**Introduction:**

Power outage incidence is increasing[[1]](#endnote-1),[[2]](#endnote-2). Climate change has increased the frequency and intensity of severe weather, the most common cause of power outages[[3]](#endnote-3),[[4]](#endnote-4),[[5]](#endnote-5). At the same time, the United States electrical grid is aging[[6]](#endnote-6),[[7]](#endnote-7). Grid components have not been modernized to withstand the previously rare extreme heat, hurricanes, precipitation and wind now commonplace with climate change[[8]](#endnote-8). As a result, US electrical customers experienced an average of 8 hours without power in 2020, the longest duration on record[[9]](#endnote-9).

Power outages pose serious health risks to vulnerable people. When power outages make air conditioners and heaters unusable, and tap water unavailable, older adults may be susceptible to stoke, myocardial infarction, and other adverse cardiorespiratory outcomes[[10]](#endnote-10),[[11]](#endnote-11),[[12]](#endnote-12),[[13]](#endnote-13). These outcomes may be caused by power outage-related heat exposure, cold exposure, or dehydration, and effects may be stronger when severe weather causes or co-occurs with outages. Loss of electricity can be life-threatening for people who use life-sustaining electricity-dependent medical devices such as at-home ventilators and oxygen tanks[[14]](#endnote-14). In children, outages increase accidents and injuries related to generator and natural gas use[[15]](#endnote-15). Outages also increase pediatric asthma emergencies from heat and humidity exposure absent air conditioning[[16]](#endnote-16).

Power outage is an understudied exposure. There is little data available describing power outage exposure across space and time, limiting research. Most epidemiological studies of outage rely on a single New York State dataset. The remaining studies use large-scale events such as hurricanes or disasters as a surrogate for power outage exposure[[17]](#endnote-17),[[18]](#endnote-18). These studies consider everyone in a city or county exposed to the event as exposed to power outage, in days or weeks following the event. Studies based on single events cannot disentangle the health effects of power outage exposure from disaster exposure, and cannot estimate exposure-response relationships between power outage exposure and health outcomes. Identifying populations most at risk is key to mitigating hazards posed by power outages. The health risks posed by outages could vary by region, change with co-occurring hazards, or differ by population and social vulnerability. Quantifying the risks of power outage through estimation of health risks can support interventions to prevent CVD, accidents and asthma in children, and other cardiorespiratory outcomes.

In our previous work, we created a new national dataset of hourly power outage exposure by county for the continental United States[[19]](#endnote-19). We used this dataset to describe power outage exposure by region and social vulnerability, finding that outages were more common in the southeast and northeast US, with high outage incidence and high social vulnerability co-occurring most frequently in the southeastern US. This dataset will allow us to characterize exposure-response relationships between power outage and health outcomes nationally, by region, and within vulnerable populations.

However, even with these new data, major challenges with power outage exposure assessment remain. First, there is no standard or widely used strategy to measure power outage exposure in the literature[[20]](#endnote-20). A single strategy to describe power outage exposure would allow comparability and aggregation of results across studies, and a well-designed measurement approach could minimize bias. Second, any definition of outage exposure relative to an outcome will depend on the health-relevant duration of a power outage: the duration at which an outage begins to cause health effects. There is no literature on the health-relevant duration of power outage with respect to any outcome. Incorrect assumptions about the health-relevant duration have the potential to bias the results of an epidemiological study of power outage and a health outcome. Finally, both the new national dataset and existing New York State data are missing large percentages of observations[[21]](#endnote-21),[[22]](#endnote-22). This missingness could also substantially bias results of an epidemiological study of power outage and any health outcome.

In this paper we will address these exposure measurement issues by developing a strategy for measuring power outage exposure. Then, we will run simulations to test how assumptions about health relevant duration of outage and missingness could bias the results of an epidemiological study of the health effects of power outage. Our results will allow us and other researchers to consistently define and measure power outage exposure using the datasets currently available, while minimizing potential bias in future epidemiological studies of power outages and health outcomes.

**Methods:**

**National PowerOutages.us dataset:**

In our previous work, we created a national dataset of power outage exposure[[23]](#endnote-23). We purchased raw power outage data from PowerOutages.us. PowerOutages.us scrapes data from utility company website APIs in real time. These utility company websites are designed for utility customer use – customers can to check to see if the utility is aware of a power outage, and know estimated power restoration times form the utility. Most utilities report the number of customers out in an area on these sites. Poweroutages.us scraped counts of customers without power from utility website APIs covering the continental US, from 2018-2020[[24]](#endnote-24).

The resulting dataset contains hourly counts of customers without power for each county. . A sub-county unit can be all customers served by a single utility in an entire county, city (where there are possibly multiple cities in a county), or neighbourhood (where there are possibly multiple neighbourhoods in a city, in turn nested in a county). Many utilities can serve the same location, so these sub-county units were not necessarily geographically distinct. Two houses next to each other might be in two different spatial units in the power outage data if they were served by different utilities. Utilities define a ‘customer’ as a grid connection, which can correspond to a household, apartment building, or business[[25]](#endnote-25).

We aggregated the power outage data to the county level by summing the number of customers out in each 10-minute period in each sub-county unit in the same county, to achieve 10-minute counts of customers out by county. We also aggregated the dataset to the hourly level by taking the average number of customers out in each of the 6 ten-minute periods in each hour. We then had hourly county-level data of counts of customers out in each county for the continental US from 2018-2020.

The New York State power outage dataset is structured similarly – counts of customers without power are reported in time intervals by power operating division, a geographic unit that varies in size throughout the state.

**Measuring power outage:**

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