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Power outages and community health: a narrative review

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Abstract

Purpose of review: Power outages, a common and underappreciated consequence of natural disasters, are increasing in number and severity due to climate change and aging electricity grids. This narrative review synthesizes the literature on power outages and health in communities.

Recent findings: We searched Google Scholar and PubMed for English-language studies with titles or abstracts containing “power outage” or “blackout.” We limited papers to those that explicitly mentioned power outages or blackouts as the exposure of interest for health outcomes among individuals living in the community. We also used the reference list of these studies to identify additional studies. The final sample included 50 articles published between 2004–2020, with 17 (34%) appearing between 2016–2020. Exposure assessment remains basic and inconsistent, with 43 (86%) of studies evaluating single, large-scale power outages. Few studies used spatial and temporal control groups to assess changes in health outcomes attributable to power outages. Recent research linked data from electricity providers on power outages in space and time and included factors such as number of customers affected and duration to estimate exposure.

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Summary: The existing literature suggests that power outages have important health consequences ranging from carbon monoxide poisoning, temperature-related illness, gastrointestinal illness, and mortality to all-cause, cardiovascular, respiratory, and renal disease hospitalizations, especially for individuals relying on electricity-dependent medical equipment. Nonetheless the studies are limited and more work is needed to better define and capture the relevant exposures and outcomes. Studies should consider modifying factors such as socioeconomic and other vulnerabilities as well as how community resiliency can minimize the adverse impacts of widespread major power outages.

Keywords

Power outage; blackout; natural disasters; energy insecurity; carbon monoxide poisoning; durable medical equipment

INTRODUCTION

In August 2003, over 50 million Americans and Canadians lost power for up to four days due to a surge of electricity along faulty transmission lines (1). In China, ice-coated transmission lines and towers collapsed during a severe winter storm in 2008, interrupting electric service to 200 million people (2). Meanwhile, hot weather and related air conditioner use triggered a blackout affecting 8 million people in Baku, Azerbaijan in July 2018 (1). The largest blackout in history affected at least 600 million people across India in July 2012 (3). The frequency and severity of these events will increase with population growth and climate change, as infrastructure damage from intense storms and floods, hydropower shortage from droughts, and increased demand as temperatures rise and strain an aging electricity grid (4-6).

Power outages worldwide

Today, South Asia has the highest system average interruption frequency index (SAIFI). The average business there experienced 26 outages per month in 2019 (7). However, even businesses in Organisation for Economic Co-operation and Development (OECD) countries experienced one power outage every other month in 2019. Outages last longest, on average, in Latin America and the Caribbean (8 hours) and Sub-Saharan Africa (7.5 hours), compared to just 2.5 hours in East Asia (8). The United States (U.S.) Energy Information Administration predicts that global electricity production will increase by 75%, from 20 trillion kilowatt-hours (kWh) in 2018 to 45 trillion kWh in 2050, driven in large part by demand in non-OECD countries (9). This increased demand will result in more power outages, with unique economic, social, and health consequences, of which we review that latter.

Causes and costs of U.S. power outages

In the U.S., major power outages increased 10-fold between 1984–2012 with the average household experiencing 470 minutes without power in 2017 (11, 12). Large blackouts, disturbances that interrupt more than 300MW (enough power for ~50,000 homes) or 50,000 customers and require reporting to the U.S. Department of Energy (13), occur more commonly in the winter and summer and year-round during the mid-afternoon (14).

Electromagnetic events and intentional cyber-physical attacks caused >25% of total U.S. power outages between 2000-2016 (Figure 1A) (10, 15). Such attacks present substantial risk to the electricity grid and could result in an outage that stretches for months across wide geographies, especially if timed after a natural disaster (16). Most widespread power outages were caused by severe weather (Figure 1B) and Florida, California, New York, and Michigan were hit hardest with 25.3 million, 22.2 million, 18.3 million, and 12.4 million affected customers, respectively (15).

Outages, particularly those related to weather, are almost always accompanied by intersecting and related phenomena that result in economic, social, and health damages (Figure 2). Economically, they interrupt business, cripple the internet, and halt many forms of transportation (8). The 2003 Northeast Blackout in Canada and the U.S. cost between \$4-10 billion (17), and electricity infrastructure repairs alone cost \$3.5 billion after Hurricane Sandy (18). Social costs include increased crime, motor vehicle crashes, psychosocial stress, and interrupted communication between emergency services, delivery of clean water, and waste removal (3, 12, 19, 20). Although, altruistic acts, including providing assistance to others, donating money, assisting with traffic, may also increase (19-22). Several factors influence the severity of economic, social, and health costs of power outages including outage frequency, duration, timing, and geographic range, as well as mitigation measures, population preparedness, and prior experience (19, 23).

Medically high-risk groups during power outages

Certain subgroups have higher risk of adverse health outcomes during power outages. These include older adults, those reliant on electricity-dependent durable medical equipment (DME, e.g., oxygen concentrators), those unable to evacuate, including nursing home patients, those reliant on others to complete activities of daily living, the heat/cold susceptible, and those with underlying conditions exacerbated by the inciting events, such as respiratory, cardiovascular, and renal disease (23-25). The number of electricity-dependent individuals is anticipated to grow in the coming years (23, 25); numbers already trend upward and rate of DME use appears higher among lower socioeconomic status individuals (26).

Documented disparities in power outage preparedness and exposure

Evidence from the U.S. suggests older adults, poorer families, and individuals of non-Hispanic Black and Hispanic race/ethnicity are least likely to have a three-day supply of food, drinking water, and medication, a preparedness measure for power outages (27-29). In New York City, only 58% of 887 people surveyed were prepared for a disaster; preparedness dipped to 45% among households with income <\$30,000 and to 28% among primary Spanish-speakers (29). Generator cost (\$2-5,000) may price out lower socioeconomic status families and those living in public housing or apartment buildings that prohibit generators (21, 29). Finally, power outages may last longer in lower socioeconomic status or communities of color (30-34), where impacts may already be greater. For example, in Florida after Hurricane Irma, higher income individuals evacuated farther and to destinations with lower power outage rates compared to their lower income counterparts (33). After Hurricane Maria, satellite imagery of Puerto Rico suggested that households with power

restored in Stage 1 earned almost double the income of households with power restored in Stages 2-3 (32). After Hurricane Sandy in New Jersey, non-Hispanic White individuals had the longest duration outages (11.2 days compared to 8.2 days for African Americans) (34). Such disparities put these already-vulnerable groups at increased risk of adverse power outage-related health outcomes.

Goal of this review

This review focuses on blackouts—the unavailability of electric power in an area—and does not address issues of energy poverty, a separate and important predictor of health (35, 36). In addition, we do not cover challenges faced by healthcare facilities during power outages. In this narrative review, we highlight themes in the current scholarship on power outages and community health and identify future avenues for research.

METHODS

We conducted searches via Google Scholar and PubMed in spring 2020 for studies written in English with titles or abstracts containing “power outage” or “blackout.” We limited papers to those that explicitly mentioned power outages or blackouts as the exposure of interest for health outcomes among individuals living in the community. The reference lists of the identified studies were also examined to identify additional relevant articles. We screened the articles to include only original primary research published between January 2004 and June 2020 that explicitly mentioned power outage or blackout as an exposure of interest. The final sample included 50 articles spanning power outage events from 1977 to 2019 (Figure 3). The majority (72%) of the studies evaluated health outcomes in the US, but we collected literature from across the globe (Appendix Figure 1). Non-US articles tended to focus on interrupted healthcare (37, 38), which was outside the scope of this review.

Exposure assessment

Single, large-scale power outages.—Nearly all studies evaluated single, large-scale power outages. While the definition of large-scale varied from study to study, many met the U.S. Department of Energy criteria: 50,000+ customers affected or an unplanned loss of 300 MW (13). Researchers assumed individuals experienced the outage if they lived or attended a healthcare facility in the region where the outage occurred. Most studies relied on pre-post outage temporal comparisons to draw inference (20, 28, 39-53) or only described health outcomes after the outage (54-71) (Figure 4A). Eight studies of single outages also incorporated geographic variability in outage distribution in the study design, in addition to using pre-post outage health measures (72-79).

Multiple power outages.—Seven studies evaluated multiple power outages (30, 80-85), with three using outage frequency to characterize long-term exposure (82, 84, 85). Others conducted longitudinal analyses. In South Africa, Gehringer and colleagues used a combination of government data, Facebook, and the local electric utility’s Twitter handle to track daily load shedding events (halted electricity distribution due to demand exceeding supply), including outage duration (30). Koroglu used standard electricity reliability data from the Maharashtra State Electricity Distribution Company in India to characterize

monthly SAIFI and system average interruption duration indices (SAIDI) values statewide (83). Zhang and colleagues linked power outage records, including total number of customers affected, from the New York State Department of Public Service (NYSPS) between 2001-2013 to the power-operating division-level (~1,700 divisions exist in New York with an average population of ~11,000 people each). They created daily exposure metrics based on proportion of customers affected and duration (in days) of power outages. Likewise, Dominianni et al. used half-hourly NYSPS data to identify outages within each of New York City's (NYC) 66 electricity grid networks (80). They defined the entire grid network area as exposed on a given day if >1,000 people were without power during the warm-season and if >75 people were without power during the cold-season. Different cutpoints were used because fewer people experienced outages during the cold season.

Outcomes

Carbon monoxide poisoning.—Twenty-three (48%) of studies included evaluated carbon monoxide (CO) poisoning (44, 45, 50, 51, 54, 55, 57-62, 64-66, 69-72, 76, 77, 85, 86), a topic previously reviewed (87-89). CO is a colorless, odorless, and tasteless gas, formed by incomplete combustion of carbon compounds. Because hemoglobin binds 250x more readily with CO than with oxygen, prolonged exposure leads to cellular hypoxia, ischemia, and death (90).

In the 23 reviewed articles, indoor use of charcoal and gasoline-powered generators caused the majority of CO poisonings. The most common symptoms of CO poisoning were headache, nausea, vomiting, dizziness, loss of consciousness, and death. The majority of studies identified CO poisoning using medical chart reviews including emergency department (ED) visits (50, 54, 55, 57, 60, 64-66, 69-72, 77), hospitalizations (58, 69-71, 76), and emergency medical service (EMS) and poison control calls (28, 44, 45, 58, 59, 65, 69, 72) coded as CO poisoning-related; several studies used laboratory confirmation or reported serum carboxyhemoglobin (COHb) levels (44, 54, 55, 59-61, 64, 70, 91). Many studies reported fatalities, particularly in the several days following storms (54, 55, 57, 59-62, 65, 69-71, 85). Over 50% of CO poisoning studies reported the use of hyperbaric oxygen therapy (44, 54, 55, 58, 59, 61, 64, 65, 69-72, 91), and higher COHb levels may be related to persistent cognitive and psychiatric changes after CO poisoning (91). In many cases, children (54, 55, 59, 72), older adults (61, 62, 65), immigrants (60, 65), and people of color (55, 60, 64, 65, 70) were disproportionately affected. Qualitative methods can provide key insights not otherwise captured. For example, Styles and colleagues also found that 62% of non-Hispanic White generator/charcoal grill/heater operators reported hearing warnings about CO poisoning in the year prior compared to just 30% of those in other racial/ethnic groups (70) and Van Sickle et al. determined fear of theft was the most common reason to place a generator indoors (71).

While most studies only catalogued CO poisoning events following power outages, a few employed a comparison time period (28, 45, 50, 72, 76, 77), allowing authors to determine if more CO poisoning occurred than expected following power outages. After the Great East Japan Earthquake of 2011, Nakajima and colleagues found 13.5x the odds of CO poisoning among patients in the disaster area (including power outage exposure) from March 11 to

April 9, 2011 compared to the same dates in 2012 (76). A spatial control also revealed higher counts of CO poisoning in the disaster area versus an unexposed region. Johnson-Arbor compared two major storms in Connecticut in 2011 and 2013, where the 2011 storm resulted in 11x the number of individuals losing power and 5x the number of CO poisonings (44).

All-cause, cardiovascular, respiratory, and renal disease healthcare visits.—In general, hospitals see fewer patients in the days leading up to storms (42), whereas more patients arrive during and after outages, often with respiratory, cardiovascular, or renal disease exacerbations (30, 40, 42, 46, 47, 53, 68, 80, 81). In a comprehensive study, Dominianni et al. evaluated three major NYC outages (1999, 2003, 2006) and localized warm- and cold-weather outages within NYC (80). In models accounting for temperature, day of week, and seasonal and long-term trends, they confirmed prior findings of increased cardiovascular and respiratory disease hospitalizations during the 2003 outage and found new evidence of elevated risk of renal disease hospitalizations during warm-season power outages and cardiovascular disease hospitalizations during cold-season power outages. Zhang and colleagues also illustrated the utility of using daily sub-city level power outage data in their study of chronic obstructive pulmonary disease (COPD) hospitalizations statewide. They used power-operating division-level (~11,000 residents per division) between 2001-2013 in New York and found the largest increases in COPD hospitalizations during the first three days after power outages, where 23% of COPD hospitalizations on power outage days could be attributed to the outage itself (81). Compared to non-power outage periods, COPD patients arriving for care during power outages had a higher number of comorbidities and healthcare costs. Interrupted use of nebulizers, and oxygen and bilevel positive airway pressure machines, as well as sensitivity of COPD patients to changing indoor conditions (e.g., lack of air conditioning or dehumidifiers) likely explained the large increase in hospitalizations.

Many acute care visits related to cardiovascular and respiratory disease exacerbation during blackouts appear to result from failure of *electricity-dependent medical devices* (41, 42, 46, 50, 51, 63, 67, 68, 80, 81, 92). For example, after the 2011 Great East Japan Earthquake, 75% of 24 new pediatric inpatients at Tohoku University Hospital relied on DME, including 13 children using ventilators (76). After Hurricane Sandy, ED visits at Beth Israel Medical Center related to respiratory device failure and “power outage” increased in all age groups and peaked the day following the disaster (41).

Older adults and children may be at particular risk during power outages. Unlike many other NYC hospitals in downtown Manhattan, Beth Israel Medical Center remained open after Hurricane Sandy and their electronic health record (EHR) data revealed a 114% increase in ED use among patients aged 80+ and a 11% decline among those aged 18-64 compared to the six-months prior (41). In addition to power outage-related care, this increase reflects spillover from other closed hospitals. In South Africa, Gehringer and colleagues evaluated repeated, daily, temporary outages on pediatric hospital admissions, finding an average treatment effect of 6 additional admissions per day due to any power outage in the two days prior (30). They found the largest effect sizes for respiratory outcomes, burns, and ear, eye,

and gastrointestinal system outcomes in models that controlled for important factors like weather and seasonal and long-term trends.

Gastrointestinal illness.—Power outages can affect food refrigeration and water system supply and disinfection, potentially precipitating gastrointestinal illness as measured via poison control calls, prescription orders, and hospital admissions (30, 45, 48, 78). However, evidence is mixed, with several studies finding no increase in gastrointestinal illness after power outages (72, 78, 86). Marx et al. employed methods from digital epidemiology to evaluate diarrheal illness after the 2003 Northeast Blackout finding that diarrheal syndrome ED visits, antidiarrheal medication sales, electrolyte sales, and worker absenteeism due to gastrointestinal illness all increased above expected in the days following the blackout (48).

Temperature-related illness.—Power outages reduce individuals' ability to control the indoor environment and may coincide with temperature extremes (both heatwaves and winter storms) resulting in illness (40, 42, 51, 53, 55, 68, 77, 80) and disturbed sleep (49) related to heat and cold exposure. Racial, socioeconomic, and age disparities exist in response to extreme temperature exposures, owing to differences including baseline health, access to generators, the urban heat island effect, and occupation (93, 94).

Maternal and neonatal health.—Four studies assessed the relationship between power outages and maternal healthcare utilization, measures of fertility, and birthweight (73, 74, 79, 83). Using monthly power outage data from 2010–2015 in India's Maharashtra state, Koroglu and colleagues evaluated the relationship between SAIFI (system average interruption frequency index) and SAIDI (duration) metrics and use of maternal health services (83). Increased monthly SAIFI but not SAIDI was associated with reduced odds of delivering in a healthcare institution (versus at home), both indices were associated with reduced odds of attendance of birth by skilled professional, and neither were related to caesarean section delivery. Outages may affect a woman's ability to travel to a healthcare facility or reduce her perception of the quality of care she will receive there, encouraging her to stay at home.

Burlando exploited a month-long 2008 blackout that occurred on the island of Zanzibar, Tanzania to study both measures of fertility (counts of live births) and birth weight (73, 74). The outage caused both a transitory negative income shock, with those who used electricity at work reporting a decrease in earnings and hours worked, and individuals to spend more time at home. With data from the island's main maternity hospital (500-900 births per month), Burlando used a difference-in-differences strategy to estimate the effect of the power outage on fertility and birthweight by comparing outcomes among mothers living in shehias (communities) with and without any electrification exposed and unexposed to the blackout at different times during pregnancy. They found that the blackout was associated with a 17% increase in live births (253 additional births) 8-10 months later (73). The outage also appeared to reduce birthweights 7-10 months later, with the strongest associations among the lowest-percentile weights (e.g., 8th-percentile weight was reduced by 2kg) (74).

Mental health and wellbeing.—Qualitative studies identified worry, anxiety, stress, and reduced wellbeing among individuals exposed to power outages, generally tied to concerns

about disrupted heating, food, water supplies, and healthcare (75, 82). In the acute setting, healthcare-seeking for mental health problems may actually decline, as was seen immediately after the 2003 Northeast Blackout in NYC (40). Therefore, alternative data, such as Twitter, may supply valuable information about population health during an outage (20). Li et al. found a sharp drop in Twitter sentiment (i.e., more negative tweets) in the first hour of a NYC power outage in 2019. Other studies have evaluated longer-term effects of power outages (56, 79, 84) In Ghana, University students who experienced power outages 4 times per week had significantly higher levels of anxiety as measured by the generalized anxiety disorder 7-item scale (84). After Hurricane Sandy, ED visits for mental health problems among pregnant women in New York increased gradually and peaked eight months later at a level 33% higher than expected based on data from prior and subsequent years (79).

Mortality.—Three studies identified increased mortality after the 2003 Northeast Blackout in New York City (NYC), which affected 8 million NYC residents (39, 47, 80). Anderson and Bell found increased accidental (+122%) and non-accidental (+25%) mortality controlling for important environmental confounding variables such as temperature, air pollutants, day-of-week, and seasonal and long-term trends (39). Dominianni and colleagues extended Anderson and Bell’s study to span major NYC blackouts in 1999, 2003, and 2006, as well as localized outages in 66 NYC electric-grid networks (80), finding significant associations between localized cold-weather, but not warm-weather, outages and all-cause and non-external mortality. Conversely, Imperato could not identify an effect of the 1977 NYC power outage on all-cause mortality as it coincided with and could not be disentangled from a heatwave (43). Other studies have tied power outage-related mortality to CO poisoning (see prior section), falls (55, 62), fire (55, 62), heat (85), and cold exposure (55).

Other outcomes.—Several studies reported increases in healthcare visits for burns, lacerations, or other injuries (40, 42, 50, 68, 77), but attributing these events to power outages, rather than co-occurring exposures such as housing damage or motor vehicle crashes has been difficult. Further, two studies reported reduced prescription refills during power outages (42, 52) and one found no change (50). After Hurricane Maria power outages lasted months in Puerto Rico and prescription refills did not revert to normal levels even one-year later (52).

REVIEW SUMMARY AND RECOMMENDATIONS

Recent studies point to a relationship between power outages and adverse health outcomes among community residents. Most have assessed single, large-scale power outages without linking events directly to patient residential addresses. New work has used data from electric utilities (80, 81, 83) and social media (30) to more accurately capture the temporal and spatial extent of outages. Consistent evidence from >20 studies across a range of power outages from hurricanes to ice storms to earthquakes finds increased rates of CO poisoning during outages as individuals use alternative fuel sources, such a generators and charcoal. We also observed moderate evidence for an association between power outages and all-cause, cardiovascular, respiratory, and renal disease hospitalizations, except for the sub-group of individuals relying on electricity-dependent medical equipment where associations

consistently pointed to elevated risk. In times and places where power outages corresponded to hot or cold ambient temperatures, we found moderate evidence of a relationship between power outage and temperature-related illness, gastrointestinal illness, and mortality. Recent studies have broadened their scope to consider additional outcomes such as mental health (19), maternal and child health (73, 74, 83), prescription refills (42, 52), and injuries (40, 42, 50, 68, 77); future work should continue to explore these and other potentially important outcomes.

Future areas for exposure assessment.

To date, most studies have focused on single power outages, which can allow better characterization of co-exposures but misses the larger burden of repeated outages and underestimates individual-level effects. Studies should consider factors such as duration (e.g., longer outages are likely much worse for health) and location (e.g., outages in San Diego likely have fewer impacts than outages in Maine in the winter). The lack of resolved spatial and temporal exposure data has also limited research. Attribution of adverse health outcomes directly to power outages will require exploiting variability in power outage locations, times, duration, and severity among populations. Zhang et al. successfully did this using NYSPS data (81). Such data are difficult to acquire and do not exist for many regions of the U.S. and world. Therefore, borrowing from digital epidemiology (95), alternative strategies may be used, including remote sensing, internet connected devices, and social media, to characterize spatiotemporal variability in power outages.

Remote sensing.—Researchers can use satellite or aircraft to measure reflected and emitted radiation of the earth. In particular, remote sensing of artificial lights at night (96) can be used to measure power outages (97). In India, Min et al. created a Power Supply Irregularity (PSI) index using nighttime satellite imagery to compute the outage index in all 600,000 villages in India from 1993-2013 (97). Likewise, Román et al. used globally-available, daily nighttime light data from NASA’s Black Marble product to track electricity grid restoration in Puerto Rico after Hurricane Maria (32). These data were used to create three metrics down to 902 barrios: (1) percent recovery; (2) number of days without electricity; and (3) number of customer-hours of interruption.

Internet connected and other consumer devices.—Meier et al. used the power status of internet-connected thermostats, of which 6 million exist in the U.S., to track outages at 15-minute intervals during Hurricane Irma and severe windstorm (98). Others have proposed using smartphones (99) or a host of internet connected devices (e.g., alarm systems, ATM networks) to track power outages (100).

Social media.—Several researchers have used Twitter feeds to track power outages (20, 101-104). One option is to use geotagged tweets (101), but these make up <1% of tweets as most users turn this function off (105). Instead, researchers can search for location-specific terms within tweets, for example, “New York City” or obtain information from registered locations from the users’ accounts (20, 104). Khan et al. also attempted to extract power outage cause in four groups: manmade, natural (e.g., “storm”), wildlife, and faulty equipment (104). This type of data may have increased utility in the future.

Co-exposures/complex disasters: One key and complicating feature of power outages is that they often occur alongside other disasters. Disentangling the impact of power outages from other physical destruction of infrastructure, such as landslides in Puerto Rico following Hurricane Maria (106, 107), fuel crises in Nepal after the 2015 earthquake (108), or windstorms in Ohio following Hurricane Ike (109) may not be possible. Bromet et al. noted a synergistic effect of multiple Sandy-related exposures, where participants experiencing 3-5 exposures (i.e., loss of power, extreme concern about finding gasoline, filing a FEMA claim, extensive home damage, and extensive possession damage) had >6x the odds of PTSD and major depressive disorder compared to those experiencing 0 exposures (56). Many studies implicitly include power outage as an exposure, but the researchers do not explicitly cite power outage as the main exposure of interest. Future work should consider the long-tail, ancillary impact of power outage-related health effects. Sustained power outages result in delayed or interrupted access to healthcare from infrastructure damage, access limitations, inability to pay (from disaster-related impoverishment), and loss of personnel (34, 83, 110). Such deferred care, from delayed treatments, unfilled prescriptions, or failure of DMEs impacts morbidity and mortality—as was in the case after Hurricane Maria in Puerto Rico, where nearly 4000 excess deaths occurred (111).

Future areas for outcome assessment.

Outcome assessment should increase in depth and breadth. Most studies only evaluated immediate effects of power outages. Future studies should expand the timescale to assess outcomes in the short-term and long-term. For example, Xiao et al. defined immediate impacts of Hurricane Sandy as the 30-days after and long-term impacts over the following year (79). They found immediate and long-term increases in ED visits for overall pregnancy complications among women in eight Sandy-exposed New York counties that exceeded increases in 54 less-exposed counties, highlighting the need to extend the relevant follow-up period. While studies have begun to assess perinatal health, future work should also consider children, another susceptible group. Additionally, studies must continue to evaluate the health of older adults, who rely more heavily on electricity-dependent medical equipment (26) and may have cognitive impairment or functional limitations (112), increasing their vulnerability to power outages.

The use of large insurance claims databases or EHRs (113), combined with better exposure assessment, will allow for investigating the impact of power outages on health in at least three important ways. First, it will allow for assessing a larger variety of health outcomes over a longer period of time. Many outcomes, such as maternal and child health or mental health, are known to be sensitive to power outages, yet remained understudied. In addition to these outcomes, exploratory analyses of large claims databases may identify currently unknown outcomes impacted by power outages. Second, it will allow for identifying and studying particularly susceptible subpopulations, such as patients with temperature-sensitive co-morbidities like multiple sclerosis or heart failure. Lastly, it will allow for a more complete description of the racial/ethnic, socioeconomic, and spatially patterned disparities in health response to power outages. Very few studies to date employ spatial and temporal control groups, rigorous statistical methods, and assess for effect modification by import socioeconomic and racial/ethnic sub-groups. This work can assist in identifying crucial

points of intervention to allow for equitable allocation of preparedness, response and recovery activities, and resources to reduce disparities.

Building resilience and supporting response.

Resiliency spans from the individual to regional and global levels and encompasses individual skills, community health, and societal resources (114).

Preparedness.—Individual and community preparedness, including access to alternative power sources, can influence the scope of effect of outages on population health. While baseline levels of individual preparedness appear low, a silver lining of repeated outages is that households become more prepared, buying additional supplies or equipment, over time (19). In Florida, CO poisoning counts increased after the first, but not the second or third consecutive hurricanes, suggesting increased awareness, preparedness, or public health warnings during subsequent hurricanes of the season (50). Personal preparedness can reduce the effect of power outages on health, but low socioeconomic status individuals have limited capacity to store food and water or own a generator (29) and marginalized groups may receive fewer disaster-related warnings (70). Instead, emergency planners should focus on bolstering community resilience—physical, economic, and social—which can take many forms, from strengthening infrastructure to reducing baseline environmental exposure levels and socioeconomic inequities to expanding social capacities (21, 75). Resilient communities deploy collective strategies such as community kitchens, checking on older adults, and providing each other with warmth, food, and shelter during outages (19, 115). Government officials and utilities can further support health and safety by providing advanced warning of power outages as well as estimated duration once the outage has begun.

Electricity infrastructure.—Several steps can be taken to improve electricity grid resiliency and response. These might include better protection against cyber-attacks and tree maintenance (1, 16, 116), improved weather forecasting that allows utilities to prepare, decentralized power generation such as solar and battery storage (117, 118), smart grid technologies like advanced metering infrastructure and isolation and service restoration to update and enhance grid reliability (1, 15). Rather than increase access to generators, modest system upgrades could also allow for low-amperage service (e.g., 20A, which would keep lights or air conditioning on) during outages, possibly paid for via monthly backup insurance payments of <\$1 per customer (119).

Supporting health during outages.—In addition to primary prevention and building resilience, some specific actions can directly support power outage-related health maintenance. For example, notifying patients pre-disaster to refill prescriptions. Prior to a mid-Atlantic blizzard CVS pharmacy randomly notified 2.2 million patients to check their medication supply and found that they had a 9% increased odds of a refill within 48 hours compared to the comparison group (120). Pre-dialysis and other forms of pre-care at healthcare facilities can allow individuals to go safely without power for longer (121). We also must further identify locations and co-morbidities among those reliant on electricity-dependent medical equipment via patient registration with utility companies and information from EHRs or publicly-available data sources like the emPOWER mapping tool (25, 26,

122), and provide community-based charging stations for medical equipment. In North Carolina, >95% of severe CO poisoning after an ice storm occurred in households without CO detectors (123). The benefit-to-cost ratio of installing a CO monitor may be as high as 7.2 to 1 (124). Low-tech interventions, like paired CO monitor and generator purchases, or engineering controls like automatic generator shutoffs, low CO generators, or simply longer generator cords could reduce CO poisoning (125). Finally, in low-resource settings where outages can limit ability to travel to hospitals or results in blackouts at hospitals themselves, mobile clinics can offer distributed access to care (126) and novel technologies, like solar and storage or oxygen reservoir systems, can support further continuity of care (127, 128).

CONCLUSION

As power outages increase in frequency and duration, researchers must expand efforts to understand their impact on individual and population health, refining methods of exposure assessment with attention to varied and disparate outcomes. There is urgent need for these data to inform disaster mitigation, preparedness and response policies (and budgets) in an increasingly energy-reliant world.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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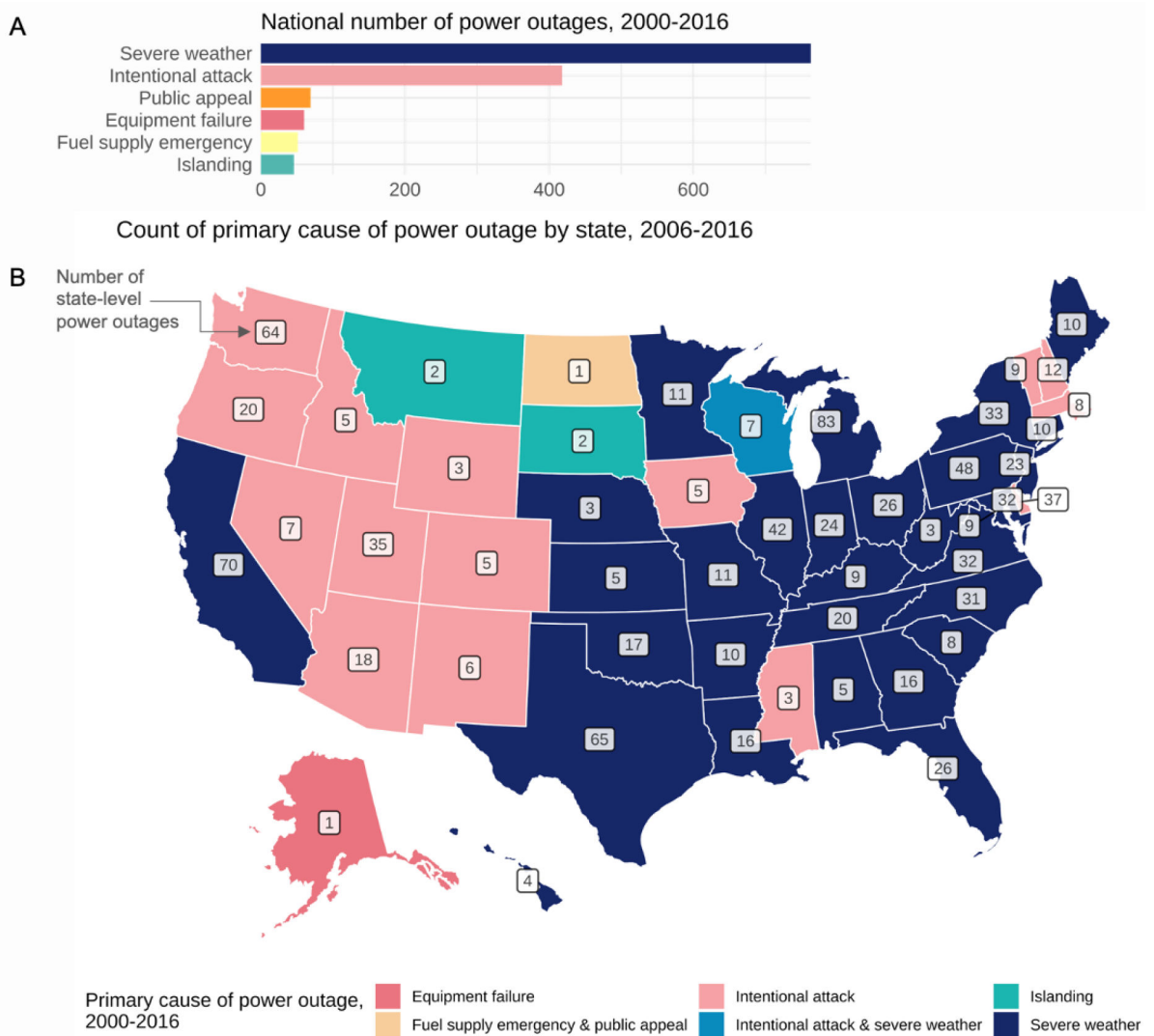


Figure 1: Summary of large power outages in the United States from 2000-2016.

A) Number of large power outages by cause between 2000-2016. B) Count of outages by primary cause type by state between 2000-2016. For example, Texas had 65 power outages caused by severe weather between 2000-2016. Data from Mukherjee et al. 2018 (10), which they assembled from publicly-available datasets. A large power outage is defined by the U.S. Department of Energy as: 50,000+ customers affected or an unplanned loss of 300 MW.

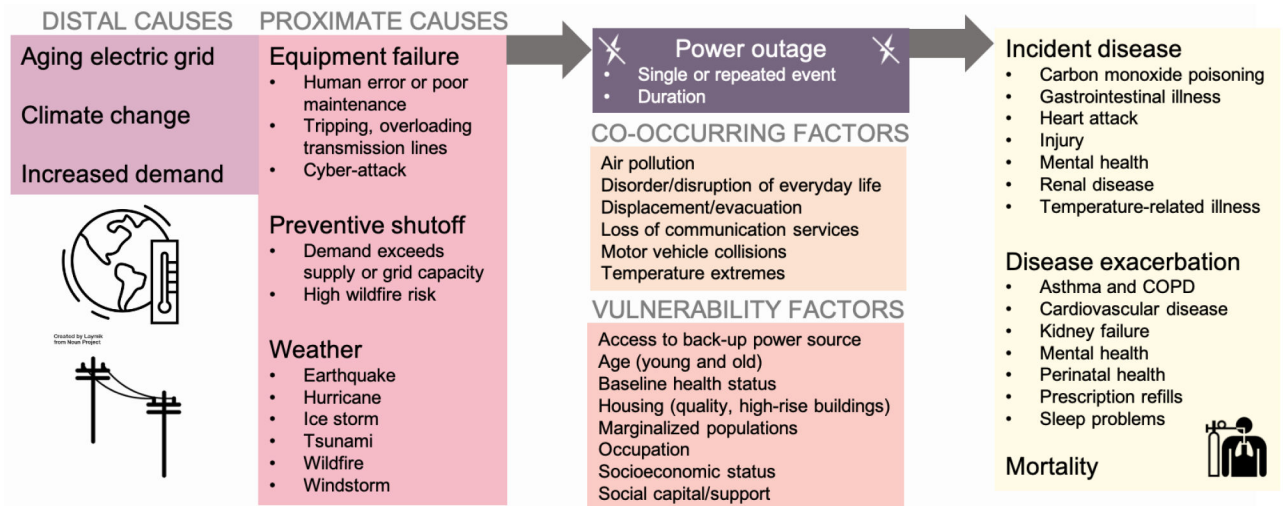


Figure 2: Schematic showing hypothesized pathways between power outages and disease exacerbation.

We illustrate co-occurring factors such as displacement, extreme temperatures, and air pollution, as well as vulnerability factors that might increase the risk of adverse health outcomes during power outages, including baseline health status, socioeconomic status, and social support.

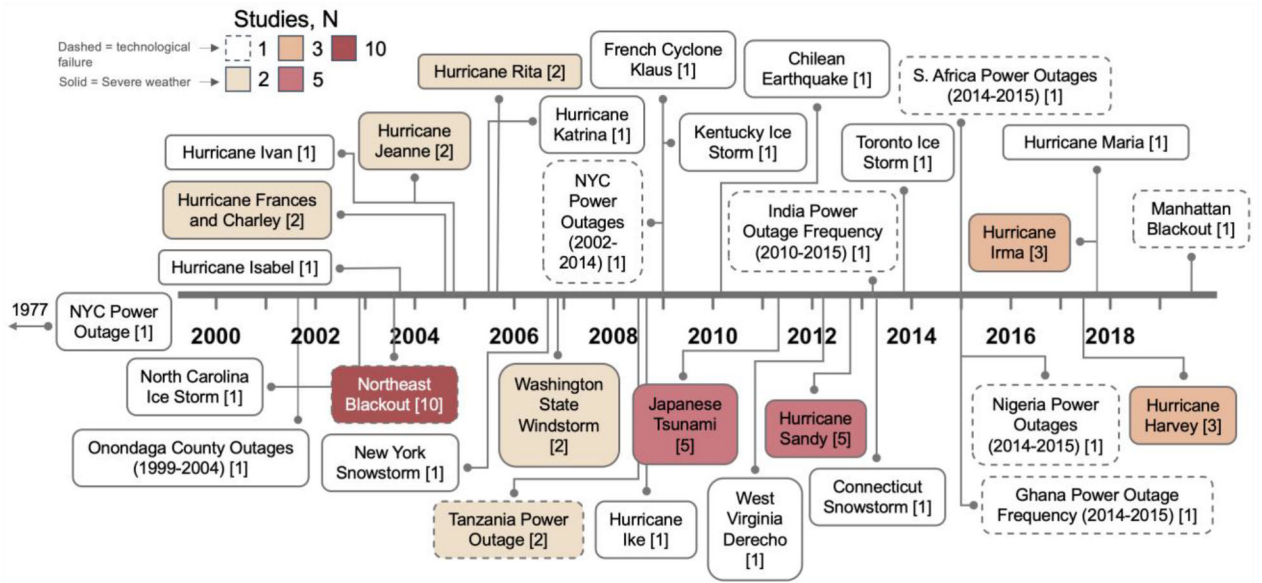


Figure 3: Timeline of the power outages evaluated by the epidemiologic literature between 2004-2020.

Dashed outlines represent outages caused by technological failure and solid outlines those caused by severe weather. Numbers in square brackets denote the number of studies evaluating the specific outage and fill colors get closer to red with more studies evaluating the outage.

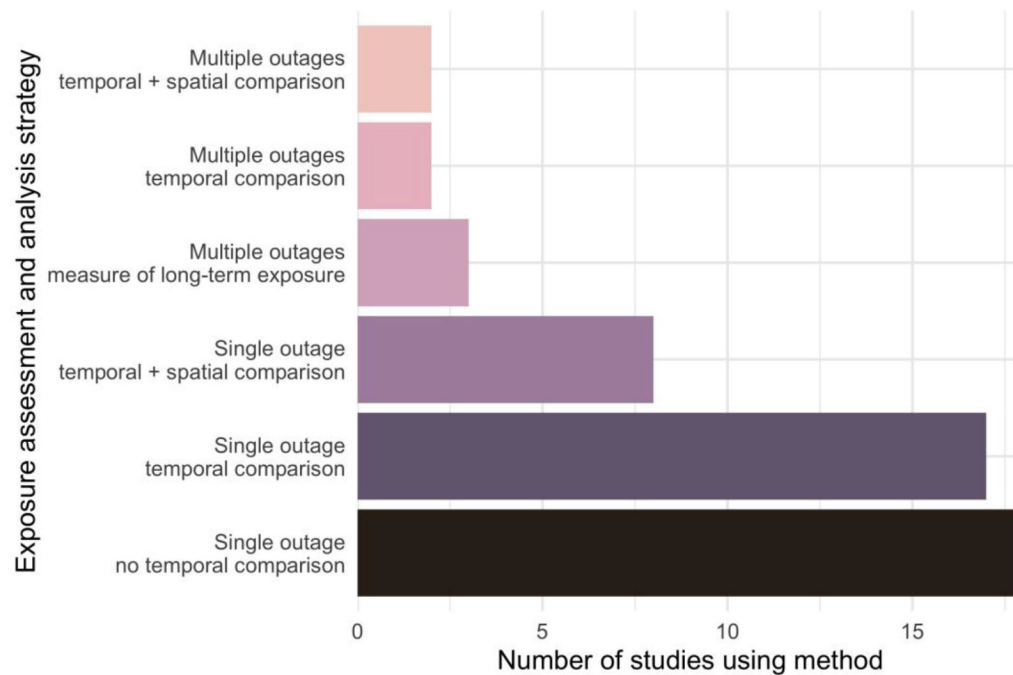


Figure 4: Exposure definition and analytic comparison groups used in 50 reviewed epidemiologic studies, 2004-2020.

Most studies evaluated a single outage by describing outcomes after the event among the exposed population (single outage, no temporal comparison). Eight studies evaluated a single outage but used both spatial and temporal comparison groups to make inference (single outage, temporal + spatial comparison). Three studies used measures of long-term exposure from multiple outages to assign levels of power outage exposure to the study population (multiple outages, measure of long-term exposure).

Table:

Recommendations for future exposure measurement and outcome assessment

Exposure assessment	Outcome assessment
<ul style="list-style-type: none"> • Consider duration of outage as a risk factor • Incorporate location of power outage (e.g., temperate versus cold climate) • Link outage and health data in space and time • Use tools from digital epidemiology: remote sensing, internet-connected devices, social media to characterize power outages • Account for co-exposures: physical hazards, psychosocial hazards, loss of property, etc. 	<ul style="list-style-type: none"> • Include both short- and long-term effects • Expand studies to include perinatal health, mental health, and outcomes among those with chronic illness • Consider susceptible populations including people of color, children, older adults, and those of lower socioeconomic status or with co-morbidities • Use large insurance databases or electronic health records to study large populations

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