Energy Research & Social Science 114 (2024) 103573

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

A comparative assessment of household power failure coping strategies in three American cities

Adam X. Andresen [a,b,*], Liza C. Kurtz [c], Paul M. Chakalian [a], David M. Hondula [d], Sara Meerow [d], Melanie Gall [e]

[a] School of Sustainability, Arizona State University, PO Box 877904, Tempe, AZ 85287, United States of America
[b] Joseph R. Biden Jr. School of Public Policy and Administration, University of Delaware, 111 Academy Street, Newark, DE 19716, United States of America
[c] Morrison Institute for Public Policy, Arizona State University, 411 N Central Avenue, Phoenix, AZ 85004, United States of America
[d] School of Geographical Sciences and Urban Planning, Arizona State University, Lattie F. Coor Hall, 975 S Myrtle Avenue, Tempe, AZ 85281, United States of America
[e] Watts College of Public Service and Community Solutions, Arizona State University, 411 N Central Avenue #750, Phoenix, AZ 85004, United States of America

ARTICLE INFO

Keywords:
Power outages
Disasters
Electricity infrastructure
Social vulnerability
Electrical grid failure

ABSTRACT

Household power outage experiences vary based on outage characteristics and the household's ability to cope with a disruption. While disaster management scholarship has produced methods to predict where the most significant impacts of a hazard may occur, these methods do not anticipate secondary effects, such as those from power outages. This research is necessary as the expected risks associated with power outages will increase in the United States due to climate change, increasing electricity demand, and aging infrastructure. To understand households' power outage experiences, we collected 896 surveys from three cities in the United States: Detroit, MI; Miami, FL; and Phoenix, AZ. Participants were recruited through Amazon's Mechanical Turk (MTurk) service to complete a survey. We hypothesized that racial/ethnic minority groups, specifically non-white households and lower-income households experienced more frequent and prolonged power outages. We also hypothesized that the same groups were more likely to have experienced more significant adverse effects, such as throwing away perishable food and not receiving assistance. We found that non-white households in Phoenix and Detroit were more likely to experience longer outages than white households; however, this association was not present in Miami and was not statistically significant in any city. Income was not a major factor in predicting food waste or assistance received during the longest self-reported outage. Further assessments in varying geographical contexts and more generalizable samples are necessary to increase understanding of how households experience power outages.

1. Introduction

Power outages are occurring more frequently [1–4]. Rising global temperatures will increase electricity demand and reduce the efficiency of electrical transmission and distribution infrastructure [5,6]. Reduced transmission efficiency can lead to brownouts and blackouts by reducing the total available electrical supply [7–10]. While anomalous weather conditions, like extreme cold and heat, cause added strain on the electric grid, leading to power outages, these events typically co-occur with natural hazards [11–14]. However, natural hazards are not the only cause; intentional acts are becoming a greater concern. From 2017 to 2022, the number of vandalism-related incidents that caused power outages increased year over year [15]. In 2023, there were multiple terrorist-related incidents of people intentionally sabotaging critical infrastructure, causing widespread power outages [16].

Although power outages are increasing in frequency, most of the existing literature on the effects of electrical infrastructure failures examines these events from a technical perspective [17,18]. Little is known about the societal impacts of power outages at multiple scales, especially at the household level [18]. For example, research has investigated how hazards affect the electric grid [18,19], how cascading effects appear with other infrastructure systems [20,21], and how long-

* Corresponding author at: Joseph R. Biden Jr. School of Public Policy and Administration, University of Delaware, 111 Academy Street, Newark, DE 19716, United States of America.

E-mail addresses: adam.x.andresen@gmail.com (A.X. Andresen), David.Hondula@asu.edu (D.M. Hondula), smeerow@asu.edu (S. Meerow), melanie.gall@asu.edu (M. Gall).

https://doi.org/10.1016/j.erss.2024.103573
Received 13 December 2023; Received in revised form 30 April 2024; Accepted 30 April 2024
Available online 19 May 2024

term stressors, like climate change, affect transmission efficiency [5,7,22–24]. Cascading effects are secondary and tertiary effects that result from a failure in one part of a tightly coupled system; the current electrical infrastructure system within the United States is a prime example of such a system [25–28]. These types of failures may threaten affected households' health and quality of life.

This study advances understanding of how people in different geographical contexts cope with and are affected by power outages. This study examines the likelihood of power outages based on participants' recall of prior outages and the adverse effects they experienced using a household survey deployed in three major cities in the United States: Detroit, MI; Miami, FL; and Phoenix, AZ. Based on the limited existing literature, we tested the following questions and hypotheses:

RQ1: What demographic groups experience more frequent and longer power outages?

H1. : Low-income and minority racial and ethnic groups, specifically non-whites, were more likely to have experienced more frequent and prolonged power outages than high-income groups and whites.

RQ2: What socioeconomic factors are associated with greater adverse effects caused by power outages?

H2. : Low-income households were more likely to have experienced greater negative impacts, such as having to throw food away, and were less likely to receive assistance than higher-income households.

2. Background

We approached the research through a social vulnerability perspective to identify potential factors that can influence someone's power outage experience. We define social vulnerability as the anticipated adverse effects from a hazard that occurs to people and households, partly shaped by demographic characteristics. Social vulnerability indicates that those of lower income and minority racial/ethnic groups are more likely to experience greater impacts from natural hazards due to lack of access to tangible and intangible resources [29–34]. Similar findings have appeared in other research that examines the role of demographics and how they contribute to one's power outage experience [7,34–36]. Because of the similarity, this research examines if previously established characteristics of social vulnerability are as relevant to other hazards and power outages.

While knowledge of the societal impacts of power outages is limited, some existing research approaches this topic from a health perspective [37]. Previous research finds that those with medical conditions are at greater risk because of the inability to plan for treatments during the outage, the need to find alternative treatment sites, or missing treatments altogether [38]. Other adverse effects identified in the literature include carbon monoxide (CO) poisoning [39,40], food poisoning [41,42], lack of access to electrical power medical devices [35,38,43–45], and increased feelings of anxiety during power outages [46–49]. Researchers have shown relationships between demographic characteristics like age, socioeconomic status, race, ethnicity, and an individual's or household's vulnerability to impacts from power outages [7,33]. Minority racial and ethnic groups and those of lower socioeconomic status tend to live in less desirable areas that have older housing and are further from essential services and resources, making them potentially more susceptible to experiencing negative power outage impacts [31,36]. Additionally, lower-income groups are more vulnerable to adverse effects from power outages as they may have to use additional funds to replace spoiled food and are more likely to experience mental health problems [50].

Experiences can also differ by the outage duration. Research in Florida following Hurricane Irma suggests that demographic factors may affect outage experience and duration [7,33]. Mitsova et al. [33] conducted telephone surveys with nearly 1000 participants affected by Hurricane Irma. They found that infrastructure service disruptions, like power outages, were a significant predictor of post-disaster recovery when controlling for race/ethnicity and age. Chakalian et al. [7] conducted semi-structured interviews with people from 42 households affected by Hurricane Irma in two Florida counties and found that older adults are more self-reliant during power outages than previously thought. However, more studies are needed to draw more decisive conclusions about this relationship between outage duration and demographic factors like race and income.

When power outages occur, they disrupt routines and force people to adapt to meet their basic needs, like preventing food from spoiling and supporting their health and well-being. Recent research has shown that the participants' attributes either increase or decrease the likelihood of using an adaptation [33,50]. Using adaptations may also require specialized knowledge to operate. Generators are one example of an adaptation choice available to address these needs, but there are dangers to their improper use. A generator is also expensive to buy, maintain, and operate.

Each person and household must consider their level of risk and decide if they can take the necessary actions to reduce the adverse effects of power outages [52]. Contexts, like geographic location and household makeup, are also critical in determining if someone can mitigate or adapt to potential negative power outage effects [53]. Therefore, more research is needed that focuses on preparations and adaptations for extended power outages and understanding how populations of concern can quickly adapt because of an outage.

3. Case study cities

We surveyed residents from three cities that differ in demographics based on the 2018 American Community Survey (ACS) 5-year estimates [54]. We used the 2018 estimates, as this information was the most recently available when we deployed the survey. Data collection occurred in February and March of 2020, before pandemic-induced lockdowns. As of 2018, the median income was $57,957 in Phoenix, $41,818 in Miami, and $31,283 in Detroit [54]. The sample composition and comparison to the recent ACS estimates are in Table 1.

Each study area has a unique climate. Below is a summary of each study site based on the typical annual weather each city experiences from the Spatial Synoptic Classification (SSC) system [55]. Phoenix is in Region 7 (Sonoran) of the SSC. This climate area experiences the highest number of dry tropical, or hot and dry, weather days, especially during the first half of summer. The summer then transitions to more days of moist tropical or hot and humid weather accompanying the monsoon season. Outside of summer, the area experiences weather classified as dry moderate, with little precipitation and moderate temperatures. Miami is in Region 5 (Tropical), on the southern extreme of the continental United States. This area primarily experiences moist tropical air that dominates the summer months with limited variance during the winter. This region is the only region in the SSC where one weather type includes >50 % of the weather every month of the year. Detroit is part of the Laurentian region (Region 3a) of the SSC and experiences the most variability between the summer and the winter. The city experiences all weather types throughout the summer. Winters typically have drier air masses and limited influence from tropical weather.

4. Methods

4.1. Data collection

Our survey was hosted in Qualtrics and deployed through Amazon's Mechanical Turk (MTurk). MTurk is a crowdsourcing platform that facilitates the completion of a broad suite of tasks by a part of the public that has opted-in to serve as workers. Despite concerns over sample biases, MTurk surveys have become a reputable survey method in the social sciences literature as scholars have proven their utility, accuracy, and internal reliability [56–61]. In the case of survey research, the

Table 1
Comparisons between each of the samples from each city and comparisons to the 2018 ACS estimates.

Demographic	Phoenix Sample (%) (*n* = 412)	2018 ACS Phoenix Estimate (%) (n = 4,561,038)	Miami Sample (%) (*n* = 243)	2018 ACS Miami Estimate (%) (n = 6,019,790)	Detroit Sample (%) (*n* = 251)	2018 ACS Detroit Estimate (%) (n = 4,304,613)
White/Caucasian	70.84	78.2	38.89	70.9	63.85	69.7
Black	5.78	5.3	17.52	21.4	16.15	22.3
Indian	1.2	2.2	3.42	0.2	1.92	0.3
Asian	7.95	3.7	5.98	2.5	5.38	4.1
Native Hawaiian/ Islander	0.48	0.2	0	0	0.38	<0.01
Other	1.92	6.9	3.0	2.9	3.84	1.2
Hispanic	9.16	30.5	33.76	44.2	3.08	4.3
Non-Hispanic	88.92	69.5	64.96	55.8	91.54	95.7

MTurk service enables administrators to deploy surveys electronically and have them completed by MTurk workers, who serve as survey participants, for compensation. There are valid concerns with using MTurk as a recruiting mechanism for survey participants, but they can be addressed. For instance, workers shared that they sometimes engage with other tasks while completing survey work but still produce high-quality results [62]. Many of the concerns that are highlighted predominantly come from experimental research where more attention is needed; in this case, this research is asking about someone's power outage experience, and we received many positive comments from participants indicating that they found the survey interesting, thereby reducing concern around inattentiveness [62].

The survey was sent in two waves, in early February 2020 and again in early March 2020, and participants received compensation for their time. In total, 896 participants across the three cities completed the survey. Based on the population estimates, when data were collected, 385 responses from each city were needed to obtain a 95 % confidence level with a 5 % margin of error with the results. A full version of the survey, with variable coding and labeling schemes, is available in the Supplemental Material.

In line with Chmielewski & Kucker [63], we also deployed mitigation measures to ensure participants provided high-quality data before being paid. Once data collection concluded, we used a two-pronged screening method to examine the data to look for low-quality data and other common issues associated with online surveys. When screening for low-quality data, we first checked how long the participants took to complete the survey. On average, the survey took participants around eight minutes to complete. There was some leniency at this stage of the process where some participants may not have seen all the questions and completed the survey faster than the average. If the time to complete the work task was less than six minutes, the participant was queried within the Qualtrics dataset to determine if they gave low-quality data or forgot to open the MTurk work task before completing the survey. This process was completed at least once per week while the survey was open. Any data considered low-quality because either the responses did not make logical sense or if they completed the survey too quickly had their work rejected and not included in the final dataset. Participants could appeal any rejection decision, and we performed a secondary check to examine their responses.

4.2. Survey structure

To provide insight and transparency into the inclusion criteria for this survey, per Mellis & Bickel [64], participants had to meet three requirements to complete the full survey. First, they had to live within the cities of interest (Phoenix, Miami, or Detroit). A separate MTurk survey task for each state allowed only participants who set their location for each state of interest to see the survey (Arizona, Florida, and Michigan). If they did not select the city of interest for the state, they were taken to a page explaining that they did not qualify for compensation. Second, participants had to previously experience a power outage. For this question, if the participant answered "No" or left the question blank, they were removed from the survey pool. Finally, participants had to reside in their homes for more than half of the year; adding this requirement allowed for screening whether the participant lived in this state as a getaway property and only spent a certain amount of time there. If the participants met all three requirements, they could continue to the rest of the survey.

The second section asked questions about generator ownership, carbon monoxide detector ownership, and maintenance. If they used a generator, other questions were asked about usage, like how far away the generator was operating from the home. The third set of questions only asked about when the most recent power outage occurred and how long it lasted. The fourth section further investigated the household experience during the longest power outage they recalled experiencing and asked how they handled it until power was restored. The last set of questions was about the household makeup, such as whether children or older adults were present in the home and the household's current financial situation.

4.3. Analysis

To test H1, we examined the role of race/ethnicity and income and how these demographic variables (independent variables) are related to power outage frequency and duration (dependent variables). Similarly, H2 tests the relationship between race/ethnicity and income (independent variable) and the likelihood of receiving assistance because of a power outage and throwing away food that spoiled because of a power outage (dependent variables). In addition to these variables, we examined other demographic factors to determine if they were correlated with power outage duration and frequency, like living with children or other adults, relying on an electronic medical device, owning a generator, or struggling to afford food. These independent variables are more broadly associated with greater adverse effects of hazards; thus, we hypothesize that the same variables are correlated with greater impacts caused by power outages [29,65]. Table 2 lists the dependent and independent variables and other potential factors used for this research.

Table 2
A list of dependent variables, independent variables, and mediating factors was analyzed in this study.

Dependent variables	Independent Variables	Mediating Factors
Experienced a power outage	Income	Children in the home
Longest outage length	Racial/ and ethnic background	Older adults in the home
Number of outages		Own a generator
		Own a medical device
		Not receiving help because of a power outage
		Recent outage length
		Thrown food away because of a power outage

The cleaning and analysis R codes are stored in this database [66].

The analysis used a Kruskal-Wallis difference-in-difference test with the demographic variables and outage duration. This test examined the average of a variable between two or more groups to determine if there is a statistically significant difference. Other tests could have been conducted but given that there were multiple choices for some independent variables, the results could have been biased, given the small number of participants within each racial and income group in each city. Because of this issue, race and income were each re-coded into a binary variable. Race was separated from those who identified as white or a minority racial or ethnic group.

Similarly, income was re-coded into a binary household income variable into two categories: less than $60,000 per year and $60,000 or more per year. Since many of the questions in the survey were listed as a binary response (yes/no), difference-in-difference testing was the appropriate analysis method to analyze the data and test the hypotheses. First, we tested if experiencing an outage correlated to the previously mentioned independent variables. Then, we assessed outage frequency and the durations of the most recent and longest outages with the same variables. The selected variables align with previously identified characteristics of social vulnerability and can best determine if a relationship exists between these variables and power outage characteristics [29,65].

5. Results

Results from the survey show a possible relationship between characteristics of social vulnerability and a household's power outage experience. In all three cities, most participants (87.6 %) said in the last five years that they had experienced a power outage. When they did lose power, those who did leave their home often stayed temporarily at a family's, friend's, or neighbor's home that did have power. Access to food became difficult for those in Phoenix and Detroit but not Miami. Few (23.3 %) participants indicated they owned a generator, but those who did bought it because of a prior outage. Concerning the proposed hypotheses for this research, we found some evidence partially supporting the hypotheses, but not in all case study sites.

5.1. Descriptive statistics

Regardless of whether they qualified for the complete survey, most participants reported experiencing a power outage in the last five years (Total 87.6 %, $n = 785$; Phoenix = 83.5 %, $n = 410$; Miami = 89.8 %, $n = 225$; Detroit = 91.5 %, $n = 261$). Participants in all three cities reported experiencing one to five power outages (Phoenix = 77.2 %, Miami = 45.5 %, Detroit = 62.7 %) or five to ten power outages (Phoenix = 16.4 %, Miami = 32.3 %, Detroit = 23.4 %) at their residence within the last five years. The most recent outage length reported by participants from Phoenix and Miami was one to six hours (Phoenix = 53.57 %, Miami = 37.2 %) or less than one hour (Phoenix = 31.3 %, Miami = 20.7 %). Detroit reported slightly longer power outages recently, with more participants reporting their most recent outage lasting one to six hours (39.5 %) or six to twelve hours (17.2 %) (Table 3).

Responses were less similar to the longest reported power outage.

Table 3
Summary statistics on the percentage of participants who experienced a power outage and the most recent outage participants experienced by city.

Variable	Phoenix (%)	Miami (%)	Detroit (%)
Experienced a power outage in the last 5 years	83.5	89.8	91.5
Experienced 1–5 power outages in the last 5 years	77.2	45.5	62.7
Experienced 5–10 power outages in the last 5 years	16.4	32.3	23.4
Most recent outage length: <1 h	31.3	20.7	15.6
Most recent outage length: 1–6 h	53.6	37.2	39.5
Most recent outage length: 6–12 h	11	11.7	17.2

Phoenix participants reported that their most prolonged power outage lasted one to six hours (55.1 %) or less than one hour (17.4 %). Miami also had participants report that their longest outage lasted one to six hours (20 %). However, this city had slightly more participants who indicated that their most prolonged outage lasted three to seven days (21.1 %). Detroit had more participants report their most extended outage times of one to six hours (24.5 %), but more reported outage lengths of one to three days (30.9 %) compared to Phoenix and Miami.

When asked about their experience during their longest reported power outage, participants in all three cities noted they were inside their homes for one to six hours (Phoenix = 57.2 %, Miami = 25.1 %, Detroit = 30 %) (Table 4). Miami participants had also reported being at home for three to seven days (23.0 %). Similarly, Detroit had participants who said they were in their homes for 12 to 24 h and one to three days (21.0 % for each of the two responses) during the outage. Those who left their home went to a family's, friend's, or neighbor's house with power. Others went to a movie theater, mall, or other commercial space (Phoenix = 28.5 %, Miami = 14.1 %, Detroit = 9.6 %) or stayed at a hotel or motel and paid for temporary lodging (Phoenix = 11.2 %, Miami = 14.1 %, Detroit = 14.9 %) (Table 5).

5.2. Power outage effects and coping mechanisms

Access to food and water during a participant's longest reported outage was not difficult for most in Phoenix and Detroit (Phoenix = 75.5 %; Detroit = 63.4 %, see Table 6). However, in Miami, only 40.1 % of participants agreed with this statement. Participants across all three cities showed they had access to water through primary sources, such as taps, sinks, and showers, during their longest reported outage (Phoenix = 78.1 %, Miami = 66.1 %, Detroit = 77.3 %). For those that did lose access to drinking water, participants primarily drank bottled water they already bought before losing power (Phoenix = 62.8 %, Miami = 48.6 %, Detroit = 52.6 %). This finding indicated that household preparedness exists for power outages, given that this choice was either the plurality or majority selection in response to the question about access to drinking water.

Few participants reported owning a generator (Phoenix = 13.3 %, Miami = 40.5 %, Detroit = 25.3 %).[1] Those who reported owning a generator have owned it for at least one year (Phoenix = 86.96 %, Miami = 89.61 %, Detroit = 85.49 %) and perform routine maintenance at least once per year (Phoenix = 37 %, Miami = 46.8 %, Detroit = 42.6 %). Those who owned a generator also reported buying it for future power outages (Phoenix = 71.7 %, Miami =100 %, Detroit = 85.5 %). These results are depicted below in Table 7.

Responses to questions about receiving assistance, owning a medical device, and managing personal conditions were similar across the study cities. Many participants did not receive assistance, whether financial or other tangible resources, such as food and water (Phoenix = 82 %, Miami = 45.8 %, Detroit = 80.7 %). Few participants relied on a medical

Table 4
Breakdown of how long survey participants stayed home during their longest reported power outage.

Variable	Phoenix (%)	Miami (%)	Detroit (%)
Stayed at their home: 1–6 h	57.2	25.1	30
Stayed at their home: 12–24 h	6.3	8.7	21.0
Stayed at their home: 1–3 days	1.5	23	21.0
Stayed at their home: 3–7 days	0.6	23	5.2

[1] The major difference in responses could be because Miami experiences seasonal hurricanes that lead to more prolonged power outages. Thus, residents in Miami are more likely to have resources, like a generator, and are more likely to receive assistance due to damage from hurricanes.

Table 5
Percent of respondents who indicated where they went if they left their home during their longest reported power outage. These percentages are based on those who experienced a power outage.

Variable	Phoenix (%)	Miami (%)	Detroit (%)
During the longest power outage: Went to a family's, friend's, or neighbor's house that had power	46.6	60.3	63.8
During the longest power outage: Went to a movie theater, mall, or other commercial space	28.5	14.1	9.6
During the longest power outage: Stayed at a hotel or motel and paid for temporary lodging	11.2	14.1	14.9

Table 6
Percentage of respondents who indicated access to food and water became difficult during a power outage and what adaptations they used to meet those needs.

Variable	Phoenix (%)	Miami (%)	Detroit (%)
Access to food and water did not become difficult because of a power outage	75.5	40.1	63.4
Could use water from primary sources (i.e., taps, sinks, and showers)	78.1	66.1	77.3
Other sources of water used: Bottled water purchased before losing power	62.8	48.6	52.6
Other sources of water used: Bottled water purchased after losing power	15.7	29.5	25.4
Water provided free from a neighbor, volunteer, or aid or emergency organization	0.9	6.0	0.9

Table 7
Results of generator-related questions. Note: Participants who indicated they owned a generator could only answer the last three rows.

Variable	Phoenix (%)	Miami (%)	Detroit (%)
Not own a generator	85.9 ($n = 347$)	58.4 ($n = 190$)	73.1 ($n = 245$)
Owning a generator (>1 year)	87 ($n = 46$)	89.6 ($n = 77$)	85.5 ($n = 62$)
Perform maintenance at least once per year	56.5 ($n = 46$)	63.6 (n = 77)	55.7 ($n = 61$)
Purchased generator to use for future power outages	71.7 (n = 46)	100 (n = 77)	85.5 (n = 62)

device in all three cities (Phoenix = 6.9 %, Miami = 12.6 %, Detroit = 6.9 %) and did not live with someone who relied on a medical device (Phoenix = 93.1 %, Miami = 80.2 %, Detroit = 92.3 %). Those who relied on a medical device managed their condition differently during their longest power outage across the three cities. Those in Phoenix and Detroit waited for power to be restored (Phoenix = 32.1 %, Detroit = 30 %) or went somewhere with power (Phoenix = 25 %, Detroit = 35 %). In Miami, those who relied on a device primarily asked for help from a friend or relative (31 %) or went somewhere else with power (25 %).

5.3. Testing race and income with outage frequency and duration

A Kruskal-Wallis difference of means test helped determine if a relationship exists between race and income with power outage length and frequency and if the differences between these groups were statistically significant. Each subsection that follows describes the associations that each dependent variable had with independent variables. First, the results from the relationships that tested our hypotheses are detailed. A compilation of all relationships and independent and dependent associations assessed are in Tables 8, 9, and 10.

5.3.1. Experiencing a power outage

This research hypothesized that low-income and minority racial and ethnic households, specifically non-whites, were more likely to have experienced more frequent and longer power outages than high-income and white households. In all three cities, responses showed that lower-income households were more likely to experience a power outage, but no statistically significant relationships emerged. Race/ethnicity was inconsistently correlated with power outage likelihood. In Phoenix, participants had an equal chance of experiencing a power outage, regardless of race/ethnicity. In Miami, racial/ethnic minority groups were more likely to experience a power outage than whites. In Detroit, whites were more likely to experience a power outage than racial/ethnic minority groups. In all cases, these suggestive relationships were not statistically significant. Future studies with larger numbers of participants could help to confirm these results.

5.3.2. Power outage frequency

Income and power outage frequency were also inconsistently correlated by city, with the only statistically significant relationship in Detroit, where lower-income households were more likely to experience more frequent power outages. Equivalent results appeared from Phoenix and Miami participants, but the relationships were not statistically significant. Correlations between race/ethnicity and power outage frequency also showed mixed results. Participants who identified as white from Phoenix and Miami experienced more frequent power outages, while racial/ethnic minority participants in Detroit experienced more frequent outages. The latter relationship was not statistically significant.

5.3.3. Power outage duration

Recent outage length showed significant associations with race and income only in Phoenix. Participants of higher income had a statistically significant relationship with longer outage times during their most recent reported power outage ($p < 0.05$). Minority groups in Phoenix were more likely to experience longer outages recently ($p < 0.01$). In contrast, the opposite was true in Detroit, with white households reporting longer outage times during their most recent outage ($p < 0.001$). In Miami, households of higher income were more likely to experience longer outages during their most recent outage and similar recent outage lengths when compared against race/ethnicity. Neither of these relationships were significant in Miami.

There were similar relationships found between the longest reported outage length and income. In Phoenix, lower-income households reported longer outage times during their longest power outage ($p < 0.05$). Racial/ethnic minority households were also more likely to report longer outage times during their longest reported power outage in Phoenix and Detroit ($p < 0.01$ in Phoenix; $p < 0.001$ in Detroit). The tables below show the results of all tests by city.

5.3.4. Power outage effects

The second hypothesis for this research assessed the relationship between the same independent variables from H1 with specific questions related to measuring adverse power outage effects. Tables 11, 12, and 13 depict the Kruskal-Wallis test results for Phoenix, Miami, and Detroit, respectively.

Not receiving help was more common among those with lower incomes in Miami and Detroit, but it was not statistically significant. Income was not a significant factor in determining who would not receive assistance during a power outage. Not receiving assistance was only significantly associated with race/ethnicity in Miami. Those who identified as a racial/ethnic minority were less likely to receive assistance during their longest power outage. Neither Phoenix nor Detroit had significant associations between race/ethnicity or income and not

Table 8
Results from Kruskal-Wallis tests with variables measuring power outage frequency and duration in Phoenix, AZ (with *p*-values). The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Experience power outage	Longest outage length	Number of Outages	Recent Outage Length
Income	Higher income: 83.7 % Lower income 87.4 % $p = 0.279$	**Higher income: 26.4 % Lower income: 16 %** $\mathbf{p = 0.01}$	Higher income: 4.3 % Lower income: 6.5 % $p = 0.332$	**Higher income: 24 % Lower income: 14 %** $\mathbf{p = 0.01}$
Live with children (< 6 years old)	Yes: 87.1 % No: 85 % $p = 0.620$	Yes: 15.1 % No: 23.2 % $p = 0.093$	Yes: 6.5 % No: 5 % $p = 0.598$	Yes: 13.2 % No: 20.8 % $p = 0.103$
Live with elderly (> 64 years old)	Yes: 85.2 % No: 85.7 % $p = 0.611$	Yes: 17.7 % No: 21.9 % $p = 0.459$	Yes: 9.7 % No: 4.7 % $p = 0.108$	Yes: 16.4 % No: 19.2 % $p = 0.601$
Own/Rent home	Own: 87.4 % Rent: 83.0 % $p = 0.493$	**Own: 17.0 % Rent: 27.3 %** $\mathbf{p = 0.046}$	Own: 6.5 % Rent: 5.0 % $p = 0.327$	Own: 15.5 % Rent: 23.8 % $p = 0.128$
Own generator	Yes: 86.8 % No: 85.2 % $p = 0.758$	Yes: 18.9 % No: 21.9 % $p = 0.62$	**Yes: 18.9 % No: 3.4 %** $\mathbf{p < 0.001}$	Yes: 19.2 % No: 19.3 % $p = 0.996$
Own Medical Device	Yes: 92 % No: 84.5 % $p = 0.309$	Yes: 8 % No: 19.3 % $p = 0.161$	**Yes: 20 % No: 4.6 %** $\mathbf{p = 0.001}$	Yes: 12 % No: 17.1 % $p = 0.508$
Race/Ethnicity	Minority: 84.8 % White: 85.8 % $p = 0.817$	**Minority: 29.7 % White: 17.9 %** $\mathbf{p = 0.009}$	Minority: 5 % White: 5.5 % $p = 0.853$	**Minority: 27.7 % White: 15.6 %** $\mathbf{p = 0.005}$
Struggle to afford food	Yes: 81.1 % No: 87.9 % $p = 0.065$	Yes: 24.7 % No: 19.5 % $p = 0.22$	Yes: 6.2 % No: 4.9 % $p = 0.594$	Yes: 22.9 % No: 17 % $p = 0.15$

receiving assistance during the longest reported outage. There were also no significant associations between income and receiving assistance during the longest power outage in any of the three study cities.

Having thrown away food because of a power outage was only associated with race and income in Detroit. Those in lower income groups had thrown away food more often because of an outage than those of higher income. Racial/ethnic minorities were more likely to report throwing away food because of a power outage in all three study sites, but this relationship was only significant in Detroit. No significant associations emerged between race/ethnicity, income, and discarding food in Phoenix and Miami.

6. Discussion

Overall, we did not find strong support for either of our hypotheses. Our first hypothesis for this research was that racial/ethnic minority households were more likely to experience longer and more frequent power outages. Race/ethnicity was associated with greater power outage duration in Phoenix and Detroit. This effect was not significant in Miami. Thus, H1 was only partially supported. The second hypothesis was that households of lower income and racial/ethnic minorities were more likely to experience greater economic impacts, like throwing food away or not receiving assistance. Income and race/ethnicity were not strongly associated with these variables, so the results did not support H2. The results suggest that income and race/ethnicity may not be as strong as anticipated predictors when examining power outage impacts.

Table 9
Results from Kruskal-Wallis tests with variables measuring power outage frequency and duration in Miami, FL (with *p*-values). The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Experience power outage	Longest outage length	Number of Outages	Recent Outage Length
Income	Higher income: 84.8 % Lower income: 87.8 % $p = 0.523$	Higher income: 59.6 % Lower income: 54 % $p = 0.077$	Higher income: 17.2 % Lower income: 18.3 % $p = 0.833$	Higher income: 39.4 % Lower income: 34.2 % $p = 0.416$
Live with children (< 6 years old)	Yes: 79.6 % No: 88.7 % $p = 0.091$	Yes: 48.1 % No: 62.4 % $p = 0.065$	Yes: 14.8 % No: 18.9 % $p = 0.493$	Yes: 40.7 % No: 33.3 % $p = 0.322$
Live with elderly (> 64 years old)	Yes: 83.3 % No: 87.4 % $p = 0.835$	Yes: 65 % No: 57.1 % $p = 0.291$	Yes: 20.3 % No: 16.8 % $p = 0.540$	Yes: 41.4 % No: 32.9 % $p = 0.248$
Own/Rent home	Own: 85 % Rent: 86.5 % $p = 0.416$	Own: 58.8 % Rent: 55.4 % $p = 0.324$	**Own: 20.8 % Rent: 12.1 %** $\mathbf{p = 0.031}$	Own: 37.3 % Rent: 32.6 % $p = 0.776$
Own generator	Yes: 84.6 % No: 87.6 % $p = 0.527$	Yes: 59.8 % No: 59.2 % $p = 0.934$	Yes: 23.1 % No: 14.6 % $p = 0.109$	Yes: 36.3 % No: 34.9 % $p = 0.833$
Own medical device	Yes: 79.3 % No: 86.8 % $p = 0.284$	Yes: 41.4 % No: 59.8 % $p = 0.063$	Yes: 20.7 % No: 16.8 % $p = 0.613$	Yes: 28.6 % No: 35 % $p = 0.473$
Race/Ethnicity	Minority: 86.9 % White: 85.9 % $p = 0.836$	Minority: 60.1 % White: 57 % $p = 0.64$	Minority: 17.4 % White: 18.8 % $p = 0.787$	Minority: 35 % White: 35.3 % $p = 0.969$
Struggle to afford food	Yes: 87.1 % No: 85.9 % $p = 0.804$	Yes: 55.6 % No: 61.1 % $p = 0.435$	Yes: 19.7 % No: 16.8 % $p = 0.594$	Yes: 34.3 % No: 35.6 % $p = 0.853$

Table 10
Results from Kruskal-Wallis tests with variables measuring power outage frequency and duration in Detroit, MI (with *p*-values). The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Experience power outage	Longest outage length	Number of Outages	Recent Outage Length
Income	Higher income: 93.1 % Lower income: 94.8 % $p = 0.565$	Higher income: 46.2 % Lower income: 47.4 % p = 0.853	**Higher income: 8.4 %** **Lower income: 17.2 %** $\boldsymbol{p = 0.032}$	Higher income: 25 % Lower income: 24.1 % $p = 0.873$
Live with children (< 6 years old)	Yes: 93.8 % No: 93.9 % $p = 0.993$	Yes: 41.5 % No: 48.5 % $p = 0.334$	Yes: 9.2 % No: 13.4 % $p = 0.377$	Yes: 23.1 % No: 25.1 % $p = 0.740$
Live with elderly (> 64 years old)	Yes: 100 % No: 92.9 % $p = 0.090$	Yes: 36.4 % No: 48.2 % $p = 0.204$	Yes: 12.1 % No: 12.1 % $p = 0.991$	Yes: 18.2 % No: 25.8 % $p = 0.346$
Own/Rent home	Own: 95.9 % Rent: 89.2 % $p = 0.131$	Own: 44.7 % Rent: 47.9 % $p = 0.328$	Own: 14.1 % Rent: 6.76 % $p = 0.239$	**Own: 19.9 %** **Rent: 34.2 %** $\boldsymbol{p = 0.045}$
Own generator	Yes: 96.9 % No: 92.7 % $p = 0.237$	Yes: 57.1 % No: 43.8 % $p = 0.065$	Yes: 19 % No: 9.9 % $p = 0.054$	Yes: 20.3 % No: 26 % $p = 0.358$
Own Medical Device	Yes: 94.1 % No: 93.9 % $p = 0.969$	Yes: 35.3 % No: 44.9 % $p = 0.441$	Yes: 23.5 % No: 11.5 % $p = 0.144$	Yes: 11.8 % No: 23.7 % $p = 0.260$
Race/Ethnicity	Minority: 91.6 % White: 95.2 % $p = 0.244$	**Minority: 58.1 %** **White: 40.4 %** $\boldsymbol{p = 0.006}$	Minority: 13.8 % White: 11.5 % $p = 0.587$	**Minority: 36.2 %** **White: 18.1 %** $\boldsymbol{p = 0.001}$
Struggle to afford food	Yes: 96.8 % No: 92.2 % $p = 0.135$	Yes: 51.6 % No: 44.2 % $p = 0.256$	**Yes: 20.4 %** **No: 7.9 %** $\boldsymbol{p = 0.003}$	Yes: 26.6 % No: 23.5 % $p = 0.578$

The findings here contradict earlier work where racial/ethnic minority groups and lower-income neighborhoods experienced more frequent power outages [4]. However, we also recognize the study's sample size and geographic limitations.

Some findings were not significant and call for further discussion. Two tests returned interesting results related to characteristics of greater vulnerability that were not a part of the tested hypotheses. Struggling to afford food and lower-income households were associated with a greater likelihood of experiencing a power outage. These tests did not have consistent significance levels across the study sites, but this relationship shows the potential for these variables to predict the likelihood of experiencing an outage [4,33]. Additionally, owning a medical device was associated with greater power outage frequency across the dataset. Despite the lack of significance, this relationship demonstrates that a key group identified as vulnerable in the hazards literature is more prone to negative power outage effects and is more likely to experience longer outages [17]. There is the possibility that this group may have recall bias as people who do rely on medical devices are more likely to notice and remember that outages occur. Increased power outages increase the likelihood that people relying on electronic medical devices will have to relocate or visit an emergency room to access electricity and use their devices.

Table 11
Results from Kruskal-Wallis tests with not receiving help and throwing food away during a power outage from Phoenix, AZ. The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Not receiving help	Thrown food away
Income	Higher income: 78 % Lower income: 77.6 % $p = 0.927$	Higher income: 34.5 % Lower income: 31.8 % $p = 0.286$
Live with children (<6 years old)	Yes: 76.3 % No: 78.2 % $p = 0.7$	**Yes: 50.6 %** **No: 27.8 %** $\boldsymbol{p = 0.00014}$
Live with older adults (>64 years old)	Yes: 75.8 % No: 78.7 % $p = 0.601$	Yes: 37.3 % No: 31.7 % $p = 0.438$
Own/Rent	Own: 78.9 % Rent: 75.2 % $p = 0.366$	Own: 32.6 % Rent: 35.6 % $p = 0.717$
Race/Ethnicity	Minority: 74.1 % White: 79 % $p = 0.288$	Minority: 40.2 % White: 30.5 % $p = 0.091$
Struggle to afford food	**Yes: 70.5 %** **No: 81.8 %** $\boldsymbol{p = 0.009}$	**Yes: 42.2 %** **No: 28.5 %** $\boldsymbol{p = 0.011}$

The findings from the survey provide two critical considerations for future research. First, this research found preliminary evidence that suggests impacts and adaptations to power outages may not always follow the demographic patterns found in other hazards studies. Instead, impacts from power outages may be structured by other factors. Second, if generic social vulnerability indices will help identify those most likely to experience more significant adverse effects, doing so may be problematic [67]. The findings here indicated a mixed relationship between traditional indicators of greater adverse effects and, in some cases, found the opposite relationship, although not always statistically significant. More research is needed to examine these patterns across space and time to make general policy recommendations.

Additionally, some findings about the distribution of outages and their impacts that appeared mixed in this study or were not investigated should be explored in future research. One is the age of the infrastructure, with older infrastructure potentially being more susceptible to extreme weather events, as age can affect an electric grid's reliability [18]. Another reason could be the physical attributes of the neighborhoods where participants live. For instance, areas with more trees, especially in more affluent neighborhoods, may increase the risk of power outages [68]. While there are conclusions that can be drawn from this work, there are limitations in generalizing to broader geographical contexts when studying the effects of power outages at larger scales of analysis. When preparing for hazards that can lead to extended power outages, the same indicators that are used to identify where the greatest impacts caused by natural hazards are not necessarily the same indicators that should be used when identifying who will be the most affected by power outages. However, when considering the secondary impacts of natural hazards, our research suggests that further inquiries are needed to determine if social vulnerability indicators can help explain why specific populations experienced longer and more frequent power outages.

While this research helps to fill a gap in the societal effects of power outage research, there are many opportunities to expand this work.

Table 12
Results from Kruskal-Wallis tests with not receiving help and throwing food away during a power outage from Miami, FL. The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Not receiving help	Thrown food away
Income	Higher income: 58.6 % Lower income: 54.8 % $p = 0.567$	Higher income: 67.1 % Lower income: 68.9 % $p = 0.792$
Live with children (< 6 years old)	**Yes: 40.7 %** **No: 61.4 %** $\boldsymbol{p = 0.008}$	Yes: 76.9 % No: 65.7 % $p = 0.185$
Live with elderly (> 64 years old)	Yes: 50 % No: 58.6 % $p = 0.25$	Yes: 75 % No: 65.2 % $p = 0.212$
Own/Rent	Own: 59.2 % Rent: 48.9 % $p = 0.097$	Own: 69.1 % Rent: 65.3 % $p = 0.287$
Race/Ethnicity	**Minority: 61:6 %** **White: 47.7 %** $\boldsymbol{p = 0.042}$	Minority: 64.9 % White: 72.9 % $p = 0.263$
Struggle to afford food	Yes: 50 % No: 58.7 % $p = 0.225$	Yes: 73.3 % No: 65.8 % $p = 0.309$

Table 13
Results from Kruskal-Wallis tests with not receiving help and throwing food away in from Detroit, MI. The percentages represent the effect sizes used to determine the statistical relationships between the two groups. Any bold entry indicates a statistically significant result.

	Not receiving help	Thrown food away
Income	Higher income: 86.2 % Lower income: 81.9 % $p = 0.343$	**Higher income: 52.3 %** **Lower income: 66.7 %** $\boldsymbol{p = 0.026}$
Live with children (<6 years old)	Yes: 80 % No: 85.7 % $p = 0.274$	**Yes: 43.1 %** **No: 64 %** $\boldsymbol{p = 0.005}$
Live with older adults (>64 years old)	Yes: 78.8 % No: 85.8 % $p = 0.291$	Yes: 71.9 % No: 56.7 % $p = 0.105$
Own/Rent	Own: 85.4 % Rent: 79.7 % $p = 0.413$	Own: 58.0 % Rent: 63.6 % $p = 0.476$
Race/Ethnicity	Minority: 80 % White: 86.7 % $p = 0.157$	**Minority: 73.4 %** **White: 51.3 %** $\boldsymbol{p = 0.001}$
Struggle to afford food	Yes: 79.8 % No: 86.7 % $p = 0.140$	**Yes: 74.4 %** **No: 49.7 %** $\boldsymbol{p = 0.0002}$

Future work could augment this research by examining the spatial relationships of participants to sites that are high restoration priority, such as critical services (e.g., hospitals, police, and fire departments), to determine if living near these sites influences the length and frequency of power outages. Work could also expand on how living in rural, suburban, or urban areas affects power restoration times. Previous research suggests that rural areas are more likely to experience longer outages and restoration times because of the electrical infrastructure's more isolated nature than urbanized areas [69,70]. Future research could examine whether a male or female head of household or various family structures is related to power outage experiences and impacts. Existing studies show that women are at greater risk of experiencing negative outcomes from disasters and, subsequently, are more susceptible to the effects of power outages [29,71]. Our survey did not ask for the participants' gender identity as the focus was on power outage effects on the household. Lastly, future research should consider a qualitative approach that uses focus groups and interviews to investigate how people experience power outages and analyze the impacts people experience, how power outages affect their mental health, and what resources were used to adapt until power was restored.

Limitations with this work came from sample sizes and the sample composition from each city. While there was enough support in Phoenix because the sample met the requirement for achieving a 95 % confidence level with a 5 % margin of error, the other sites did not. Future research should examine these issues using larger representative samples, so the results are generalizable to the populations they are investigating. Because of the small sample size in this study, statistical significance was difficult to realize for some components of the analysis where there were few respondents. For instance, people who did not own a generator were not asked how often they perform maintenance on their generator or if they bought it because of a power outage; this question was only asked to generator owners, which was a small part of the sample. There are also concerns surrounding recall bias, given that we asked people to remember a power outage experience that may have occurred many years ago, and their memory could be skewed when remembering how long they were without power. Future research should consider survey deployments that capture information about recent events while the memories are fresh in participants' minds.

Given the timing the survey was deployed, more responses could have been collected. However, as the public health lockdowns began in mid-March of 2020, the team agreed that the data collection had to stop. Doing so could have introduced several factors that could not be controlled within the survey responses, which were new and novel so no prior experience could guide decision-making.

There are mitigation measures that future studies should implement to enhance data reliability if researchers plan to use MTurk as a data collection method. First, following the protocol mentioned in Chmielewski et al. [63], we conducted a thorough screening of the initial results when approving MTurk worker tasks to check for low-quality data. We took further steps to ensure we collected high-quality data, which future studies can employ, including targeting a specific state through MTurk and within the survey and being more specific with the location of interest by providing options for what major city the participant lives closest to. If the participant does not choose the city of interest, they are removed from the survey. While workers were upset by being suddenly removed from the survey, and thus compensation, this mitigation measure helps ensure high-quality data from workers. Additionally, a secondary measure of seeing how long a participant completed the survey can check if the participant forgot to open the MTurk task before starting the survey. This measure can also confirm if the participant sped through the survey to earn the compensation or if the participant did not open the task when they started the survey.

7. Conclusions

In this work, we surveyed 896 participants in three major cities across the United States (Detroit, MI; Miami, FL; Phoenix, AZ) to understand household experiences during power outages and what factors influence the frequency, duration, and impacts of power outages. The hypotheses for this research were that participants of racial/ethnic minorities and lower income were more likely to experience more frequent and longer power outages and greater adverse effects because of a power outage. Race/ethnicity was associated with a few of the dependent variables in Phoenix and Detroit and partially supported the first hypothesis. Also, income and race/ethnicity were not as strongly associated with outage-related variables as initially hypothesized. The only significant relationships that emerged were that racial/ethnic minority groups were more likely to not receive help in Miami and were more likely to have thrown food away in Detroit. Also, those of lower income from Detroit, were more likely to have thrown food away that spoiled because of a power outage, unlike those from higher incomes. Because of the evidence collected here, we recommend further research establish a more robust empirical basis for understanding who is at greater risk of experiencing adverse effects from power outages.

The future climate will pose many issues for the physical infrastructure and people. Electricity demand will increase given the expected increase in global temperatures and the growing population, specifically in the United States. While adaptations are necessary to reduce these impacts, people will be affected by any highly interdependent electrical grid system failures. Investments are needed to increase the robustness of electrical infrastructure so that the number of future electrical disturbances may be reduced, and the cascading effects are less crippling from future failures.

CRediT authorship contribution statement

Adam X. Andresen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Liza C. Kurtz:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Paul M. Chakalian:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **David M. Hondula:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sara Meerow:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation. **Melanie Gall:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the Urban Resilience to Extreme Events (UREx) office at Arizona State University for their financial support of this work through the Graduate Research Grant and the Graduate and Professional Student Association at Arizona State University for their financial support of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103573.

References

[1] J.A. Casey, M. Fukurai, D. Hernández, et al., Power outages and community health: a narrative review, Curr Envir Health Rpt 7 (2020) 371–383, https://doi.org/10.1007/s40572-020-00295-0.

[2] U.S. Energy Information Administration. Peak hourly U.S. electricity demand in July was the second highest since 2016. 2023. Available from: https://www.eia.gov/todayinenergy/detail.php?id=60602#. Accessed 4 December 2023.

[3] A. Kenward, U. Raja, Blackout: Extreme Weather, Climate Change, and Power Outages, Princeton, 2014.

[4] P.J. Marcotullio, O. Braçe, K. Lane, C.E. Olson, J. Tipaldo, J. Ventrella, T. Matte, Local power outages, heat, and community characteristics in new York City, Sustain. Cities Soc. 99 (2023) 104932.

[5] N.L. Miller, K. Hayhoe, J. Jin, M. Auffhammer, "Climate, extreme heat, and electricity demand in Californ"a, J. Appl. Meteorol. Climatol. 47 (6) (2008) 1834–1844, https://doi.org/10.1175/2007JAMC1480.1.

[6] Sathaye, J., Dale, L., Larsen, P., & Al., E. (2012). Estimating risk to california energy infrastructure from projected climate change. In *Climate Change*. https://escholarship.org/uc/item/17582969.

[7] P.M. Chakalian, L.C. Kurtz, D.M. Hondula, After the lights go out: household resilience to electrical grid failure following hurricane Irma, Am. Soc. Civil Eng. 20 (4) (2019) 1–14, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000335.

[8] M.T.H. Van Vliet, J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, P. Kabat, Vulnerability of U.S. and European electricity supply to climate change, Nature Climate Change 2 (9) (2012) 676–681, https://doi.org/10.1038/nclimate1546.

[9] M.D. Bartos, M.V. Chester, Impacts of climate change on electric power supply in the Western United States, Nat. Clim. Chang. 5 (8) (2015) 748–752, https://doi.org/10.1038/n climate2648.

[10] Feng, K., Min, O., & Lin, N. (2020). Hurricane-blackout-heatwave compound hazard risk and resilience in a changing climate. *arXiv preprint arXiv:2012.04452*.

[11] H. Ren, Z.J. Hou, X. Ke, Q. Huang, Y. Makatov, Analysis of weather and climate extremes impact on power system outage, in: IEEE Power and Energy Society General Meeting, 2021, https://doi.org/10.1109/PESGM46819.2021.9637938, 2021-July, 11–15.

[12] S.A. Shield, S.M. Quiring, J.V. Pino, K. Buckstaff, Major impacts of weather events on the electrical power delivery system in the United States, Energy 218 (2021) 1–12.

[13] B. Stone, E. Mallen, M. Rajput, A. Broadbent, E.S. Krayenhoff, G. Augenbroe, M. Georgescu, Climate change and infrastructure risk: indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona, Urban Clim. 36 (October 2020) (2021) 100787, https://doi.org/10.1016/j.uclim.2021.100787.

[14] Y. Wang, J. Wu, H. Yi, Analysis on several blackouts caused by extreme weather and its enlightenment, IOP Conference Series: Earth and Environmental Science 766 (1) (2021), https://doi.org/10.1088/1755-1315/766/1/012020.

[15] US Department of Energy (2021). Electric disturbance events (OE-417) annual summaries. Accessed July 27, 2022. https://www.oe.netl.doe.gov/OE417_annual_summary.aspx.

[16] M. Carter, 9 Investigates: Testing NC Power Grid Security after Recent Attacks, WSOC TV, 2023, February 24. Retrieved April 19, 2023, from, https://www.wsoctv.com/news/local/9-investigates-attacks-substations-test-nc-power-grid-security/LSHGSROR4BEQ7OR T7OBOFQA6HA/.

[17] A.X. Andresen, L.C. Kurtz, D.M. Hondula, S. Meerow, M. Gall, Understanding the social impacts of power outages in North America: a systematic review, Environ. Res. Lett. 18 (5) (2023) 053004, https://doi.org/10.1088/1748-9326/acc7b9.

[18] S.D. Matthewman, H. Byrd, Blackouts: a sociology of electrical power failure, Social Space (2014) 1–25. Retrieved from, http://socialspacejournal.eu/Sz%C3%B3sty%20numer/Steve%20Matthewman%20Hugh%20Byrd%20%20Blackouts%20a%20sociology%20of%20electrical%20power%20failure.pdf.

[19] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, V. Vittal, Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance, IEEE Trans. Power Syst. 20 (4) (2005) 1922–1928, https://doi.org/10.1109/TPWRS.2005.857942.

[20] S.V. Buldyrev, R. Parshani, G. Paul, H.E. Stanley, S. Havlin, Catastrophic cascade of failures in interdependent networks, Nature 464 (7291) (2010) 1025–1028, https://doi.org/10.1038/nature08932.

[21] I. Dobson, D.E. Newman, Cascading blackout overall structure and some implications for sampling and mitigation, Int. J. Electr. Power Energy Syst. 86 (Mar) (2017) 29–32, https://doi.org/10.1016/j.ijepes.2016.09.006.

[22] K. Hayhoe, M. Robson, J. Rogula, M. Auffhammer, N. Miller, J. VanDorn, D. Wuebbles, An integrated framework for quantifying and valuing climate change impacts on urban energy and infrastructure: A Chicago case study, J. Great Lakes Res. 36 (2) (2010) 94–105, https://doi.org/10.1016/j.jglr.2010.03.011.

[23] J.A. Dirks, W.J. Gorrissen, J.H. Hathaway, D.C. Skorski, M.J. Scott, T.C. Pulsipher, M. Huang, Y. Liu, J.S. Rice, Impacts of climate change on energy consump- tion and peak demand in buildings: a detailed regional approach, Energy 79 (Jan) (2015) 20–32, https://doi.org/10.1016/j.energy.2014.08.081.

[24] D. Burillo, M. Chester, B. Ruddell, Electrical grid vulnerabilities to rising air temperatures in Phoenix, Arizona, Procedia Eng. 145 (Jan) (2016) 1346–1353, https://doi.org/10.1016/j.proeng.2016.04.173.

[25] A. Andresen, Understanding the Social Impacts of Power Outages: A Case Study Comparison Across US Cities, 2020.

[26] S.M. Rinaldi, J.P. Peerenboom, T. Kelly, Identifying, understanding, and analyzing critical infrastructure interdependencies, IEEE Control Syst Mag 21 (6) (2001) 11–25.

[27] USGCRP (United States Global Change Research Program), in: D.R. Reidmiller, C. W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, B.C. Stewart (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II, U.S. Global Change Research Program, Washington, DC, USA, 2018, p. 1515, https://doi.org/10.7930/NCA4.2018.

[28] G. Pescaroli, D. Alexander, Understanding compound, interconnected, interacting, and cascading risks: a holistic framework, Risk Anal. 38 (11) (2018) 2245–2257, https://doi.org/10.1111/risa.13128.

[29] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q. 84 (2003), https://doi.org/10.1111/1540-6237.8402002.

[30] W.N. Adger, Vulnerability, Glob. Environ. Chang. 16 (2006) 268–281.

[31] N. Coleman, A. Esmalian, A. Mostafavi, Equitable resilience in infrastructure systems: empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions, Natural Hazards Review 21 (4) (2020) 04020034, https://doi.org/10.1061/(asce)nh.1527-6996.0000401.

[32] D. Mitsova, A.M. Esnard, A. Sapat, B.S. Lai, Socioeconomic vulnerability and electric power restoration timelines in Florida: the case of hurricane Irma, Nat. Hazards 94 (2) (2018) 689–709, https://doi.org/10.1007/s11069-018-3413-x.

[33] D. Mitsova, M. Escaleras, A. Sapat, A.M. Esnard, A.J. Lamadrid, The effects of infrastructure service disruptions and socioeconomic vulnerability on hurricane

recovery, Sustainability (Switzerland) 11 (2) (2019) 1–16, https://doi.org/10.3390/su11020516.
[34] A. Stock, R.A. Davidson, J. Kendra, V.N. Martins, B. Ewing, L.K. Nozick, K. Starbird, M. Leon-Corwin, Household impacts of interruption to electric power and water services, Nat. Hazards (2022) 0123456789, https://doi.org/10.1007/s11069-022-05638-8.
[35] A. Esmalian, M. Ramaswamy, K. Rasoulkhani, A. Mostafavi, Agent-based modeling framework for simulation of societal impacts of infrastructure service disruptions during disasters, in: Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilien–E - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2019, 2019, pp. 16–23, https://doi.org/10.1061/9780784482445.003.
[36] N.M. Flores, H. McBrien, V. Do, M.V. Kiang, J. Schlegelmilch, J.A. Casey, The 2021 Texas power crisis: distribution, duration, and disparities, J. Expo. Sci. Environ. Epidemiol. 33 (1) (2023) 21–31.
[37] C. Klinger, O. Landeg, V. Murray, Power outages, extreme events and health: a systematic review of the literature from 2011-2012, PLoS Currents 1 (JAN) (2014), https://doi.org/10.1371/currents.Dis.04eb1dc5e73dd1377e05a10e9edde673.
[38] M. Abir, S. Jan, L. Jubelt, R.M. Merchant, N. Lurie, The impact of a large-scale power outage on hemodialysis center operations, Prehosp. Disaster Med. 28 (6) (2013) 543–546, https://doi.org/10.1017/S1049023X13008844.
[39] C.E. Fife, L.A. Smith, E.A. Maus, J.J. McCarthy, M.Z. Koehler, T. Hawkins, N. B. Hampson, Dying to play video games: carbon monoxide poisoning from electrical generators used after hurricane ike, Pediatrics 123 (6) (2009), https://doi.org/10.1542/peds.2008-3273.
[40] A. Schnall, R. Law, A. Heinzerling, K. Sircar, S. Damon, F. Yip, A. Wolkin, Characterization of carbon monoxide exposure during hurricane Sandy and Subsequent Nor'easter, Disaster Med. Public Health Prep. 11 (5) (2017) 562–567, https://doi.org/10.1017/dmp.2016.203.
[41] K.M. Kosa, S.C. Cates, S.L. Godwin, R.J. Coppings, L. Speller-Henderson, Most Americans are not prepared to ensure food safety during power outages and other emergencies, Food Prot. Trends 31 (7) (2011) 428–436.
[42] K.M. Kosa, S.C. Cates, S. Karns, S.L. Godwin, R.J. Coppings, Are older adults prepared to ensure food safety during extended power outages and other emergencies?: findings from a National Survey, Educ. Gerontol. 38 (11) (2012) 763–775, https://doi.org/10.1080/03601277.2011.645436.
[43] P.W. Greenwald, A.F. Rutherford, R.A. Green, J. Giglio, Emergency department visits for home medical device failure during the 2003 North America blackout, Acad. Emerg. Med. 11 (7) (2004) 786–789, https://doi.org/10.1197/j.aem.2003.12.032.
[44] S.B. Miles, H. Gallagher, C.J. Huxford, Restoration and impacts from 4 September 8, 2011, San Diego power outage, Journal of Infrastructure Systems 20 (2) (2014), https://doi.org/10.1061/(ASCE)IS.1943-555X.0000176.
[45] S.B. Miles, N. Jagielo, Socio-technical impacts of hurricane isaac power restoration, in: Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management - Proceedings of the 2nd International Conference on Vulnerability and Risk Analysis and Management, ICVRAM 2014 and the 6th International Symposium on Uncertainty Modeling, 2014, https://doi.org/10.1061/9780784413609.058 (pp. 567–576).
[46] B. Adhikari, et al., Earthquakes, fuel crisis, power outages, and health Care in Nepal: implications for the future, Disaster Med. Public Health Prep. 11 (5) (2017) 625–632, https://doi.org/10.1017/dmp.2016.195.
[47] J. Burger, M. Gochfeld, Health concerns and perceptions of central and coastal New Jersey residents in the 100days following superstorm Sandy, Sci. Total Environ. 481 (1) (2014) 611–618, https://doi.org/10.1016/j.scitotenv.2014.02.048.
[48] C. Dominianni, K. Lane, S. Johnson, K. Ito, T. Matte, Health impacts of citywide and localized power outages in new York City, Environ. Health Perspect. 126 (6) (2018), https://doi.org/10.1289/EHP2154.
[49] J. Moreno, D. Shaw, Community resilience to power outages after disaster: a case study of the 2010 Chile earthquake and tsunami, International Journal of Disaster Risk Reduction 34 (2019) 448–458, https://doi.org/10.1016/j.ijdrr.2018.12.016. Elsevier Ltd.
[50] S. Lin, et al., What happened to our environment and mental health as a result of hurricane Sandy? Disaster Med. Public Health Prep. (2016) 314–319, https://doi.org/10.1017/dmp.2016.51.
[52] T. Grothmann, A. Patt, Adaptive capacity and human cognition: the process of individual adaptation to climate change, Glob. Environ. Chang. 15 (3) (2005) 199–213, https://doi.org/10.1016/j.gloenvcha.2005.01.002.
[53] R.A. Davidson, et al., Managing disaster risk associated with critical infrastructure systems: a system-level conceptual framework for research and policy guidance, Civ. Eng. Environ. Syst. 39 (2) (2022) 123–143, https://doi.org/10.1080/10286608.2022.2067848.
[54] U.S. Census Bureau, "ACS 5-year Estimates Data Profiles", 2014–2018 *American Community Survey 5-year Estimates* (DP05), accessed May 1, 2020. https://data.census.gov/table?g=040XX00US26&d=ACS+5-Year+Estimates+Data+Profiles&tid=ACSDP 5Y2018.DP05.
[55] S.C. Sheridan, Synoptic Spatial Classification. http://sheridan.geog.kent.edu/ssc.html, 2011. (Accessed 15 May 2023).
[56] H. Aguinis, I. Villamor, R.S. Ramani, MTurk research: review and recommendations, J. Manag. 47 (4) (2021) 823–837.
[57] John A. Bates, Brian A. Lanza, Conducting psychology student research via the mechanical Turk crowdsourcing service (Report), North Am. J. Psychol. 15 (2) (2013) 385–394.
[58] M. Buhrmester, T. Kwang, S. Gosling, Ama'on's mechanical Turk: a new source of inexpensive, yet high-quality, data? Perspect. Psychol. Sci. 6 (1) (2011) 3–5.
[59] G. Paolacci, J. Chandler, P.G. Ipeirotis, Running experiments on Amazon mechanical Turk, Judgm. Decis. Mak. 5 (5) (2010) 411–2975.
[60] N.A. Smith, I.E. Sabat, L.R. Martinez, K. Weaver, S. Xu, A convenient solution: using MTurk to sample from hard-to-reach populations, Ind. Organ. Psychol. 8 (2) (2015) 220–228.
[61] Amanda Jensen-Doss, Zabin Salim Patel, Elizabeth Casline, Vanesa A. Mora Ringle, Kiara R. Timpano, Using mechanical Turk to study parents and children: an examination of data quality and representativeness, J. Clin. Child Adolesc. Psychol. 51 (4) (2022) 428–442, https://doi.org/10.1080/15374416.2020.1815205.
[62] D. Hauser, G. Paolacci, J. Chandler, Common concerns with MTurk as a participant pool: evidence and solutions, Handbook of Research Methods in Consumer Psychology (2019) 319–337.
[63] M. Chmielewski, S.C. Kucker, An MTurk crisis? Shifts in data quality and the impact on study results, Soc. Psychol. Personal. Sci. 11 (4) (2020) 464–473.
[64] A.M. Mellis, W.K. Bickel, Mechanical Turk data collection in addiction research: utility, concerns and best practices, Addiction 115 (10) (2020) 1960–1968.
[65] B. Bolin, L.C. Kurtz, Race, class, ethnicity, and disaster vulnerability, in: H. Rodríguez, W. Donner, J. Trainor (Eds.), Handbook of Disaster Research. Handbooks of Sociology and Social Research, Springer, Cham, 2018, https://doi.org/10.1007/978-3-319-63254-4_10.
[66] Andresen, A., D. Hondula, E. Kurtz, P. Chakalian. (202") Understanding Household Power Outage Experiences: A Case Study Comparison across U.S. Cities. DesignSafe-CI. doi:10.17603/ds2-rzp6-ks38.
[67] M.A. Painter, S.H. Shah, G.C. Damestoit, F. Khalid, W. Prudencio, M.A. Chisty, O. Wilhelmi, A systematic scoping review of the Social Vulnerability Index as applied to natural hazards, Natural Hazards (2024) 1–92.
[68] J.R. Nelson, T.H. Grubesic, J.A. Miller, A.W. Chamberlain, The equity of tree distribution in the most ruthlessly hot city in the United States: Phoenix, Arizona, Urban Forestry & Urban Greening 59 (2021) 127016.
[69] M.O. Román, E.C. Stokes, R. Shrestha, Z. Wang, L. Schultz, E.A. Sepúlveda Carlo, M. Enenkel, Satellite-based assessment of electricity restoration efforts in Puerto Rico after hurricane Maria, PloS One 14 (6) (2019), https://doi.org/10.1371/journal.pone.0218883.
[70] D.A. Call, Changes in ice storm impacts over time: 1886-2000, Weather, Climate, and Society 2 (1) (2010) 23–35, https://doi.org/10.1175/2009WCAS1013.1.
[71] E. Enarson, A. Fothergill, L. Peek, Gender and disaster: foundations and new directions for research and practice, Handbook of Disaster Research (2018) 205–223.