a few seconds and blackout incidents that persist longer than a few minutes. We focus on the distribution system (the supply system of energy from distribution substations to end users) rather than the transmission system (the supply system of high voltage bulk energy from a generating source to distribution substations) since we are interested in environmental interactions. The electrical distribution system is denser and covers a greater geographical area than the transmission system. It therefore operates within a wider range of environmental conditions, and is more exposed to hazardous environmental events and conditions. It also accounts for most of the interruptions experienced by electricity consumers [7,20]. We consider a number of infrastructural characteristics including feeder type (overhead or underground), age associated with feeder type, closeness to other major infrastructures, together with a number of environmental characteristics such as proximity to desert areas, vegetation, and bird abundance. Our results should be useful for understanding and improving residential electrical infrastructure reliability.

The structure of the paper is as follows. The next section offers a description of the recorded causes of unscheduled outages in the electrical power distribution system. Section 3 details the data and methods used in the analysis. It describes an outage model that is calibrated specifically for Phoenix, Arizona, but is sufficiently general in structure to be applied to other urban areas. Section 4 describes our results. These are then discussed in Section 5. A final section offers our conclusions.

2. Background

Reliability events comprise any deviation from a pure 60-cycle per second alternating current supply, typically at 120 V for residential customers or 480 V for commercial and industrial customers. In practice, however, reliability events at the customer level are taken to be interruptions (incidents where voltage falls to zero) captured in any of the main reliability indices: The System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), or the Momentary Average Interruption Frequency Index (MAIFI) [21]. An interruption is a complete loss of power supply experienced directly by customers. Causes can range anywhere from errors in generation to component failures in the distribution system [22,23]. Interruptions are often caused by outages, or when a component of the electrical infrastructure is not available to perform its function [20,24]. However, outages do not necessarily lead to interruptions experienced by customers [25]. Outages are either scheduled in advance by utility companies or are forced by unscheduled events. In this paper, we only consider unscheduled outages in the distribution system.

Unscheduled power outages are caused by distribution equipment failure induced by factors typically classified as ‘environmental’ or ‘non-environmental’ [7,20]. Non-environmental factors include innate problems in the equipment and its use. Age is a contributing element to electrical equipment failure as with most mechanical equipment [26]. With increasing age, power distribution systems deteriorate becoming more vulnerable to disruption. Overloading distribution lines is another important non-environmental factor causing outages [27]. Power supply lines have limited carrying capacity. When demand exceeds the supply limit, distribution lines overload causing overheating which can lead to sagging, reducing ground clearance, potentially leading to contact with proximal vegetation and intermittent failure. Proper demand forecasting and reliable software support systems help avert problems of overloading. Otherwise, overloading can lead to outages in the distribution system if load shedding is not conducted [28]. Overloading also accelerates insulation age thereby reducing the physical lifespan of the distribution infrastructure [29].

Equipment failure also occurs when deteriorating components interact with adverse ‘environmental’ conditions. These include both environmental events such as electrical, rain, winter, wind or dust storms, and interference by vegetation or animals [20]. Weather-related events such as lightning, extreme temperatures, tornadoes, ice storms, cyclones, and flooding are major contributors to power outages [16,20,30–32]. Fire, especially in the presence of combustible material, can cause electrical faults [33]. High ambient temperatures can reduce distribution efficiency by reducing the transducer’s ability to dissipate heat to the environment [34]. Fire, lightning, or heat waves may exacerbate the heat induced by overloading, exemplifying a potentially important interaction. Overhead distribution components can be affected by lightning primarily through direct flashes and less frequently through indirect flashes [20,35]. In contrast, extremely cold temperatures can lead to icing of distribution components such as insulators and reducing electrical performance [36]. Flooding and ‘water treeing’ (where water penetrates insulation) can short-circuit underground distribution lines while excessive rain may short-circuit overhead lines [37]. Electrical infrastructure can also be impaired depending on its location with respect to an earthquake’s impact radius [19].

Interactions exist between weather events and other environmental conditions. Trees unduly close to overhead lines frequently induce adverse interfaces [38]. A tree outside a right-of-way that can fall within five feet (or about 1.524 m) of a distribution line is considered to be a ‘danger tree’ [39]. The effect of vegetation on power distribution reliability ranges from brief contacts that cause faults by bridging two conductors, to tree fall that brings overhead lines down [40,41]. Growing branches can intrude upon conductors, animals can move branches into conductors, and dead trees can fall interfering with equipment [42]. Tree-to-line contact is most likely to occur if combined with a severe weather event. Tornadoes, hurricanes, and major thunderstorms are accompanied by high wind speeds that cause branches to sway into power lines and, in the worst case, cause trees to fall across lines [43]. In the Northeast U.S., for example, it has been estimated that between 20% and 50% of unscheduled outages are due to vegetation interference with overhead power lines [13].

Other species also come into contact with both overhead and underground power distribution cables, frequently causing interruptions [44]. Squirrels, birds, snakes, rats, mice, gophers, ants, raccoons, and other large animals cause interruptions on a regular basis [10,11,14,20,45,46]. Birds, including raptors (large birds of prey) and other smaller species, are a common cause of ‘animal’ faults on distribution systems, substations, and transmission systems due to nesting, excrement, and other activities [20]. Raptors are attracted to poles that truss overhead lines [47]. Birds in flight can also collide with overhead lines causing bird electrocutions and reduced electrical reliability. Bird electrocutions are most commonly