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TOPICAL REVIEW

The climate-energy nexus: a critical review of power grid components, extreme weather, and adaptation measures

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Abstract

Extreme weather events and weather anomalies are on the rise, creating unprecedented struggles for the electrical power grid. With the aging of the United States power grid, the status quo for maintaining the transmission and distribution system, demand, generation, and operations will no longer suffice under the current and future conditions. Such conditions will require a shift in thinking and operating the power grid toward a weather-driven power system. This paper conducts a comprehensive review of each component of the power grid regarding the current leading weather events related to major power outages in the United States. For each event, contemporary issues and possible adaptations are presented, following a parallel comparison of the power grid development and knowledge of global climate modeling. Further, a background in global climate modeling is provided through the lens of an energy professional to aid in emission scenarios used in future studies. Overall, this paper works toward bridging the gap between weather and climate-related studies and operating the power grid in an uncertain climatic landscape while offering possible adaptations and solutions at a short-term and long-term scale.

In 2000, the United States (U.S.) National Academy of Engineering ranked electrification as the most beneficial engineering achievement of the 20th century (Constable and Somerville 2003). While an impressive feat, the current state of the power grid faces numerous challenges, especially concerning the bi-directional impacts of extreme weather events and climate change explained in figure 1.

The climate-grid nexus will require novel approaches to grid operations and updated power infrastructure. This nexus goes beyond technical implications, as climate models inform behavioral and policy shifts, which create a socio-politico-technical feedback process. A tipping point may be imminent—a time of mass change in behavior through adopting previously unpopular practices for climate action and adaptation. An example is the literature showing that social norms are a significant predictor of the probability of a household installing rooftop solar or energy efficiency measures (Lenton *et al* 2019, Moore *et al* 2022). These interactions are fundamental to climate policy and emission outcomes.

This review aims to synthesize knowledge on the current state of the power grid and how future climate may impact its operation, with a focus on extreme weather events rather than the long-term gradual impacts of climate change at multi-year timescales. It presents a parallel historical assessment of the development of the power grid together with contemporary milestones in our knowledge of climate change. From there, an exposition into how climate and weather may impact the power grid moving forward, observed problems within the grid-climate nexus, and possible solutions to create a more robust, weather-driven power system in the face of climate change are presented. The chosen approach examines categories of literature primarily focused on the Continental U.S. (CONUS) but remains insightful for other regions experiencing similar extreme weather events.The literature reviewed highlights gaps within the realms of transmission and

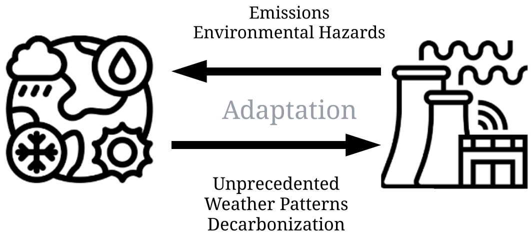

Figure 1. Energy-Climate Nexus Bi-Directional Impacts. In one direction, the power grid has endured unprecedented weather patterns such as heatwaves and extreme cold fronts. These factors impact energy production, power plant efficiency, and electrical demand; the latter often increases during these events. In the other direction, efforts to pursue decarbonization of the power grid are underway to reduce the impact of fossil-fuel generation on climate and the environment. However, decarbonization introduces more variable generation and Distributed Energy Resources (DERs). These wind, solar, and other zero-carbon energy technologies fundamentally change the balance of supply and demand.

distribution, demand, generation, operations, and adaptations for the most common weather phenomena that may impact the grid in a changing climate.

The remainder of this paper is outlined as follows:

1. Historical Context: This section provides a background of the knowledge surrounding climate change and the development of the CONUS power grid, considering technical knowledge and policy.
2. Extreme Weather Events: This section provides an overview of how the intensity and frequency of extreme weather events have changed over the past few decades. Next, an elucidation of historical weather events and future concerns (simulated predictions of the future) is provided regarding their impact on power grid components.
3. Adaptations: This section considers extreme events through the lens of adaptation measures for each power grid component. Adaptation measures implemented in practice and knowledge gaps in the current literature are discussed.
4. Conclusion and Future Works: This section summarizes the observed problems and possible solutions to bridge the gap between energy and climate professionals to plan for and operate a weather-driven power system.

1. Historical context

This section presents factors that have contributed to the current power grid infrastructure and operations while describing advancements in climate modeling and understanding. Historical events offer the potential to inform technology and policy moving forward and highlight discrepancies in knowledge. For instance, many historical records regarding power infrastructure may have been lost as areas have switched utilities or formed electric municipalities or cooperatives. While these events are not covered in this section, given their localized nature, a broad overview of significant milestones regarding the power grid and climate history is provided and illustrated in figure 2.

1.1. Energy history

Since the beginning of the Industrial Revolution, increases in atmospheric greenhouse gas have marked the onset of large-scale anthropogenic climatic change (Intergovernmental Panel on Climate Change 1990). The power grid, a cornerstone of modern society, began development in the late 1880s. In 1870, Thomas Edison built the first Direct Current (D.C.) generator. However, the Alternating Current (A.C.) system by Nikola Tesla took center stage in 1888 when Westinghouse Electric purchased Tesla's A.C. system patent. This time is known as the 'current-wars' as D.C., and A.C. systems and their supporters battled to determine whose system would power the world for centuries (Cohn 2017).

Ultimately, in 1893, Westinghouse Electric Company outbid Edison General Electric to power the Chicago World's Fair, leading to a victory for the A.C. system. Shortly after, in 1895, the Folsom Powerhouse in California brought high-voltage A.C. over long-distance transmission lines for the first time, earning an Institute of Electrical and Electronics Engineers (IEEE) milestone for the birthplace of the A.C. grid. IEEE milestones honor technical contributions with significant outcomes (IEEE Milestones Program 2017). A majority of the power system was then constructed through the rise of industrial America (1876–1900).

In the early 1930s, the passage of the Public Utility Holding Company Act allowed electric utilities to be recognized as public goods of importance, outlining restrictions and regulatory oversight of utility operations (Code of Federal Regulations 1935).

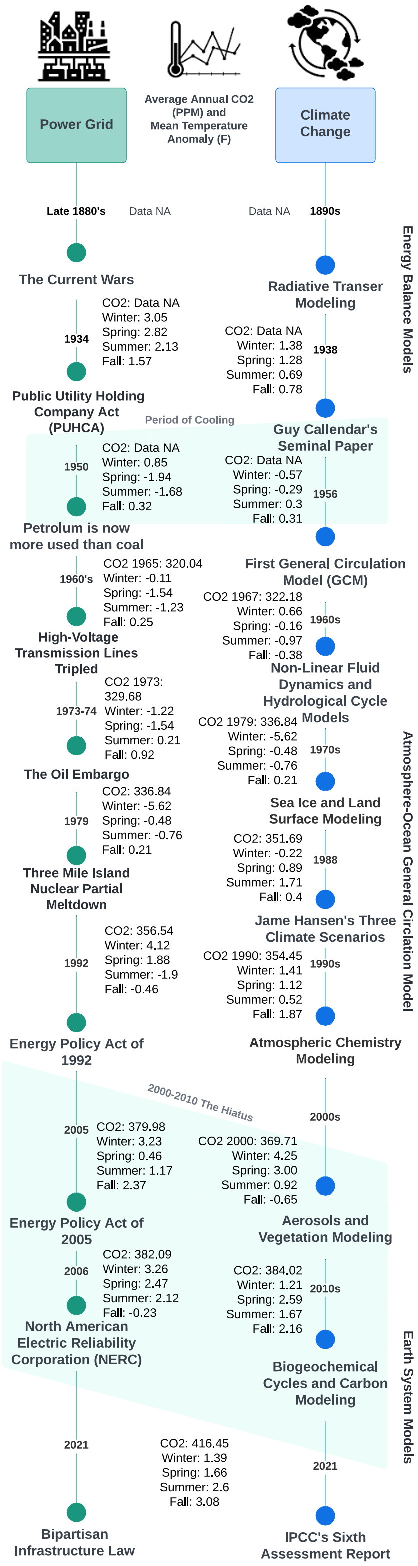

Figure 2. Energy and Climate Timeline. The timeline provides the average annual CO_2 levels (ppm) for the CONUS Atmospheric Administration and National Oceanic (2022) and the average seasonal temperature anomalies (°F) Environmental Protection Agency (2022). A key takeaway is an increase in CO_2 (ppm) and average temperatures among the CONUS. The climate timeline is adapted from Terando *et al* (2020).

In 1950, a change in the most-consumed source of electricity occurred, as petroleum replaced coal as the most used source (Energy Information Administration 2021). Then, the transmission system became the focus of the power grid between 1960–1969, as the number of miles of high-voltage transmission lines tripled from one decade prior, equating to more than 60 000 circuit miles expanding the electrical grid (Brown and Sedano 2004).

Entering the 1970s, the energy industry encountered challenges punctuated by the oil embargo, which motivated research in alternative energy sources, like solar, and more efficient energy practices, including Demand Response (DR) and temperature regulations in commercial buildings (United States Department of Energy 2023). Concurrently, the Federal Energy Regulatory Commission (FERC) was founded in 1977 to regulate the interstate transmission of energy in the U.S. (Federal Energy Regulatory Commission 2023).

The Three Mile Island Nuclear accident on 28 March, 1979, resulted in push-back against nuclear energy as an alternative energy source when one of the two nuclear reactors experienced a partial meltdown (United States Nuclear Regulatory Commission 2024). The 1980s were characterized by Three Mile Island, focusing on nuclear power regulation.

Entering the 1990s, policy movements were brought forth due to the recognition of global warming and the depletion of the ozone layer (Tuttle *et al* 2016). The Energy Policy Act of 1992 required transmission line owners to allow electric generation companies open access to their networks. This led to restructuring how the electric industry operated to create competition in power generation (United States Department of Energy 2022a).

Further, the Energy Policy Act of 2005 allowed incentives and loan guarantees for alternative energy production to advance innovative technologies that avoid emissions, which granted FERC new responsibilities, including monitoring environmental matters, energy markets, and reliability of high voltage power lines (United States Department of Energy 2022a).

The North American Electric Reliability Corporation (NERC), developed in 2006, became responsible for developing and enforcing reliability standards, including seasonal and long-term reliability metrics (Nevius 2020). In 2021, the passing of the Biden-Harris Bipartisan Infrastructure Law was passed, enabling 60 new U.S. Department of Energy (DOE) programs (United States Department of Energy 2022b).

1.2. Climate history

In the 1890s, Energy Balance Models (EBMs) focusing on radiative transfer modeling were used to understand the climate. EBMs performed simple, one-dimensional calculations of the radiation balance from the Sun's energy and the outgoing energy from earth (North *et al* 1981, Terando *et al* 2020).

In 1938, Guy Callendar released a timely study linking Carbon Dioxide (CO_2) levels in the atmosphere to global temperatures. Callendar was the first to publicly demonstrate that earth's land temperature had increased over the past half-century (Callendar 1938). Callendar's work was largely ignored until the late 1950s when scientists began questioning the rise in CO_2 and the correlation between burning fossil fuels. During this time, Norman Phillips developed the first Global Climate Model (GCM, originally called General Circulation Model) in 1956 (Phillips 1956).

While the power grid was experiencing rapid growth, the 1960s marked a shift in climate models, moving from EBM to Atmosphere-Ocean General Circulation Models, incorporating the use of nonlinear fluid dynamics and the hydrological cycle. In 1967, Syukuro Manabe and Richard Wetherald released a climate modeling study that would later be voted 'The most influential climate change paper of all time' (Manabe and Wetherald 1967).

Entering the 1970s, sea ice, and land surface modeling become regular features in Atmosphere-Ocean General Circulation Models, continuing to expand the thermodynamic and dynamic complexity of such models (Terando *et al* 2020). In 1988, climate change was entering global acknowledgment as James Hansen and a team from the National Aeronautics and Space Administration released a study with three climate scenarios: Scenario A being heavy emissions and scenario C being drastic emissions cuts, with scenario B being in-between (Hansen *et al* 1988).

Recognition of climate change prompted the Intergovernmental Panel on Climate Change (IPCC) to publish its first assessment report. The IPCC has since published assessment reports every six to seven years (Intergovernmental Panel on Climate Change 1990).

The U.S. Global Change Research Program (USGCRP) was developed in 1990. The USGCRP is a federal program for research and investments to advance knowledge around the global environment and societal impacts (United States Global-Change Research Program 2024). Further, the final component of Atmosphere-Ocean General Circulation models, Atmospheric Chemistry, was widely adapted (Terando *et al* 2020).

In the 2000s, an anomaly occurred as the trend of increasing global mean surface temperatures paused or slowed between 2000 and 2010 despite a continuous rise in CO_2 levels. This event is known as the *hiatus*. The hiatus has traditionally been characterized as external forcing, internal climate variability, or a combination of the two (Fyfe *et al* 2016). This decade marked significant advancements in computational power, incorporating aerosols and vegetation modeling within climate models, expanding the components of what we consider GCMs today (Terando *et al* 2020). Throughout the 2010s, climate modeling introduced biogeochemical cycles and carbon modeling. Models that include such cycles are referred to as Earth System

Models (ESMs). More about ESMs and GCMs, along with Representative Climate Pathways (RCPs), are discussed in the Supplemental Material.

2. Extreme weather events

Climate change may impact the intensity and frequency of extreme weather, such as heat waves and cold fronts, and may exacerbate extreme events such as wildfires (Coumou and Rahmstorf 2012). The National Oceanic and Atmospheric Administration (NOAA) reported that in 2023, the U.S. experienced 28 climate and weather-related events exceeding one billion or more losses in U.S. Dollars (USD). The 1990–2022 annual average was 7.9 events. Further, these events resulted in 492 deaths, the eighth highest amount of weather-related deaths in the CONUS since the 1980s (NOAA National Centers for Environmental Information 2023, Smith 2024).

Power systems are vulnerable to drought (Kimmell and Veil 2009, Union of Concerned Scientists 2012), water availability (Voisin *et al* 2020), flood (Souto *et al* 2022), high wind (Mohammadi *et al* 2020, Li 2023), high ambient air temperature (U.S. Government Accountability, Office 2014, Choobineh *et al* 2016), wildfires (Choobineh and Mohagheghi 2016, Umunnakwe *et al* 2022), and ice (Wang *et al* 2017, Dumas *et al* 2019). Such vulnerabilities are troublesome to public use and financially burdensome, shown in figure 3, and are likely to increase due to climate change.

The urgency to understand extreme weather events and be proactive in upgrading aging power infrastructure is evident, considering that 83% of major reported power outages in the U.S. between 2000–2021 were attributed to weather-related events. Further, there was an increase of 64% more major reported outages in 2011–2021 than in 2000–2010, with approximately 78% of outages in 2011–2021 being caused by weather-related events, shown in figure 4 (Climate Central 2022).

Resilient power systems research is increasing in popularity. Power system resilience definitions vary, as do reliability metrics, evaluation protocols, and system improvement strategies discussed in Jufri *et al* (2019), Bhusal *et al* (2020). The term resilience is derived from the Latin word resilio, which means to 'spring back.' As such, grid resilience conceptually relates to the ability of the grid to recover from disruptions (Alexander 2013). In comparison, grid reliability relates to the ability of the grid to perform under certain conditions and for a given time interval (International Electrotechnical Commission 2024).

The remainder of this section will discuss extreme weather events concerning power system transmission and distribution, generation, operations, and demand. Each section will discuss historical events and future concerns (simulated studies). If a weather event does not significantly impact a level of the power grid, that level will be omitted; similarly, if there are no significant stand-alone historical events, only future concerns will be discussed. A summary of key findings from this section is provided in table A2 of the supplemental material.

2.1. Heatwaves

A heat wave is an extended period of excessive heat or atmospheric heat stress (Zuo *et al* 2015). The World Meteorological Organization defines a heat wave as a period with a daily maximum temperature of 5 °C above the typical temperature for five or more consecutive days. The typical temperature is defined based on a multi-decadal period, such as 1961–1990 (McCarthy *et al* 2019).

Transmission and distribution systems are heavily impacted by heat waves. Overhead conductors, or power lines, will operate less effectively in extreme temperatures because power providers rate transmission system ampacity based on historical temperature data (Kimp *et al* 2019). The line capacity is limited by the maximum typical operating temperature, traditionally around 80 °C Line operating temperature is impacted by the current flowing through the line, the ambient temperature, and wind speed.

Aside from overhead conductors, heat waves can cause complete failures, brownouts, or fires from system substations, particularly transformer banks. The actual peak-load capability of transformers depends on the ambient temperature, which varies significantly from the designed nameplate rating typically assumed to be 30 °C (Li *et al* 2005). Ambient temperatures impact transformers via the transformer's hot spot conductor temperature (HST). The HST is the highest temperature area in the transformer due to the flux leaking through the transformer windings.

Electrical demand is heavily influenced by outdoor temperatures as approximately 75% of electricity is used by residential and commercial buildings, with 16.2% of energy used contributing to space cooling in residential buildings and 10.2% for space cooling in commercial buildings in 2022 (U.S. Energy Information Administration 2022). Extreme heat was the direct cause of only 1.9% of major power outages from 2000–2021.

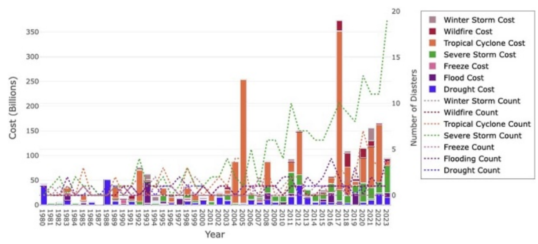

Figure 3. U.S. Natural Disaster Occurrence and Cost since 1980. The cost data is represented by the solid bars in USD and is Consumer Price Index adjusted. The event occurrences are presented by dashed lines for each year. Both cost and occurrence data are provided by NOAA National Centers for Environmental Information (2023). A consistent increase in wildfire costs has been present since 2017. Tropical cyclone occurrence and cost do not correlate, while events such as drought and flood most commonly alternate over the years.

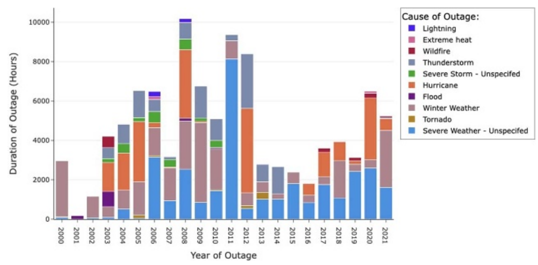

Figure 4. Duration of Major Power Outages in the CONUS. The power outage duration in hours shown per weather event for power outages impacting 500 000 customers or more between 2000–2021 Climate Central (2022).

2.1.1. Historical events

A recent example of heatwave impacts on demand is during the 2022 September heatwave in California, when the highest electricity peak demand on record for the California Independent System Operator (CAISO) was reached on 6th September, 2022, at 51 426 MW. CAISO reported that the Western Interconnection set a new peak demand that day at 164.6 GW (California Independent System Operator 2022a). While this event did not result in rolling blackouts, DR was heavily utilized. In September, DR was responsible for a demand decrease of 1882 MW. Regarding DR, Mayhorn *et al* (2015) has dubbed four terms to describe how building loads can respond to the grid provided in table 1. Lastly, Battery Energy Storage Systems (BESS) could provide grid stability during heatwaves, as BESS provided 6.8% of supply during the September heatwave in California (California Independent System Operator 2022a).

2.1.2. Future events

For transmission and distribution systems, Sathaye *et al* (2012) conducted a study for the California Energy Commission and found that transmission capacity could potentially be reduced 7%–8% with an increase in air temperatures, specifically a 5 °C increase on an August day. While Bartos *et al* (2016) investigated 121 planning areas in the U.S. during peak summer demand and found summer reductions of transmission capacity ranging from 1.9%–5.8% on average from 2040–2060, compared to 1990–2010, depending on the GCM and emissions scenario, due to rises in ambient air temperature.

Sathaye *et al* (2013) found a decrease in transformer capacity up to 2.7% induced by increases in ambient temperatures, which would require a projected 3.5% more generation needed to overcome losses.

The relationship between environmental variables, including ambient temperatures, will vary across regions and substations size, Swift *et al* (2001), Li *et al* (2005), Sathaye *et al* (2013)work to quantify the impacts of ambient temperatures on transformer capacity and lifespan, as Li *et al* (2005) found a decrease in transformer capacity equating to 0.7% for every 1 °C increase in ambient temperature. However, this varies, given the allowable HST limit and the cooling equipment installed.

In Steinberg *et al* (2020), generation capacity and load are investigated through 2050, primarily considering drought and temperature deviations. Intuitively, demand increased with increases in temperature for the CONUS, with an average demand increase of 1%–2% for every 1 °C increase in air temperature with regional differences, the magnitude of change depended on the chosen climate scenario.

Heatwaves impact generation primarily through efficiency losses. For the Central and Eastern U.S., thermal, fossil-fuelled and nuclear power plants that supply 11% of electric power production for the entire U.S. is studied in Vliet van *et al* (2012). Results found that plant reductions of 25% occurred on 29–30 days,

Table 1. Demand Response Terminology. Terms used to describe demand response strategies that could be used under periods of grid strain (Mayhorn *et al* 2015, Fallahi and Henze 2019).

Shaping	A type of demand response that changes the load profiles of buildings and electric vehicle charging to be aligned with the grid.
Shifting	Shifting the load, usually on an hourly basis. This could be done to avoid curtailment of renewable energy resources or due to a shortage of generation.
Shedding	Typically considered with DR, as the load is shed at peak demand to match the supply.
Shimmying	Similar to shedding, but is more of an ancillary service given it targets loads that can adjust within seconds to minutes

50% on 15 days, and 90% for one day. Through the lens of compliance contingencies for thermal plant cooling, such as water temperature violations and stream flow waivers, an average reduction in generating capacity of 2%–3% is predicted for thermoelectric plants by the 2060s with streamflow waivers. However, reductions up to 12% are possible if waivers are not granted (Liu *et al* 2017a). While Miara *et al* (2013) suggests a 2.5% decrease in capacity in summer and highlights the need for regional studies to better understand thermal plants' environmental, hydrological, and energy impacts.

Outside of thermal generation, solar energy production decreases with rising temperatures dependent on the material and type of solar plant. This occurs due to panels generating less voltage, which decreases efficiency in producing electricity. For Concentrated Solar Power (CSP) and Solar Photovoltaic (PV), Crook *et al* (2011) used GCMs to study solar production worldwide. In the U.S., CSP showed an increase in the Northwest and a decrease in the Southwest, while PV output is predicted to experience a minor decrease in the Western U.S. However, more regional studies should be performed.

To adjust to more frequent heatwaves in the future Alawad *et al* (2021) considers heatwaves from an operational standpoint under conditions from the 2011 Texas Heatwave, a 40-day period having a consecutive temperature above 38 °C.

Other studies such as Choobineh *et al* (2016) investigate how the optimal operation of a distribution system can change during a heatwave. Findings suggest that dispatch cost increases with increased temperatures; further, the dispatch model purchases less power from the grid despite an increase in load. This occurs under heatwaves due to the effect of temperature on the overhead line and gives prominence to the argument that even with adequate capacity, the system becomes strained due to energy transport constraints (generation limitations, equipment inefficiencies, increased prices, and line losses) under high temperatures.

2.2. Extreme cold temperatures

Winter temperatures in the U.S. and worldwide are warming. However, winter weather extremes may become more frequent in the Northern Hemisphere. This means fewer snowfall events overall but more extreme events when they do occur (Quante *et al* 2021). However, some model projections have suggested that winter weather will become milder, with less frequent snowfall. Winter weather can be controversial due to its connection with arctic variability. Currently, the Arctic is warming at twice the global average rate, and simultaneously, many regions, including the U.S., are experiencing more severe winter weather.

In Cohen *et al* (2021), a disruption in the stratospheric polar vortex pairing wave reflection and stretching is linked to extreme cold in the U.S. while Cohen *et al* (2020) shows that high-latitude blocking, slow-moving high-pressure systems at high altitudes are related to more frequent, heavier snowfalls in the Eastern U.S. Further, their atmospheric intercomparisons show that a relatively warmer arctic can be associated with increased extreme winter weather, in the Eastern U.S. and the upper Midwest U.S.

From an infrastructure standpoint, winter weather can cause extreme loads on power lines due to icing and cold soil temperatures that could impact substations. Ice build-up on power lines, which is especially dangerous for transmission lines, can cause galloping conductors when the wind blows into the iced conductor and creates a gallop or jumping motion that can lead to a fault or subsequent outage (North American Electric Reliability Corporation 2021). Additionally, the weight of the ice may cause sagging or a collapse of the power line (North American Electric Reliability Corporation 2021).

Considering substations, soil resistivity increases with snow or frozen soil, which increases ground resistivity, touch voltage, and step voltage (He *et al* 2003), which could create safety issues. At the same time, power switches may also struggle in freezing temperatures.

Winter weather primarily impacts power system operations through increased demand and market prices (Lin *et al* 2022). The electricity market is impacted by the increase in demand, power line failures, generation decreases, and an increase in the price of natural gas, which would impact the clearing price of the electricity market.

Winter weather related to snow, ice, and freezing rain accounts for 22% of weather-related major power outages. Winter weather-related outages may occur due to the increase in load associated with cold temperatures as buildings need to be heated. Such outages may also occur due to a lack of energy resources or the ability to transport resources.

2.2.1. Historical events

A large-scale example occurred in 1998 in Eastern Canada and the Northeast U.S. when freezing rain destroyed approximately 1000 transmission towers and 30 000 utility poles, causing power outages and disrupting transportation systems (Jeong *et al* 2019). Alternative methods are used by utilities in Canada to defrost overloaded lines. Quebec, Canada, has the only high voltage D.C. not used for transmission but for de-icing multiple A.C. power lines, known as the Levis De-Icer (Kirby *et al* 2008).

In December 2022, National Grid, an electricity and gas provider in Buffalo, New York, experienced blackouts that impacted thousands of customers due to substations going offline due to frozen transformers, responsible for stepping down the voltage to the distribution level (National Grid 2022), creating the need for greater weatherization procedures for transmission and distribution systems.

In 2014, a polar vortex impacting the Eastern interconnect set a new winter peak demand for the CONUS at 140 510 MW in the Pennsylvania-New Jersey-Maryland Interconnection (PJM) territory. PJM is a regional transmission organization that governs electricity operations for 13 states and the District of Columbia. During the 2014 polar vortex, PJM implemented DR three times, one DR event lasting over four hours, to attempt to reach an equilibrium between supply and demand (Wang *et al* 2017). As the outage rate for generators, primarily for thermal generation, in the PJM territory was 22% compared to the previous average of 7% (Interconnection 2014).

The 2021 Texas Winter Freeze is a recent example of how extreme winter weather can impact power generation. One prominent cause of the cascading failures was that approximately 40% of natural gas production was unavailable. Freezing gas wells and pipelines that transport natural gas were two significant causes relating to compressor stations experiencing power outages. Compressor stations maintain natural gas flow and pressure from the pipelines. Texas is more prone to warm periods. Thus, most power stations are not in buildings, which traditionally helps minimize overheating but exposes them to freezing winter conditions (Busby *et al* 2021). It is important to note that other energy resources, such as coal, nuclear, and wind, also struggled to generate electricity during this time, primarily due to inadequate weatherization.

Relating to natural gas well freezing or 'freeze-offs,' there are typically two ways this occurs:

1. Above-ground and wellhead structures may be vulnerable to simple freezing, as the liquid turns to ice and blocks the wellhead or outward-bound pipes, although buried pipelines could be susceptible to this with extremely low ground temperatures.
2. Combined high-pressure and low-temperature environments turn liquid and liquifiable hydrocarbons into hydrate masses that block the line.

System design criteria typically use 30 years or, in some cases, 100-year historical data for design assumptions. The 2021 Texas Freeze surpassed historical weather, with record low temperatures from the past 150 years. Thus, the system design was not meant to withstand such cold weather conditions (Smead 2021). Moving forward, it is essential for traditionally warm climates, especially those in the Southern U.S., to take preventative measures even if historical freezing temperatures are not typical. In the case of Texas, previous winter storms have affected the state, including those in 1989, 2003, and 2011.

Regarding the Texas 2021 freeze, emergency load shedding was implemented to avoid a system-wide blackout. During the three coldest days of the winter freeze, the electricity wholesale market reached a maximum cost of $9000/MWh. The wholesale cost before the freeze ranged from $20/MWh–$40/MWh. Concurrently, natural gas reached a maximum wholesale cost of $117/MWh, with prior costs ranging from $0.88–$1.17/MWh)

2.2.2. Future events

Future concerns for power infrastructure include findings from Jeong *et al* (2019), Li (2023)who predict that ice loads pose a threat to infrastructure in Northern North America, but Southern North America and the Northeast coast may experience a decrease in ice loads. This highlights the spatial complexity of climatic change and its impacts on critical infrastructure.

With increased building electrification, the electrical load will likely increase during severe winter weather. This creates a question regarding dual-season/winter peaking in electrical grid operations.

Traditionally, in the U.S., the annual peak is in the summer, and heating was often gas-powered. For instance, Keskar *et al* (2023) suggests that areas within PJM, such as West Virginia, Virginia, and Kentucky, may exhibit winter peaking behaviors in the future. Winter peaking could be particularly challenging for investor-owned utilities since most must submit integrated plans to the state's public utility commission (Keskar *et al* 2023). Additionally, battery storage systems may also struggle during extremely cold temperatures as they hold less charge and drain more quickly (Lu *et al* 2022). Although winter peaking often occurs in Europe, the implications for grid operations with a transition from winter to summer peaking or dual peaking remain unknown.

To operate the grid, Keskar *et al* (2023) suggests seven policy recommendations for grid planners and operators to ensure grid reliability throughout the winter weather. These include increasing transmission capacity, resource adequacy planning for the relationship between temperature and generator failures, implementing similar policies used by winter peaking regions, and determining demand-side management techniques suitable for a winter peak.

2.3. Droughts

Similar to the predicted changes in winter weather, there are differing projections for precipitation events, with the most agreement among increases in rainfall extremes, periods of heavy rainfall, and periods with extreme drought. Drought impacts are seasonal and regional. The Southwest U.S. is predicted to experience extreme or megadroughts (Williams *et al* 2020), while the Northern Great Plains, Southeast, and Northeast may experience periods of heavy precipitation creating an overall increase in precipitation (Peterson *et al* 2013). In Harp and Horton (2022), the intensity distribution in precipitation is predicted to change across the CONUS, with increases in average precipitation for the Eastern U.S. and mixed results for the Western U.S., likely due to extremes.

Significant impacts on hydroelectric power from droughts include dead pooling, water flow operating issues, and conservation needs. Dead pooling is when reservoir levels are lower than turbine intake, causing power generation to stop until water levels rise. Water flow operating issues occur when water reservoir levels are too low for hydropower operations. Conservation needs to limit reservoir releases to supply water for municipals or other needs. Dead pooling and water flow operating issues could also be a side effect of flooding if stream flows are dammed to prevent downstream damages, such as the destruction of natural or built environments.

Droughts can cause extreme hardships for the power grid, as they often span across large, multi-basin areas. Thus, generation limitations are often not limited to a single plant. Concurrent plant operating limitations across a grid region can occur, increasing the dependence on power imports for the region and power outages or rolling blackouts (Voisin *et al* 2020). Further, approximately 70% of U.S. generation capacity requires cooling while more than 48% requires fresh surface water for the cooling, which would be tied to hydrological drought (Union of Concerned Scientists 2012, Dieter *et al* 2018). Although droughts may often be coupled with anomalously high temperatures (Mazdiyasni and AghaKouchak 2015), they have not been classified as a cause of major power outages in the CONUS.

2.3.1. Historical events

Approximately one-third of U.S. thermoelectric capacity reports a primary water source as a lake or reservoir. Reservoirs were the reported water source for approximately 25% of curtailments between 2000–2015. Such curtailments are most commonly caused by a lack of cooling water, high intake temperatures, or high discharge temperatures.

Regarding hydroelectric generation, Washington, California, and Oregon contribute the highest percentage of hydroelectric power to the grid, specifically the Western Interconnect. Droughts in 2021 presented the lowest hydropower generation in the Western Interconnect since 2001. This results in generation levels nearly 16% below the average for the 21st century. Beyond the Western Interconnect, total annual precipitation strongly correlates with total annual generation from hydropower plants in five out of eight climate regions in the U.S. (Turner *et al* 2022).

2.3.2. Future events

In Cohen *et al* (2014), a study investigating water rights availability, power system operations, and electric power growth finds surface water availability had the most significant decrease in the Southwest, with regional differences in water withdrawal resources. Most of the water withdrawal attributed to existing nuclear and coal-fired plants in the East, where water is less constrained. The report also highlights how averaged projections may be misleading regarding power system sensitivity, as individual systems often experience stress during weather events, not the average.

Findings from North American Electric Reliability Corporation (2022) highlight Resource Adequacy and Risk issues across the U.S., including decreases in energy output from hydropower generation due to drought and low snowpack in the West, drought, and heat events that could heavily influence peak demand in Texas and the Midcontinent Independent System Operator capacity limitations resulting in energy emergencies at peak demand. Accordingly, Bartos and Chester (2015) found that renewable power generation is generally less vulnerable to the impacts of climate change, with the most significant constraints coming from an extreme drought event. By the mid-century, a ten-year drought could reduce summertime capacity by 6.6–8.0 GW, 3%–4% of the Western Interconnection.

Due to droughts' impacts on generation, it is vital to better understand the balance between supply and demand during precipitation extremes. In Jornada and Leon (2016), electric generation decision-making using a multiobjective function to minimize cost and water withdrawal is studied, while Kumar *et al* (2022) incorporates water into the economic dispatch problem. Further, Wu *et al* (2010), Hadji *et al* (2015), Kravits *et al* (2022a, 2022b) incorporate water metrics in the Optimal Power Flow (OPF) problem. A common finding suggests that implementing water constraints as part of the OPF may result in more proactive rather than reactive operations. Such advancements in operational frameworks for periods with water stresses have the potential to aid in identifying system vulnerabilities and intercomparison of vulnerabilities across the network (Kravits *et al* 2022a).

In contrast, an electric grid dispatch model provides insight into years of increased stream flow followed by years of drought. This model shows that years with increased precipitation only sometimes equate to increased hydropower generation due to spill events. Overall, they found a slight decrease or no change in hydropower generation but greater temporal variability (Tarroja *et al* 2016). Precipitation may also impact production costs and utility profit margins. Moving forward, dose-response functions should be further explored as they are a type of regressions model that can quantify the physical response of a system component in the system to its exposure to climate stress (Dumas *et al* 2019).

2.4. Non-hurricane and non-tornadic extreme winds

Wind is defined as the movement of air caused by uneven temperatures or heating of the earth due to solar radiation or the earth's rotation, while the speed of wind is proportional to the pressure gradient. This means higher pressures create higher winds. There have been disagreements in models for how climate change will impact the wind. Recent studies, provide insight that by 2100, the Western U.S. and the Atlantic Coast of the U.S. will experience a decrease in wind speeds, while the central plains in the U.S. will see an increase in wind speed (Deng *et al* 2022). Looking at the short term, Zeng *et al* (2019) suggests that wind speeds are growing stronger for parts of the globe, but similarly suggests an overall decrease for the U.S. However, extreme winds, especially when paired with hurricanes, are expected to increase.

Wind can have direct and indirect impacts on the power system. Extreme winds can directly cause conductor slap, blow down equipment or vegetation onto equipment, or cause other equipment failures, especially capacitor banks that are often outside for cooling effects. Wind speed and direction directly impact wind power production, as wind turbines cannot produce electricity with wind speeds that are too low or too high. The wind speeds related to wind power production are called the 'cut-in speed' and differ depending on the wind turbine design.

Indirectly, wind can increase other phenomena or be combined with other phenomena, discussed in sections 2.5–2.7. Considering the direct impacts of wind on the power system, Northeast utilities estimate 38% of their service territory power outages result from extreme winds and reported an average 8-hour restoration time (Li *et al* 2014).

Directly wind, thus wind power generation, impacts power system operations through power system dynamics and the intermittent nature of wind power generation. While the focus of this paper is not power system dynamics, a review of such challenges is provided in Ahmed *et al* (2020) and includes voltage support, frequency, and power system harmonics. Wind power generation is impacted by wind speed and direction, as well seasonality and duration (Li and Kopp 2023) which impacts power system operations through cost, as the clearing price for wind power is significantly lower than thermal power plants, and through carbon emissions, as wind power production is carbon emission-free. Extreme wind may impact operations due to damaged power lines or poles and the transmission and distribution system.

2.4.1. Future events

Extreme winds predominately impact transmission and distribution systems through structural damage. To study structural impacts on the power system, lattice power towers are modeled to capture buckling and post-buckling effects, joint slips, and power tower failures due to extreme winds. These events can be catastrophic given that power towers carry overhead power lines, generally high-voltage transmission lines. To model the lattice transmission towers, finite element modeling is paired with a Monte Carlo simulation for uncertainties of failures. Findings conclude that buckling from extreme wind, on average, decreases load-bearing by 30%. Additionally, findings show that elements experience partial failures prior to complete failure. These findings could be used to assess vulnerabilities and aid in recovery strategies (Mohammadi *et al* 2020).

Specific to distribution and low-voltage power lines is the fragility of wooden poles to extreme wind speeds, especially as power infrastructure is aging, with most wooden poles being over 30 years old (Pansini 2020). One way to gauge the impacts of wind on power infrastructure is fragility curves and damage functions. Fragility curves provide a probability of system or component failure in response to exposure to extreme wind. Damage functions relate the intensity of wind to the mean damage ratio. Numerous methods exist to develop these curves, including judgmental, empirical, analytical, and hybrid (Dumas *et al* 2019).

Time-dependent fragility curves are studied in Shafieezadeh *et al* (2014) concerning wind speeds, using regulated wooden pole types. Findings conclude that focusing on examining poles 25 years and older in wind-prone areas was consistently determined as the most high-risk parameter across pole types. This promotes using such methods in risk-informed decision-making for maintenance, inspections, and replacements. Further, the study found a failure probability of one for transmission lines at winds of 65 $\frac{m}{s}$ and poles at 100 $\frac{m}{s}$.

Due to the cut-in and cut-out speeds, wind speed and direction impact wind power production. In Pryor and Barthelmie (2010), a review of climate change impacts on the wind energy industry was conducted, highlighting that many studies focus on wind availability, but other climatic factors such as extreme winter storms, icing the wind turbine blades, high and low temperatures, impacting physical components, the ability to access remote wind farms, and extreme wind gust that result in curtailing the wind turbine, need to be understood at a deeper level.

While Sailor *et al* (2008) used two GCMs to estimate wind energy potential under climate change. The results showed a considerable disagreement between the models, with one model suggesting minimal impacts on wind resources, while the second model suggests mean wind reductions of 10%–15%.

Similarly, Karnauskas *et al* (2018) finds that when using RCP 4.5–8.5 with 10 GCMs, wind power decreases 8%–10% for the CONUS, yet increases in the Eastern U.S. by 2050. In contrast, Pryor *et al* (2012) suggest that wind power generation will decrease in the Western, Northeast, and Northwest U.S. but increase in parts of Texas and Kansas. Overall, extreme winds' impact need to be understood further, but the CONUS should expect a decrease in generation in some areas.

This agrees with Pryor *et al* (2023) who studies the change in wind power capacity factors and projected power under climate change, using dynamic down scaling techniques. Findings suggest that projected power remains largely unchanged East of the rocky mountains in North America. However, five wind energy facilities show significant decreases, three in the midwest, one in the Northern Greater Plains, and one in the Northeast. Further, Jung and Schindler (2019) finds a decrease in average near-surface wind especially in U.S. West, using a suite of models and RCP 8.5.

Offshore wind, the U.S. has a goal to have 30 GW of offshore wind capacity by 2030 win (2023). Yet, limited research is available regarding the impacts of climate change on off-shore wind in the U.S. Fatigue damage and structural saftey of off-shore wind turbines were found to be sensitive to conditions such as wind speed and wave height in future climate scenarios, while non-structural components were found to be more robust Wilkie and Galasso (2020). In the United Kingdom, (Abdelaziz *et al* 2024) studies off-shore wind potential during times of low wind speeds. While (James *et al* 2023) highlights how climate variables such as wind speed, wave height, and sea ice melt will impact off-shore wind in the future.

2.5. Wildfires

In the U.S., wildfire severity has notably increased since 1985. The Fourth National Climate Assessment published in 2018, projects that annual burn area in the contiguous Western U.S. will increase between 200% and 300% by mid-century (Dzaugis *et al* 2018). When investigating the impacts of anthropogenic climate change seasonally, Williams *et al* (2019) found that anthropogenic warming is likely to increase summer wildfires by drying fuels. Large fires are likely to increase due to continued warming and a gradual decrease in fall precipitation in the Western U.S. These weather patterns could suggest a prolonged wildfire season, as seen with the Marshall Fire in December of 2021, becoming Colorado's most destructive wildfire in terms of buildings destroyed, totaling 1091 residential and commercial buildings combined (Boulder County Government 2022).

Wildfires ignited by electric infrastructure often correlate with larger burn areas and higher remediation costs due to wildfire occurrence when fire danger is high. The probability and frequency of electric-caused wildfires occurred with increased wind speeds. Electric power infrastructure can induce wildfires, including downed power lines, vegetation exposure, conductor slap, and infrastructure failure. These accidents can produce fault currents or sparks in windy, hot, dry, and heavily vegetated places that may ignite a wildfire. The most common source is contact between power lines and vegetation (Russell *et al* 2012, Jazebi *et al* 2020). Wildfires account for 2.4% of outages, yet 65% were within 2017–2021.

2.5.1. Historical events

Approximately 80% of past vegetation-related issues for power systems result from fallen trees or branches into transmission and distribution systems. These incidents are often caused by trees that are not part of the electric utility's right-of-way (Russell *et al* 2012). However, vegetation management is a challenging and expensive task (Wischkaemper *et al* 2008). In the U.S., it is common for utilities to trim approximately 12 feet of clearance away from distribution lines. However, a case study in the Southeastern U.S. suggests that vegetation debris from up to 100 feet from power lines could evoke damage to the system (Guikema *et al* 2006).

The most destructive and deadliest wildfire in the history of California, the 2018 Camp Fire, was caused by faulty power line components. The Camp Fire resulted in 85 deaths, 18 804 structures destroyed, and $400 billion in total cost (insured losses, debris removal, and victim aid). Between 2015 and 2020, electric power caused an average of 10% of wildfires in California while being responsible for an average of 33% of acres burned and 70% of damages ($17.5 billion) (Cal-Fire 2020). Between 2000-2016 wildfires cost utilities in California more than $700 million in damages (Dale *et al* 2018).

Wildfires can also impact power generation, as in 2020 CAISO experienced an approximately 30% reduction in solar production due to wildfire smoke, which contains airborne particles with a diameter of 2.5 micrometers (PM2.5) that reduces the exposure of sunlight to solar arrays, reducing the electricity produced (York 2020).

Current approaches utilities take to operate the grid during wildfires include Public Safety Power Shut-Offs (PSPS). PSPS turns off or de-energizes the power to lines in areas with high wildfire risk. De-energization effectively reduces fire risk by preventing fault events that could ignite a wildfire (California Public Utilities Commission 2023). However, PSPS can result in prolonged blackouts, having adverse health, economic, and societal impacts, particularly for venerable socio-economic communities, often in rural WUI areas (Sotolongo *et al* 2020). Approximately one-third of wildfire-related outages were due to PSPS.

2.5.2. Future events

Another threat to the wildfire-power infrastructure nexus is the expansion of the Wildland-Urban Interface (WUI), where the built environment imposes the natural environment. It is estimated that around 50 million residential buildings are in the WUI, and approximately one million additional homes enter the WUI every three years (Burke *et al* 2021). This means distribution systems and transmission lines have emerged in the WUI. Distribution lines impose a threat as they are three times more likely to ignite a wildfire than transmission lines on a per-mile basis (Pacific Gas and Electric Company 2019).

A late-summer wildfire season in the Western U.S., is projected to pose a reliability risk to the bulk power system (North American Electric Reliability Corporation 2022). Further, in Cai *et al* (2023), the years 2017–2020 are studied relating to solar power generation and solar power forecasting errors in CAISO during wildfires. In this study, 2019 was used as the baseline year, as it was the year with the smallest wildfires. Compared to 2019, each year studied experienced reduced solar power production and increased forecasting errors during a wildfire event. Regions with a high penetration of solar energy should consider how wildfire events may impact the generation mix and be prepared to use backup generation.

To address these issues, recent studies have aimed to balance the effect of blackouts with wildfire risk (Rhodes *et al* 2021, Rhodes and Roald 2022, Umunnakwe *et al* 2022). A dispatch model considered how preventive wildfire risk measures impact both wildfire risk and power systems reliability in Rhodes *et al* (2021). The optimization problem aims to reduce the risk of wildfires from power lines and meet the maximum load and was successful in serving more load at a lower risk.

Building upon Rhodes *et al* (2021), Rhodes and Roald (2022)implemented a rolling horizon co-optimization problem, optimizing both power shut-offs considering wildfire risk and post-wildfire restoration. Results suggest that using a longer forecast horizon allows for a better understanding of the impacts of line de-energization. However, a longer forecast horizon typically results in more significant forecast errors. The larger the restoration budget, which represents the available resources to inspect and restore power lines, the greater the number of lines de-energized and more quickly restored. A higher vulnerability threshold increases system redundancy, increasing wildfire risk and power line operational security. While Umunnakwe *et al* (2022) found spatial resolution to be an important factor in modeling PSPS, as forced outages due to de-energization were decreased with the use of more granular spatial models.

2.6. Hurricanes

Hurricanes are tropical storms that need warm ocean temperatures, high moisture levels in the air, low vertical wind shear, and a disturbance (i.e. thunderstorms) to form. Hurricanes are challenging to predict, and their relation to climate change is an active field of research.

Yet, recent findings suggest that Atlantic hurricanes are increasing in intensity at a rate not explained by natural variability Bhatia *et al* (2019). Similarly, Holland and Bruyere (2014) found a 25%–30% increase in category four and five hurricanes for each 1 °C increase, paired with a decrease in category one and two hurricanes, but suggested that the increase in category four and five hurricanes is likely to level off beyond a certain warming threshold dependent on the region.

Regarding hurricane wind speeds, Knutson *et al* (2020) finds an increase in surface wind speeds during a hurricane event, ranging from 1%–10%, along with a medium to high confidence in an increase in more intense, category 4–5 hurricane events for North America. Similarly, Webster *et al* (2005) finds a significant increase in category 4 and 5 hurricanes in the East Pacific, with the smallest increase in the North Atlantic. However, the number of hurricanes decreased in each region except for the North Atlantic. Alternatively, Rendfrey *et al* (2021) found an increase in hurricane occurrence in the Eastern Pacific basin and an increase in the northerly latitudes over the North Atlantic, with associated rainfall increasing. At the same time, wind speed remains stationary, increasing in only a few simulations. Regarding power systems, hurricanes were the cause of 15% of major power outages between 2000 and 2021.

2.6.1. Historical events

Hurricane impacts on the power system have been widespread in recent years. Hurricane Maria devastatingly destroyed Puerto Rico's grid in 2017, which took approximately 11 months to completely restore, marking the most continuous blackout in U.S. history, with only 65% of the grid being restored by the end of January 2018, as 80% of utility poles and a significant portion of transmission lines were destroyed (United States Department of Energy 2018a). The following year, in 2018, Hurricane Michael became the first category five hurricane to make landfall in the CONUS, resulting in outages spanning six states and 1.7 million customers (United States Department of Energy 2018b).

In the case of Hurricane Maria, wind force vs. deforestation and rainfall vs. landslide were shown to be the most significant in terms of coupled hurricane factors through correlation factor analyses and modeled structural failures (Chen *et al* 2021).

For power generation, natural gas systems are a crucial issue when considering hurricanes. During Hurricane Katrina, approximately 88% of daily gas production was shut-in (i.e. the valves of natural gas wells are closed to stop production), and 20% of natural gas capacity remained shut-in through 2005. Similarly, 80% of natural gas was shut-in during Hurricane Rita. Considering coal, the Mississippi River was used for coal transport, which was interrupted for multiple weeks after Hurricane Katrina (Gil and McCalley 2011).

For Hurricane Sandy, approximately 32 000 consumers were affected due to the lack of gas distribution, highlighting large-scale disruptions caused by hurricanes and the loss of transmission or gas pipeline, which could quickly distribute in the system and lead to cascading failures. The interdependency between the electric power and natural gas systems has increased due to the gas-operated distributed generation and electric gas compressors (Davidson *et al* 2003, He *et al* 2018, Waseem and Manshadi 2020). Additionally, other times of power generation, such as ground-mounted solar power, could be impacted by flooding due to hurricanes.

2.6.2. Future events

In Yuan *et al* (2016), numerous optimization models were tested to effectively budget resources for hardening against hurricanes, a resilient distribution network planning problem. Findings suggest a two-stage robust optimization problem adequately includes the uncertainty of such natural disasters, extending the use of traditional N-K interdiction models. N-K models model the number of K power components that, if failed, would result in a worst-case power disruption, as N represents the number of power lines in the system.

Similar to wildfires, distribution systems suffer more from hurricane damage than transmission systems, given the materials used in distribution system infrastructure and design (Davidson *et al* 2003). However, numerous studies have identified vulnerabilities in the transmission system, such as in Liu and Singh (2011), which uses a load model, generation system, and transmission network to explore the nonlinear relationship of hurricane parameters and increment multipliers failure rates of the transmission lines. The models effectively evaluated the temporal and spatial impacts of the power system against hurricanes and found that power line damages are a primary reason for power outages during hurricanes.

Power system operations during hurricanes traditionally entail immediate solutions to reduce impacts as they occur, especially if the transmission and distribution system is severely damaged and the ability to transport power is limited. A generation redispatch strategy to determine the optimal generation level of operable generators during a hurricane is studied in Abdelmalak and Benidris (2022), which minimizes load curtailments during component failures by approximately 40% by redispatching power supply after subsequent failures.

Additionally, microgrids offer a novel approach to operations during hurricanes. In Mitra and Ranade (2007), Chanda and Srivastava (2016), Chen *et al* (2017), Liu *et al* (2017b), methods proving microgrids enhance network resilience and offer a self-supply of electricity during emergencies are explored. While Amirioun *et al* (2018) runs a resilience-constrained OPF to minimize load curtailment using microgrids during floods. In Watson and Etemadi (2020), microgrid resilience is modeled using Hurricane Harvey as a case study, in which outages were significantly reduced.

2.7. Compounded events

Compounded climate events result from various hazards or extreme climate variables co-occurring in or across locations. There are multiple categories of compounded climate events defined in Crimmins and Singh (2023), but this section focuses on multivariate climate events and temporally compounding climate events. Multivariate climate events, such as heatwaves and drought, co-occur in a single location. Temporally compounding events are successive and occur in a single area; an example could be stand-alone extreme winds causing a distribution power pole to blow over, which then starts a wildfire (Crimmins and Singh 2023). Overall, compounded climate events are significantly less studied than single extreme weather events, creating a large knowledge gap in the frequency and impacts in which they may occur. For future work, Bevacqua *et al* (2021) provides guidance for how to study compounded events.

2.7.1. Historical events

Although not in the CONUS, the summer of 2010 in Russia is a prime example of compounding events that mirror similar events in the U.S. West, but at a larger scale. Russia experienced below average precipitation that resulted in a summer drought, which coincided with an unprecedented heatwave. The drought, compounded with the heatwave, led to widespread wildfires. These wildfires increased the death-toll due to air pollution across major cities, as more than 10 000 Moscow citizens died during these events (Barriopedro *et al* 2011, Zscheischler *et al* 2018). Considering the CONUS, 2020 had widespread droughts combined with abnormal ambient temperatures throughout the West and central states. This additionally intensified Western wildfires. On a national scale, December 2020 the largest area of land since 2012 was experiencing extreme drought conditions, which was emphasized by record heat in parts of the PNW (dro 2023). Lastly, when considering the top 25 extreme weather events for the CONUS, extreme winds are often coupled with blizzards, wildfires, and severe storms (U.S. Department of Commerce 2023).

2.7.2. Future events

The impacts of wind and solar in Texas are studied in Craig *et al* (2020), and findings suggest that wind power production may increase due to changes in wind speed, simultaneously demand will increase due to an increase in ambient temperatures, creating issues with supply and demand. While Tavakol *et al* (2020) studies the impacts of hot, dry, and windy events, which are more likely to occur during a heatwave and drought. Results show that hot, dry, and windy events increase from Southwest Kansas into Northwest Texas, which could also create supply and demand issues if wind speeds are too high. Turner *et al* (2019) studies the impacts of increased demand due to ambient temperature and drought, and finds the loss of load to double by 2035 due to demand increase and water scarcity. Additionally, the study found that while power outages were more frequent, they were also shorter in duration, offering adaptation measures the ability to improve power system performance in the years to come. Considering thermal power plants under a co-occurring heatwave and drought, Lubega and Stillwell (2018) creates operational rules that determine the minimal number and magnitude of thermal variance from a power grid perspective, which allows power plant and power grid operators to input information. With increased temperatures and decreased precipitation, thermal variances increase, highlighting the importance of contingency planning. While, Cohen *et al* (2022) links hydrology models with a grid planning model to test future power grid scenarios, including an increased demand with reduced hydropower due to drought, with multiple RCPs. While results varied for each RCP, generation and transmission capacity increased, along with operating costs. Lastly, Gurgel *et al* (2024) studies the gap in supply and demand in the Central U.S. and finds the most significant supply gap at 21% to occur in the Lakes-Mid Atlantic region as a result of increased demand and decreases in thermal generation due to heat and drought.

2.8. Adaptations

This section considers the extreme events and their adaption measures for components of the power grid. When considering adaption measures, it is important to note that extreme events do not occur with equal

Table 2. Common Power System Hardening Measures (Hoffman and Bryan 2010, Pacific Gas and Electric 2021). System hardening improves system infrastructure durability and stability, improving resilience and reliability through the lens of weather-related activity. System hardening is especially useful in existing power infrastructure. The measures provided are commonly implemented system hardening techniques.

Event	Hardening
Extreme Wind	Upgrading damaged poles and structures Strengthening poles with guy wires Burying power lines underground Vegetation management
Wildfires	Burying power lines underground Vegetation management Replacing wooden poles Installing wider cross-arms Replacing bare lines with insulated lines
Flooding	Elevating substations or control rooms Relocating or constructing new lines and facilities
Modernization	Deploying sensors and controls (smart grid technologies) Installing databases or tooling Replacing or upgrading aging infrastructure

frequency in areas of the CONUS or globally. Adaption measures should be prioritized as power system vulnerabilities are troublesome to public use and financially burdensome, shown in figure 3, and are likely to increase due to climate change.

System hardening is defined as '...physically changing the infrastructure to make it less susceptible to damage from extreme wind, flooding, or flying debris' by the U.S. DOE (Hoffman and Bryan 2010). Standard system hardening activities utilities use are provided in table 2.

Further, microgrids are one solution to make the conventional grids better suited to deploy large-DERs. Since microgrids can be islanded or operated while the conventional grid is down, making them part of the three phases of power system resilience:

1. Preparedness
2. Mitigation
3. Restoration

Thus, microgrids aid in preparedness and restoration considering low probability high impact events, which are often hard to predict (North American Electric Reliability Corporation 2012). For more fundamental knowledge about microgrids, Ustun *et al* (2011), Parhizi *et al* (2015)offer in-depth reviews.

2.8.1. Heatwaves

Considering approaches for adapting to heat waves, past experiences such as the September 2022 heatwave in California offer invaluable insight. CAISO released adaptation strategies that supported the grid throughout the heat wave. These include but are not limited to an increase in resource adequacy, including 3500 MW of battery storage, state programs to provide non-market resources (including emergency/flex alerts to customers), emergency assistance that allows for energy flow to and from the CAISO grid, this demonstrates the importance of resource-sharing and a connected grid (California Independent System Operator 2022a). Areas identified to be improved operations coordination between day-ahead and real-time battery dispatch, a software upgrade related to how the market chooses or curtails low-priority exports under unconventional conditions, and changing the calculations used in the Western Energy Imbalance Market resource sufficiency test, which includes power flow feasibility, balancing supply and demand, flexible generation ramping, and bid-in range capacity (California Independent System Operator 2022b).

To increase awareness of the impacts of heatwaves on the grid, a better understanding of the variability of both load and power transport regionally is needed, as well as operational strategies that can minimize rolling blackouts. One solution could be increasing renewable energy generation capabilities with more advanced operation strategies and the DERs to aid in curtailment measures. This may require advances in inverter technology, more efficient scheduling for BESS, and advances in operational software. Thus, more research should be performed.

2.8.2. Extreme cold temperatures

Adaptations for extreme winter weather should balance power system resiliency, reliability, and crew dispatch safety. Protecting the distribution and transmission system during extreme winter weather is often a manual endeavor in the U.S., which includes crews removing the ice or salting the power lines. Predictive models such as those studied in Zarnani *et al* (2012) offer solutions for crew dispatch and preparedness for such tasks, yet aerial vehicles also hold the potential to perform such tasks.

Weatherizing power generation plants plays a vital role in maintaining power production. Weatherization may include line heating, antifreeze injectors, and enclosures to trap heat in the winter and release heat in the summer for natural gas infrastructure and equipping wind turbines with antifreeze coatings and heating elements. However, retrofitting existing natural gas plants is expected to be a costly endeavor (Smead 2021). There is progress in winter infrastructure weatherization. In February 2023, FERC approved two standards, 'Extreme Cold Weather Reliability' and 'Directing Modification Of Reliability', which target power generators' retrofitting and construction process during winter weather. Weatherization alone will not be enough if fuel, particularly natural gas, is not available. Resource adequacy measures must consider the relationship between generator outages, generator maintenance, and temperature, thus reconsidering annual maintenance measures in winter for traditionally warm climates such as Texas.

Additionally, regions such as Alaska may experience an increase in cost between 10% and 20% by 2030 to maintain and expand public infrastructure due to climate change (Larsen *et al* 2008). Alaska is particularly vulnerable to climate change; as a traditionally cold climate, it is warming two to three times the average global rate, putting infrastructure at risk due to permafrost thawing and floods increasing. Thus, system hardening, modernization, and weatherization are vital in proactive strategies. However, more research on equitably adapting the power grid in rural communities and tribal lands should be further studied and considered.

2.8.3. Drought

Adaptive measures for both thermal generators and hydropower plants are not straightforward. For thermal power plants, new plants should avoid once-through cooling systems and utilize water reuse strategies, while existing plants should be retrofitted for reuse strategies. Retrofitting thermal and hydropower plants includes adjusting intake level requirements to be lower. Other adaptation strategies for both generation types include increasing monitoring of reservoirs and stream flows, increasing power production efficiency, and increasing water storage capacity, aquifer storage, and groundwater recovery without causing harmful environmental impacts. Further, utilities should create contingency plans for times of extreme drought. Droughts can cause interdependence between regions as power may need to be exported, and scenarios creating water restrictions for users have created opportunities for better operations within the water-power nexus.

For improved operations, future studies should link OPF programs with physics-based models, hydrologic/hydraulic models, RCMs, or system loadings and include more exogenous parameters across multiple time steps and regions. Exogenous parameters include any parameter that may change depending on the system or parameters the system operator can not control. These could include optimization weights, generator water consumption, rate of generator water withdrawal, and system loadings, many of which would change per timestamp (Kravits *et al* 2022b).

Overall, thermal and hydropower are significant contributors to the U.S. power grid, with hydropower aiding in carbon migration efforts as the largest percentage of renewable energy generation. Thus, operating the power grid during droughts, without outages or water use constraints for the general public, is an area of increasing research interest.

2.8.4. Non-hurricane and non-tornadic extreme winds

Adaption strategies for wind alone predominately consist of frequent inspections and system hardening measures, as presented in table 2. Infrastructure materials (wood or steel poles) and bracing strategies (guy wires) should be deployed for wind-prone areas. As Li (2023) highlights the importance of the structural design of wind turbines and the structural reliability of wind power poles from simulated results using 15 RCMs and RCP8.5. Adaption measures should consider construction cost and structural safety, as structural reliability is projected to decrease in many areas across North America. Alternatively, retrofitting the current system to include underground power lines would prevent wind-driven damages and routine vegetation management procedures.

Modernization of the power grid, such as increased sensor technology to detect wind speeds at vulnerable power poles and upgrading aging infrastructure, would provide additional robustness to protect the grid against extreme winds, especially for extreme winds of long duration (Li and Kopp 2023). For the transition to a weather-driven power system, more consistent and comprehensive data collection procedures and models are needed to inform decisions for system hardening.

More research in forecasting wind events and the advantages of statistical analysis or downscaling methods for power system planners and operators should be considered for wind power generation, installation and design, equipment cooling strategies, and infrastructure planning for both on and off-shore wind.

2.8.5. Wildfires

Multiple strategies exist to predict, prevent, and detect wildfires associated with power systems reviewed in Jazebi *et al* (2020). Predictive models hold significant merit in preventing and predicting wildfires. At the same time, advances in satellite imaging and sensing, stationary, and mobile ground-based solutions are advancing wildfire detection (Guikema *et al* 2006).

Limitations to previous studies include using non- comprehensive vulnerability thresholds for power system security. This includes metrics such as N-1 security, meaning the network can maintain normal operations if a single contingency failure occurs. Research should consider implementing PSPS on realistic networks and investigate ways to speed up the optimization solution (Rhodes and Roald 2022).

Another adaptation measure is under-ground power lines in wildfire-prone areas, explored in Taylor and Roald (2022). An optimization problem selects which power lines should be prioritized for under-grounding in a region with significant wildfire risk and cost considerations. Despite wildfire risk variability across different days, the method consistently chooses high-risk lines for under-grounding. For physical infrastructure, table 2 provides guidance for practical system hardening recommendations to protect the system from or during wildfire events.

2.8.6. Hurricanes

System hardening is the predominant adaptation measure for hurricanes. These measures include those from 2 referring to extreme winds, flooding, and modernization. Hurricanes pose unique complications, as vulnerable substations may need to be relocated, elevated, or placed in waterproofed rooms, which could change the layout of the grid.

Smart grid technologies are suggested to aid in power recovery and response efforts for hurricane events. As such, two research areas regarding hurricanes include demand-side management and adaptive topology control. Customer participation in DR, which is not typically associated with hurricanes, could aid in servicing critical loads, such as emergency buildings or hospitals. Adaptive topology control could aid power flow rerouting for critical infrastructure by sophisticated switching for transmission and distribution components. Powering critical infrastructure is especially important during hurricanes, as in the case of Puerto Rico; if a system is destroyed, outages can be prolonged.

Proactive strategies have been tested in Mahzarnia *et al* (2020) that aid in recognizing critical infrastructure prior to expected hurricane conditions. These strategies should be further explored as they prevent infrastructure from being damaged or highlight damaged infrastructure for quicker response times.

2.8.7. Adaptation summary

Adaption measures for a weather-driven power system are crucial to the security of the power grid, critical infrastructure, and safety. As shown in figures 3 and 4, the financial burden and personal burden of power system destruction and power outages are substantial and increasing with intensity and frequency, with variances given the region. A summary of the adaptation recommendations for the future, which includes system hardening techniques that are currently being implemented from table 2, and knowledge gaps in the current literature are provided in table 3. While each of the extreme events investigated in this review have unique characteristics, thus unique adaptation recommendations, it is evident that system hardening and weatherization are preliminary actions to consider in expanding and contributing to a robust grid in the face of climate change.

3. Conclusions and future work

This review intended to illustrate historical and projected impacts within the climate-energy nexus in the U.S. Climate and weather impact each level of the power system through transmission and distribution, demand, generation, operations, and adaptations. The literature reviewed in this paper presents a set of observed problems and possible solutions for both climate and energy modelers. Those that pertain to the climate-energy nexus are summarized in figure 5.

From a weather-driven power system perspective, more research involving intercomparison and standardization of climate modeling inputs, methods, emission scenarios, and use cases should be explored, with traceable sensitivity to allow for improved implementation from end-users. Additionally, the likelihood or probability of emission scenarios should be determined in consultation with climate experts to aid in interdisciplinary work and guide energy modelers to proper use cases.

Collaboration between climate modelers and energy modelers is recommended for the publication of datasets that can be used in energy modeling software and analysis. This would include addressing issues such as GCM downscaling to appropriate scales, extracting relevant meteorological variables, and providing

Table 3. Summarization of Adaptation Measures and Knowledge Gaps. A summary of power system adaption measures suggested for the future and knowledge gaps suggested for future studies is provided for each extreme weather event.

Extreme Weather Event	Adaptation Measure	Knowledge Gaps
Heatwaves	• Increase resource adequacy (including battery storage) • Demand response programs • Resource-sharing • Software upgrade related to operations	• Understanding the variability of both load and power transport regionally • Developing operational strategies that can minimize rolling blackouts
Extreme Cold Temperatures	• Weatherization • Resource adequacy	• Resource adequacy measures that consider the relationship between generator outages, generator maintenance, and temperature. • Ice removal in unsafe conditions for crew dispatch and structural load changes.
Droughts	• Retrofitting thermal gas plants to use water reuse strategies • Avoiding once-through cooling systems • Increasing monitoring of reservoirs and stream flows • Increasing power production efficiency • Increasing water storage capacity • Contingency plans	• Understanding regional interdependence on the power grid • Operational studies linking OPF programs with physics-based models, hydrologic/hydraulic models, RCMs, or system loadings with exogenous parameters across multiple time steps and regions • Resource adequacy
Non-Hurricane and Non-Tornadic Extreme Winds	• Frequent inspections • System hardening measures • Structural design considerations • System Hardening • Sensor technology to detect wind speeds at vulnerable power poles • Modernization	• Forecasting wind events • Methods for statistical analysis or downscaling methods for wind power generation installation and design, equipment cooling strategies, and infrastructure planning • Off-shore wind impacts for the CONUS
Wildfires	• Satellite imaging and sensing • Stationary and mobile ground-based technology for wildfire detection • PSPS • System hardening	• Operational studies including metrics such as N-1 security • Optimizing PSPS on realistic networks and investigate • Predicting the impacts on solar power generation
Hurricanes	• System hardening • Demand-side management • Adaptive topology control to prioritize critical infrastructure	• Smart grid technologies • Recognizing critical infrastructure prior to expected hurricane conditions

GCM or regional model outputs at timescales used in energy modeling, typically at 15 minutes to one hour annually (Craig *et al* 2018, Weber *et al* 2018).

Further, considerations for how to appropriately integrate important climate or weather variables into energy models to enable climate assessments or alternative operation scenarios should be further explored. Incorporating climate variables into energy models holds the potential to bridge the gap between physical climatic models, capacity expansion, and infrastructure and operational cost. Additionally, incorporating multiple climate variables would contribute to a limited body of knowledge surrounding compounded climate events and their impacts on energy systems.

Lastly, the power system should address aging infrastructure through a lens of climate sensitivity or risk. While beneficial, updating old infrastructure with the same equipment may be insufficient for a weather-driven power system. Thus, in-depth regional analysis should be employed for system hardening and retrofitting, as these are not 'one size fits all' solutions. For instance, underground power lines may be

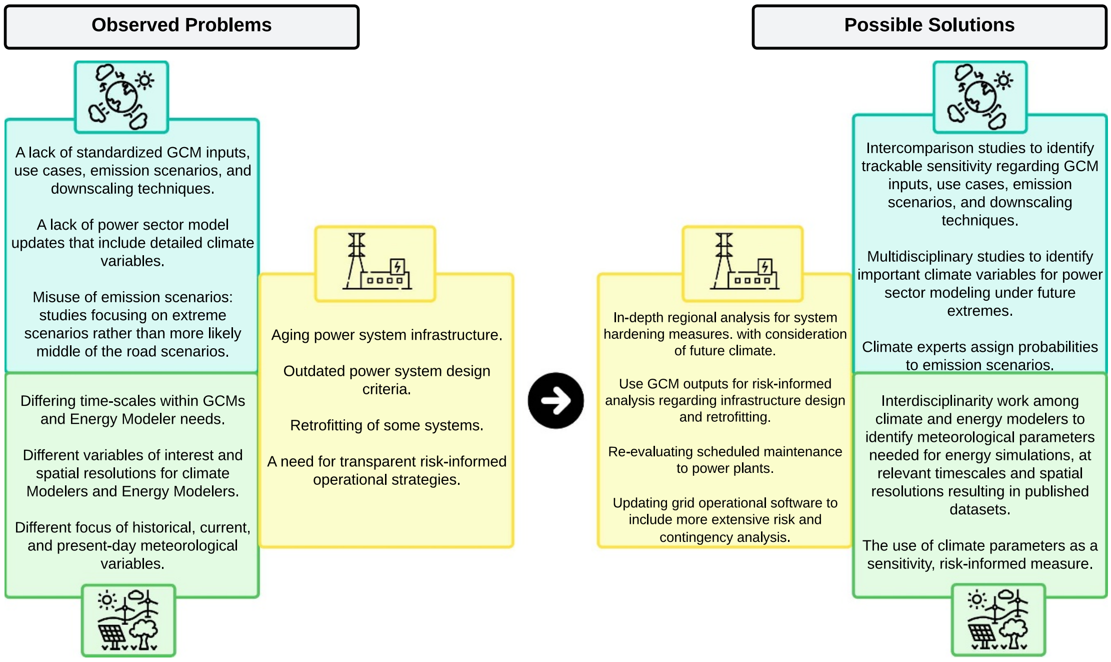

Figure 5. Current Climate-Energy Nexus Problems and Solutions. Regarding the problems and solutions, blue boxes refer to the climate system, yellow boxes refer to the power system, and green boxes refer to both the climate and power systems.

optimal in areas with high winds and wildfires but could experience severe damage in earthquake-prone areas. Conversely, power systems can be the cause of disasters like wildfires, creating liability issues for electric utilities. Additionally, it is important to study how to operate the power grid during anomalous weather events to create a precedent for upgrading operational software to include extensive risk and contingency analysis.

Deepening our understanding of the intersection of climate change, extreme weather events, and the power system is of utmost importance to climate modelers, energy modelers, economists, and policymakers, as electricity is a driver of modern society. Moving toward a weather-driven power system will require interdisciplinary work among actions to the observed problems provided in this paper.

Data availability statement

No new data were created or analysed in this study.

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References

Abdelaziz S, Sparrow Sarah N, Hua W and Wallom David C H 2024 Assessing long-term future climate change impacts on extreme low wind events for offshore wind turbines in the UK exclusive economic zone *Appl. Energy* **354** 122218

Abdelmalak M and Benidris M 2022 Proactive generation redispatch to enhance power system resilience during hurricanes considering unavailability of renewable energy sources *IEEE Trans. Ind. Appl.* **58** 3044–53

Ahmed Shakir D, Al-Ismail Fahad S M, Shafiullah Md, Al-Sulaiman Fahad A and El-Amin Ibrahim M 2020 Grid integration challenges of wind energy: a review *IEEE Access* **8** 10857–78

Alawad A, Alnakhli A and Dehghanian P 2021 Optimal energy management of a power transmission grid under a heatwave exposure *2021 North American Power Symp. (NAPS)* pp 1–6

Alexander D E 2013 Resilience and disaster risk reduction: an etymological journey *Nat. Hazards Earth Syst. Sci.* **13** 2707–16

Amirioun M H, Aminifar F and Lesani H 2018 Towards proactive scheduling of microgrids against extreme floods *IEEE Trans. Smart Grid* **9** 3900–2

Atmospheric Administration and NOAA National Oceanic 2022 Climate change: atmospheric carbon dioxide

Barriopedro D, Fischer Erich M, Luterbacher J, Trigo Ricardo M and García-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe *Science* **332** 220–4
Bartos Matthew D and Chester Mikhail V 2015 Impacts of climate change on electric power supply in the Western United States *Nat. Clim. Change* **5** 8
Bartos M, Chester M, Johnson N, Gorman B, Eisenberg D, Linkov I and Bates M 2016 Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States *Environ. Res. Lett.* **11** 114008
Bevacqua E *et al* 2021 Guidelines for studying diverse types of compound weather and climate events *Earth's Future* **9** e2021EF002340
Bhatia Kieran T, Vecchi Gabriel A, Knutson Thomas R, Murakami H, Kossin J, Dixon Keith W and Whitlock Carolyn E 2019 Recent increases in tropical cyclone intensification rates *Nat. Commun.* **10** 635
Bhusal N, Abdelmalak M, Kamruzzaman Md and Benidris M 2020 Power system resilience: current practices, challenges and future directions *IEEE Access* **8** 18064–86
Boulder County Government 2022 Marshall fire damage assessment list
Brown M and Sedano R 2004 Electricity transmission: a primer
Burke M, Driscoll A, Heft-Neal S, Xue J, Burney J and Wara M 2021 The changing risk and burden of wildfire in the United States *Proc. Natl Acad. Sci.* **118** e2011048118
Busby Joshua W, Baker K, Bazilian Morgan D, Gilbert Alex Q, Grubert E, Rai V, Rhodes Joshua D, Shidore S, Smith Caitlin A and Webber Michael E 2021 Cascading risks: understanding the 2021 winter blackout in Texas *Energy Res. Soc. Sci.* **77** 102106
Cai M, Ravi V, Lin C-A, Sengupta M and Zhang Y 2023 Impact of wildfires on solar generation, reserves and energy prices *2023 IEEE Green Technologies Conf. (GreenTech)* pp 20–24
Cal-Fire 2020 Redbooks
California Independent system operator 2022a Heat wave analysis final september 2022
California Independent System Operator 2022b Western energy imbalance market resource sufficiency evaluation metrics report covering february 2022
California Public Utilities Commission 2023 Utility public safety power shutoff plans.
Callendar G S 1938 The artificial production of carbon dioxide and its influence on temperature *R. Meteorol. Soc.* **64** 223–40
Chanda S and Srivastava Anurag K 2016 Defining and enabling resiliency of electric distribution systems with multiple microgrids *IEEE Trans. Smart Grid* **7** 6
Chen C, Wang J and Ton D 2017 Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: an integrated solution *Proc. IEEE* **105** 1267–88
Chen S-E, Pando Miguel A, Irizarry Agustín A, Baez-Rivera Y, Tang W and Ng Y 2021 Resiliency of power grid infrastructure under extreme hazards - observations and lessons learned from hurricane maria in Puerto Rico *Advanced Geotechnical and Structural Engineering in the Design and Performance of Sustainable Civil Infrastructures* (Springer) pp 1–17
Choobineh M and Mohagheghi S 2016 Power grid vulnerability assessment against wildfires using probabilistic progression estimation model *2016 IEEE Power and Energy Society General Meeting (PESGM)* pp 1–5
Choobineh M, Tabares-Velasco P C and Mohagheghi S 2016 Optimal energy management of a distribution network during the course of a heat wave *Electr. Power Syst. Res.* **130** 230–40
Climate Central 2022 Surging weather-related power outages-climate central
Code of Federal Regulations 1935 Public Utility Holding Company Act of 1935
Cohen J *et al* 2020 Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather *Nat. Clim. Change.* **10** 20–29
Cohen J, Agel L, Barlow M, Garfinkel Chaim I and White I 2021 Linking Arctic variability and change with extreme winter weather in the United States *Science* **373** 1116–21
Cohen S M, Macknick J, Averyt K and Meldrum J 2014 Modeling climate-water impacts on electricity sector capacity expansion
Cohen Stuart M, Dyreson A, Turner S, Tidwell V, Voisin N and Miara A 2022 A multi-model framework for assessing long- and short-term climate influences on the electric grid *Appl. Energy* **317** 119193
Cohn J 2017 *The Grid: Biography of an American Technology* (The MIT Press)
Constable G and Somerville B 2003 *A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives* (National Academies Press)
Coumou D and Rahmstorf S 2012 A decade of weather extremes *Nat. Clim. Change* **2** 491–6
Craig Michael T, Cohen S, Macknick J, Draxl C, Guerra Omar J, Sengupta M, Haupt S E, Hodge B-M and Brancucci C 2018 A review of the potential impacts of climate change on bulk power system planning and operations in the United States *Renew. Sustain. Energy Rev.* **98** 255–67
Craig Michael T, Jaramillo P, Hodge B-M, Nijssen B and Brancucci C 2020 Compounding climate change impacts during high stress periods for a high wind and solar power system in Texas *Environ. Res. Lett.* **15** 024002
Crimmins Allison R and Singh D 2023 Compound events
Crook Julia A, Jones Laura A, Forster Piers M and Crook R 2011 Climate change impacts on future photovoltaic and concentrated solar power energy output *Energy Environ. Sci.* **4** 3101–9
Dale L, Carnall M, Wei M, Fitts G and McDonald S 2018 Assessing the impact of wildfires on the California electricity grid 79
Davidson Rachel A, Liu H, Sarpong Isaac K, Sparks P and Rosowsky David V 2003 Electric power distribution system performance in carolina hurricanes *Nat. Hazards Rev.* **4** 36–45
Deng K, Liu W, Azorin-Molina C, Yang S, Li H, Zhang G, Minola L and Chen D 2022 Terrestrial stilling projected to continue in the northern hemisphere mid-latitudes *Earth's Future* **10** e2021EF002448
Dieter Cheryl A, Maupin Molly A, Caldwell Rodney R, Harris Melissa A, Ivahnenko Tamara I, Lovelace John K, Barber Nancy L and Linsey Kristin S 2018 *Estimated use of Water in the United States in 2015* vol 1441 p 76
Dumas M, Kc B and Cunliff Colin I 2019 Extreme weather and climate vulnerabilities of the electric grid: a summary of environmental sensitivity quantification methods
Dzaugis M, Avery Christopher W, Crimmins A, Easterling David R, Kunkel Kenneth E, Maycock Thomas K, Reidmiller David R, Stewart Brooke C and Vose Russell S 2018 *appendix 5: Frequently Asked Questions. Impacts, Risks and Adaptation in the United States: The Fourth National Climate Assessment* vol II
Energy Information Administration 2021 Nonfossil fuel sources accounted for 21% of U.S. energy consumption in 2020
Environmental Protection Agency 2022 United States. Climate Change Indicators: Seasonal Temperature
Fallahi Z and Henze Gregor P 2019 Interactive buildings: a review *Sustainability* **11** 3988
Federal Energy Regulatory Commission 2023 About FERC | Federal Energy Regulatory Commission

Fyfe John C *et al* 2016 Making sense of the early-2000s warming slowdown *Nat. Clim. Change* **6** 224–8
Gil Esteban M and McCalley James D 2011 A U.S. energy system model for disruption analysis: evaluating the effects of 2005 hurricanes *IEEE Trans. Power Syst.* **26** 1040–9
Guikema S D, Davidson R A and Liu H 2006 Statistical models of the effects of tree trimming on power system outages *IEEE Trans. Power Deliv.* **21** 1549–57
Gurgel A C, Reilly J, Morris J, Schlosser C A, Gao X, Yuan M and Tapia-Ahumada K 2024 Assessing compounding climate-related stresses and development pathways on the power sector in the central U.S *Mitigation and Adaptation Strategies for Global Change* vol 29 p 27
Hadji B, Mahdad B, Srairi K and Mancer N 2015 Multi-objective economic emission dispatch solution using dance bee colony with dynamic step size *Energy Proc.* **74** 65–76
Hansen J, Fung I, Lacis A, Rind D, Lebedeff S, Ruedy R, Russell G and Stone P 1988 Global climate changes as forecast by Goddard Institute for space studies three-dimensional model *J. Geophys. Res.: Atmos.* **93** 9341–64
Harp Ryan D and Horton Daniel E 2022 Observed changes in daily precipitation intensity in the United States *Geophys. Res. Lett.* **49** e2022GL099955
He C, Dai C, Wu L and Liu T 2018 Robust network hardening strategy for enhancing resilience of integrated electricity and natural gas distribution systems against natural disasters *IEEE Trans. Power Syst.* **33** 5787–98
He J, Zeng R, Gao Y, Tu Y, Sun W, Zou J and Guan Z 2003 Seasonal influences on safety of substation grounding system *IEEE Trans. Power Deliv.* **18** 788–95
Hoffman P and Bryan W 2010 Hardening and resiliency: U.S. energy industry response to recent hurricane seasons
Holland G and Bruyére Cindy L 2014 Recent intense hurricane response to global climate change *Clim. Dyn.* **42** 617–27
IEEE Milestones Program 2017 IEEE Milestones
Interconnection PJM 2014 Analysis of operational events and market impacts during the january 2014 cold weather events
Intergovernmental Panel on Climate Change 1990 Overview preface to the IPCC overview
International Electrotechnical Commission 2024 International Electrotechnical Commission (IEC). IEC glossary
James M, Haldar S, Varghese R, Bhattacharya S and Pakrashi V 2023 Chapter 28 - Climate change effects on offshore wind turbines *Wind Energy Engineering* 2nd edn pp 413–22
Jazebi S, León F de and Nelson A 2020 Review of wildfire management techniques-part I: causes, prevention, detection, suppression and data analytics *IEEE Trans. Power Deliv.* **35** 430–9
Jeong Dae D I, Cannon Alex J and Zhang X 2019 Projected changes to extreme freezing precipitation and design ice loads over North America based on a large ensemble of Canadian regional climate model simulations *Nat. Hazards Earth Syst. Sci.* **19** 857–72
Jornada D and Leon V J 2016 Robustness methodology to aid multiobjective decision making in the electricity generation capacity expansion problem to minimize cost and water withdrawal *Appl. Energy* **162** 1089–108
Jufri F H, Widiputra V and Jung J 2019 State-of-the-art review on power grid resilience to extreme weather events: definitions, frameworks, quantitative assessment methodologies and enhancement strategies *Appl. Energy* **239** 1049–65
Jung C and Schindler D 2019 Changing wind speed distributions under future global climate *Energy Convers. Manage.* **198** 111841
Karnauskas K B, Lundquist J K and Zhang L 2018 Southward shift of the global wind energy resource under high carbon dioxide emissions *Nat. Geosci.* **11** 38–43
Keskar A, Galik C and Johnson Jeremiah X 2023 Planning for winter peaking power systems in the United States *Energy Policy* **173** 113376
Kimmell T A and Veil J A 2009 Impact of drought on U.S. steam electric power plant cooling water intakes and related water resource management issues
Kimp L 2019 Guide for determination of bare overhead transmission conductors, 47
Kirby N M, Bilodeau H, Granger M, Galibois D and Horwill C 2008 De-Icer Installation at Lévis substation on Hydro Québec's High Voltage System *IEEE T&D Conf.*
Knutson T *et al* 2020 Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* **101** E303–22
Kravits J, Baker K, Kasprzyk J and Stillwell Ashlynn S 2022a Assessing trade-offs between water, emissions and cost in multi-objective optimal power flow *2022 IEEE Power & Energy Society General Meeting (PESGM)* pp 1–5
Kravits J, Kasprzyk Joseph R, Baker K and Stillwell Ashlynn S 2022 Incorporating thermoelectric power plant water use into multi-objective optimal power flow *Environ. Res.* **2** 015005
Kumar Y, Hoesly R, Venkatesh A, Shuster E and Iyengar A 2022 Effects of short-term water constraints on electricity dispatch: a case study of ERCOT and SPP regions *ACS ES&T Water.* **2** 749–58
Larsen P, Goldsmith S, Smith O, Wilson M, Strzepek K, Chinowsky P and Saylor B 2008 Estimating future costs for Alaska public infrastructure at risk from climate change *Glob. Environ. Change* **18** 442–57
Lenton Timothy M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 Climate tipping points - too risky to bet against *Nature* **575** 592–5
Li G, Zhang P, Luh Peter B, Li W, Bie Z, Serna C and Zhao Z 2014 Risk analysis for distribution systems in the Northeast U.S. Under wind storms *IEEE Trans. Power Syst.* **29** 889–98
Li S H 2023 Impact of climate change on wind energy across North America under climate change scenario RCP8.5 *Atmos. Res.* **288** 106722
Li S H and Kopp Gregory A 2023 Duration of extreme synoptic wind speeds for North America in a changing climate and its engineering implementation *Struct. Safety* **104** 102349
Li X, Mazur R W, Allen D R and Swatek D R 2005 Specifying transformer winter and summer peak-load limits *IEEE Trans. Power Deliv.* **20** 185–90
Lin J, Bao M, Liang Z, Sang M and Ding Y 2022 Spatio-temporal evaluation of electricity price risk considering multiple uncertainties under extreme cold weather *Appl. Energy* **328** 120090
Liu L, Hejazi M, Li H, Forman B and Zhang X 2017a Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations *Nat. Energy* **2** 8
Liu X, Shahidehpour M, Li Z, Liu X, Cao Y and Bie Z 2017b Microgrids for enhancing the power grid resilience in extreme conditions *IEEE Trans. Smart Grid* **8** 589–97
Liu Y and Singh C 2011 A methodology for evaluation of hurricane impact on composite power system reliability *IEEE Trans. Power Syst.* **26** 145–52
Lu Z *et al* 2022 Riemannian surface on carbon anodes enables li-ion storage at $-35\,^{\circ}$C *ACS Central Sci.* **8** 905–14

Lubega W N and Stillwell Ashlynn S 2018 Maintaining electric grid reliability under hydrologic drought and heat wave conditions *Appl. Energy* **210** 538–49
Mahzarnia M, Moghaddam M P, Baboli P T and Siano P 2020 A review of the measures to enhance power systems resilience *IEEE Syst. J.* **14** 4059–70
Manabe S and Wetherald R T 1967 Thermal equilibrium of the atmosphere with a given distribution of relative humidity *J. Atmos. Sci.* **24** 241–59
Mayhorn Ebony T, Widder Sarah H, Parker Steven A, Pratt Richard M and Chassin Forrest S 2015 Evaluation of the demand response performance of electric water heaters
Mazdiyasni O and AghaKouchak A 2015 Substantial increase in concurrent droughts and heatwaves in the United States *Proc. Natl Acad. Sci.* **112** 11484–9
McCarthy M, Armstrong L and Armstrong N 2019 A new heatwave definition for the UK *Weather* **74** 382–7
Miara A, Vörösmarty C J, Stewart R J, Wollheim W M and Rosenzweig B 2013 Riverine ecosystem services and the thermoelectric sector: strategic issues facing the Northeastern United States *Environ. Res. Lett.* **8** 025017
Mitra J and Ranade Satish J 2007 Power system hardening through autonomous, customer-driven microgrids *2007 IEEE Power Engineering Society General Meeting* pp 1–4
Mohammadi Y D, Shafieezadeh A and Cha K 2020 Effect of modelling complexities on extreme wind hazard performance of steel lattice transmission towers *Struct. Infrastruct. Eng.* **16** 898–915
Moore Frances C, Lacasse K, Mach Katharine J, Shin Yoon Y A, Gross Louis J and Beckage B 2022 Determinants of emissions pathways in the coupled climate-social system *Nature* **603** 103–11
National Grid 2022 Western New York: National Grid Crews Battling Blizzard, Treacherous Conditions as they Work to Restore Service to Affected Customers
Nevius D 2020 The history of the North American electric reliability corporation
NOAA National Centers for Environmental Information 2023 NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2023)
North American Electric Reliability Corporation 2012 Severe impact resilience: considerations and recommendations
North American Electric Reliability Corporation 2021 2021 state of reliability an assessment of 2020 bulk power system performance
North American Electric Reliability Corporation 2022 2022 Summer reliability assessment
North G R, Cahalan R F, Coakley J James A 1981 Energy balance climate models *Rev. Geophys.* **19** 91–121
Pacific Gas and Electric Company 2019 Pacific gas and electric company amended 2019 wildfire safety plan 179
Pacific Gas and Electric 2021 Community wildfire safety program: electric system hardening and vegetation management
Pansini Anthony J 2020 *Electrical Distribution Engineering* 3rd edn
Parhizi S, Lotfi H, Khodaei A and Bahramirad S 2015 State of the art in research on microgrids: a review *IEEE Access* **3** 890–925
Peterson T C *et al* 2013 Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States: state of knowledge *Bull. Am. Meterol. Soc.* **94** 821–34
Phillips N 1956 The general circulation of the atmosphere: a numerical experiment *R. Meteorol. Soc.* **82** 123–64
Pryor S C, Barthelmie R J and Schoof J T 2012 Past and future wind climates over the contiguous USA based on the North American regional climate change assessment program model suite *J. Geophys. Res.: Atmos.* **117** D19
Pryor S C, Coburn J J, Barthelmie R J and Shepherd T J 2023 Projecting future energy production from operating wind farms in North America. Part I: dynamical downscaling *J. Appl. Meteorol. Climatol.* **62** 63–80
Pryor S and Barthelmie R 2010 Climate change impacts on wind energy: a review *Renew. Sustain. Energy Rev.* **14** 430–7
Quante L, Willner Sven N, Middelanis R and Levermann A 2021 Regions of intensification of extreme snowfall under future warming *Sci. Rep.* **11** 16621
Rendfrey Tristan S, Bukovsky Melissa S, McCrary Rachel R and Fuentes F R 2021 An assessment of tropical cyclones in North American CORDEX WRF simulations *Weather Clim. Extremes* **34** 100382
Rhodes N, Ntaimo L and Roald L 2021 Balancing wildfire risk and power outages through optimized power shut-offs *IEEE Trans. Power Syst.* **36** 3118–28
Rhodes N and Roald L 2022 Co-optimization of power line shutoff and restoration for electric grids under high wildfire ignition risk
Russell B D, Benner Carl L and Wischkaemper Jeffrey A 2012 Distribution feeder caused wildfires: mechanisms and prevention *2012 65th Annual Conf. for Protective Relay Engineers* pp 43–51
Sailor D J, Smith M and Hart M 2008 Climate change implications for wind power resources in the Northwest United States *Renew. Energy* **33** 2393–406
Sathaye Jayant A, Dale Larry L, Larsen Peter H, Fitts Gary A, Koy K, Lewis Sarah M and Lucena A F P de 2013 Estimating impacts of warming temperatures on California's electricity system *Glob. Environ. Change* **23** 499–511
Sathaye J, Dale L, Larsen P, Fitts G, Koy K, Lewis S, Lucena A 2012 Estimating risk to california energy infrastructure from projected climate change
Shafieezadeh A, Onyewuchi Urenna P, Begovic Miroslav M and DesRoches R 2014 Age-dependent fragility models of utility wood poles in power distribution networks against extreme wind hazards *IEEE Trans. Power Deliv.* **29** 131–9
Smead R G 2021 ERCOT-The Eyes of Texas (and the world) are upon you: what can be done to avoid a february 2021 Repeat *Clim. Energy* **37** 14–18
Smith A 2024 2023 A historic year of U.S. billion-dollar weather and climate disasters
Sotolongo M, Bolon C and Baker S H 2020 California power shutoffs: deficiencies in data and reporting 16
Souto L, Yip J, Wu W-Y, Austgen B, Kutanoglu E, Hasenbein J, Yang Z-L, King Carey W and Santoso S 2022 Power system resilience to floods: modeling, impact assessment and mid-term mitigation strategies *Int. J. Electr. Power Energy Syst.* **135** 107545
Steinberg Daniel C, Mignone Bryan K, Macknick J, Sun Y, Eurek K, Badger A, Livneh B and Averyt K 2020 Decomposing supply-side and demand-side impacts of climate change on the US electricity system through 2050 *Clim. Change* **158** 125–39
Swift G W *et al* 2001 Adaptive transformer thermal overload protection *IEEE Trans. Power Deliv.* **16** 516–21
Tarroja B, AghaKouchak A and Samuelsen S 2016 Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation *Energy* **111** 295–305
Tavakol A, Rahmani V and Hamington Jr J 2020 Probability of compound climate extremes in a changing climate: a copula-based study of hot, dry and windy events in the central United States *Environ. Res. Lett.* **15** 104058
Taylor S and Roald Line A 2022 A framework for risk assessment and optimal line upgrade selection to mitigate wildfire risk *Electr. Power Syst. Res.* **213** 108592

Terando A, Reidmiller D, Hostetler S, Littell J, Beard D, Weiskopf S, Belnap J and Plumlee G 2020 Using information from global climate models to inform policymaking-The role of the U.S. Geological Survey *Open-File Report* 2020–1058

Turner S W D, Voisin N, Fazio J, Hua D and Jourabchi M 2019 Compound climate events transform electrical power shortfall risk in the Pacific Northwest *Nat. Commun.* **10** 1–8

Turner Sean W D, Voisin N, Nelson Kristian D and Tidwell Vincent C 2022 Drought impacts on hydroelectric power generation in the Western United States

Tuttle D, Gülen G, Hebner R, King C, Spence D, Andrade J, Wible J, Baldwick R and Duncan R 2016 The history and evolution of the U.S. electricity industry

U.S. Department of Commerce 2023 Top 25 historical weather events

U.S. Energy Information Administration 2022 Electricity explained: use of electricity

U.S. Government Accountability, Office 2014 Climate change: energy infrastructure risks and adaptation efforts | U.S. GAO

Umunnakwe A, Parvania M, Nguyen H, Horel John D and Davis Katherine R 2022 Data-driven spatio-temporal analysis of wildfire risk to power systems operation, IET generation *Trans. Distrib.* **16** 2531–46

Union of Concerned Scientists 2012 The UCS EW3 Energy-Water Database | Union of Concerned Scientists

United States Department of Energy 2018a Energy resilience solutions for the PR grid final june 2018, United States Department of Energy

United States Department of Energy 2018b Hurricane Michael situation reports - 2018 (available at: www.energy.gov/ceser/articles/hurricane-michael-situation-reports-october-2018)

United States Department of Energy 2022a Alternative fuels data center - key federal legislation (available at: https://afdc.energy.gov/laws/key_legislation)

United States Department of Energy 2022b Bipartisan infrastructure law

United States Department of Energy 2023 Timeline of events (available at: www.energy.gov/lm/timeline-events-1971-1980)

United States Global-Change Research Program. Our Changing Planet 2024 The FY 1990 research plan

United States Nuclear Regulatory Commission 2024 Backgrounder on the three mile island accident: 1971 to 1980

Ustun T S, Ozansoy C and Zayegh A 2011 Recent developments in microgrids and example cases around the world-a review *Renew. Sustain. Energy Rev.* **15** 4030–41

Vliet Michelle T H van, Yearsley John R, Ludwig F, Vögele S, Lettenmaier Dennis P and Kabat P 2012 Vulnerability of US and European electricity supply to climate change *Nat. Clim. Change* **2** 676–81

Voisin N, Dyreson A, Fu Tao O'C M, Turner Sean W D, Zhou T and Macknick J 2020 Impact of climate change on water availability and its propagation through the Western U.S. power grid *Appl. Energy* **276** 115467

Wang F, Xu H, Xu T, Li K, Shafie-khah M and Catalão João P S 2017 The values of market-based demand response on improving power system reliability under extreme circumstances *Appl. Energy* **193** 220–31

Waseem M and Manshadi Saeed D 2020 Electricity grid resilience amid various natural disasters: challenges and solutions *Electr. J.* **33** 106864

Watson Eileen B and Etemadi A H 2020 Modeling electrical grid resilience under hurricane wind conditions with increased solar and wind power generation *IEEE Trans. Power Syst.* **35** 929–37

Weber C, McCollum David L, Edmonds J, Faria P, Pyanet A, Rogelj J, Tavoni M, Thoma J and Kriegler E 2018 Mitigation scenarios must cater to new users *Nat. Clim. Change* **8** 845–8

Webster P J, Holland G J, Curry J A and Chang H-R 2005 Changes in tropical cyclone number, duration and intensity in a warming environment *Science* **309** 1844–6

Wildfire Management 2023

Wilkie D and Galasso C 2020 Impact of climate-change scenarios on offshore wind turbine structural performance *Renew. Sustain. Energy Rev.* **134** 110323

Williams A P, Abatzoglou John T, Gershunov A, Guzman-Morales J, Bishop Daniel A, Balch Jennifer K and Lettenmaier Dennis P 2019 Observed impacts of anthropogenic climate change on wildfire in California *Earth's Future* **7** 892–910

Williams A P, Cook Edward R, Smerdon Jason E, Cook Benjamin I, Abatzoglou John T, Bolles K, Baek Seung H, Badger Andrew M and Livneh B 2020 Large contribution from anthropogenic warming to an emerging North American megadrought *Science* **368** 314–8

WINDExchange: Offshore Wind Energy 2023 (available at: https://windexchange.energy.gov/markets/offshore) (United States Department of Energy)

Wischkaemper J, Benner C and Russell D 2008 Electrical characterization of vegetation contacts with distribution conductors - investigation of progressive fault behavior *2008 IEEEPES Transmission and Distribution Conf. and Exposition* pp 1–8

Wu L H, Wang Y N, Yuan X F and Zhou S W 2010 Environmental/economic power dispatch problem using multi-objective differential evolution algorithm *Electr. Power Syst. Res.* **80** 1171–81

York S 2020 Smoke from California wildfires decreases solar generation in CAISO

Yuan W, Wang J, Qiu F, Chen C, Kang C and Zeng B 2016 Robust optimization-based resilient distribution network planning against natural disasters *IEEE Trans. Smart Grid* **7** 2817–26

Zarnani A, Musilek P, Shi X, Ke X, He H and Greiner R 2012 Learning to predict ice accretion on electric power lines *Eng. Appl. Artif. Intell.* **25** 609–17

Zeng Z *et al* 2019 A reversal in global terrestrial stilling and its implications for wind energy production *Nat. Clim. Change* **9** 979–85

Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77

Zuo J, Pullen S, Palmer J, Bennetts H, Chileshe N and Ma T 2015 Impacts of heat waves and corresponding measures: a review *J. Clean. Prod.* **92** 1–12