DOI: 10.1088/2516-1083/aca9b4

A Synthesis and Review of Exacerbated Inequities from the February 2021 Winter Storm (Uri) in Texas and the Risks Moving Forward

Sergio Castellanos[1], Jerry Potts[1], Helena Tiedmann[1], Sarah Alverson[1], Yael R. Glazer[2], Andrew Robison[3], Suzanne Russo[4], Dana Harmon[3], Bobuchi Ken-Opurum[3], Margo Weisz[3], Frances Acuna[5], Keri Stephens[6], Kasey Faust[1], Michael E. Webber[2]

[1] Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 301 E Dean Keeton St C1700, Austin, TX, 78712, USA

[2] Mechanical Engineering, The University of Texas at Austin, 1 University Station C2200, Austin, TX, 78712, USA

[3] Texas Energy Poverty Research Institute, 611 S. Congress Ave., Austin, TX, 78704

[4] Pecan Street Inc., 3924 Berkman Dr., Austin, TX, 78723, USA

[5] Go Austin/Vamos Austin, 3710 Cedar St., Austin, TX, 78705, USA

[6] Communication Studies, The University of Texas at Austin, 300 West Dean Keeton, Austin, TX, 78712, USA

Published in https://iopscience.iop.org/article/10.1088/2516-1083/aca9b4/meta

Abstract

A severe winter storm in February 2021 impacted multiple infrastructure systems in Texas, leaving over 13 million people without electricity and/or water, potentially $100 billion in economic damages, and almost 250 lives lost. While the entire state was impacted by temperatures up to 50°F colder than normally expected for this time of year as well as abnormal levels of snow and ice accumulation, the responses and outcomes from communities were inconsistent and exacerbated prevailing social and infrastructure inequities that are still impacting those communities. In this contribution, we synthesize a subset of multiple documented inequities stemming from the interdependence of the water, housing, transportation, and communication sectors with the energy sector, and present a summary of actions to address the interdependency of infrastructure system inequities.

Keywords: energy systems, extreme weather events, resilience, equitable energy transition

---

1. Introduction

In February 2021, a severe winter storm (colloquially known as Winter Storm Uri or the Valentine's Day Storm of 2021) left more than 13 million Texans without electricity, hundreds dead, millions under a boil water notice or without water, insurance claims for damage exceeding $10 billion [1], and billions of dollars in abnormally high energy bills [2]. Although the winter storm was not the most extreme event Texas has faced in the last century [2], its impact on the natural gas, electricity, and water/wastewater infrastructure was profound [3–6]. At the same time, this event elucidated many infrastructure, communication, and emergency response challenges that disproportionately impacted some communities.

Among the myriad infrastructure-related challenges, some of the most notable include: (1) sustained blackouts in the power generation sector and frozen infrastructure in the natural gas supply chain; (2) road blockages impeding access to critical services and food; (3) ruptured indoor plumbing, poor thermal envelope insulation, and poor air circulation in housing; and (4) frozen water treatment equipment coupled with geographically extensive, multi-day boil water orders. In addition to the expense, trauma, and disruption, there were nearly 250 official deaths [7], though an unofficial analysis of excess deaths suggests the total exceeded 700 people [8].

The fragile and complex interdependence between our built environment and personal well-being was evident in many instances. These infrastructure-related challenges exceeded both energy and water agencies' abilities to be both proactive and reactive to the public's communication needs [9–11]. Furthermore, this disaster – like many others – amplified pre-existing vulnerabilities and exposed systemic inequities prevalent in our built environment [11]. If actions are not taken to correct or strengthen current system and policy deficiencies, these vulnerabilities are at risk of being further exacerbated and propagating asymmetric harms across communities.

In this contribution, we provide a non-exhaustive summary and synthesis of outcomes interconnected with the energy sector and identify inequitable outcomes for some groups and communities during the storm. While a timeline of the event and pre-existing resiliency gaps at the state level are well documented, we begin with a brief background section to provide relevant context to better understand the effects of natural disasters and the unique conditions which led to Uri's lasting impact. Then, we discuss how those impacts manifested within the energy sector and then propagated through a number of other interdependent sectors, including the water, transportation, housing, and communications sectors. Furthermore, we identify opportunities that can address and reduce the disproportionate impacts as more disasters occur in the future as an outgrowth of the ongoing climate crisis.

2. Extreme Weather Events and Poor Planning Cause Disasters and Exacerbate Disparities

2.1 Background

There is an abundance of literature demonstrating how the impact and recovery from weather disasters tend to be unequally distributed across income and demographic groups [12]. In the case of Texas, as recently as 2017 an analysis of Hurricane Harvey's economic impact revealed that lower-income and minority-dominant areas received less support in disaster assistance, even after controlling for insurance and Federal Emergency Management Agency (FEMA)-assessed damage [12]. Furthermore, the different responses to hurricanes in Texas, Florida, and Puerto Rico suggest that a delayed distribution of resources can significantly increase storm-related mortalities and exacerbate health disparities over time [13].

Similarly, cold weather events have the potential to cause lasting damage to affected regions. Texas, in particular, has experienced numerous extreme cold weather events that have had significant impacts across the state. Perhaps most relevant is the 2011 Groundhog Day Blizzard, which left 4.4 million people without power in the Southwest United States [6]. Similar to this 2021 Winter Storm, the Groundhog Day Blizzard caused many parts of the natural gas system to freeze and power plants to fail across the state of Texas to such an extent that the Electric Reliability Council of Texas (ERCOT) implemented rolling blackouts to maintain grid stability [14]. Earlier in Texas' history, a similar event occurred during the winter of 1989, which marked the first instance where ERCOT needed to resort to load shed events at this scale. After the 1989 and 2011 storms, recommendations were made regarding proper winterization of the gas grid and power sector to prepare for future winter storms. Nevertheless, these measures were not effectively implemented in both instances [15,16]. These gaps were coupled with additional inadequacies within the ERCOT market leading up to the storm. The lack of interconnections to other power grids limited ERCOT's ability to receive support from neighboring ISOs. Moreover, ERCOT's operation as an energy-only market discourages electricity suppliers to build additional reserve capacity. However, given the severity of the event, it is unclear if additional interconnections or transitioning to a capacity market would have had a substantial impact on outcomes during the winter storm [3]. The lack of preparation and inadequate regulation was sorely felt in the wake of the 2021 Winter Storm. During the event, areas of Texas experienced temperatures up to 40 degrees lower than what is typical for this time of year and approached 0°F in many major population centers [5]. Sub-freezing temperatures persisted for multiple days, prolonging the impact of the large amounts of snow and ice accumulation that occurred early in the event [17].

The lack of preparation coupled with the abnormal weather conditions further demonstrated the inequitable distribution of the impacts of natural disasters across multiple sectors. The consequences of these impacts continue to manifest and evolve long after the event. What follows is a summary of some of the impacts recorded across the electric, water, housing, and transportation sectors as a result of Winter Storm Uri and how they affect the Texas energy system. A first order interaction between the different systems is represented in Fig. 1, which follows a similar structure to this synthesis.

DOI: 10.1088/2516-1083/aca9b4

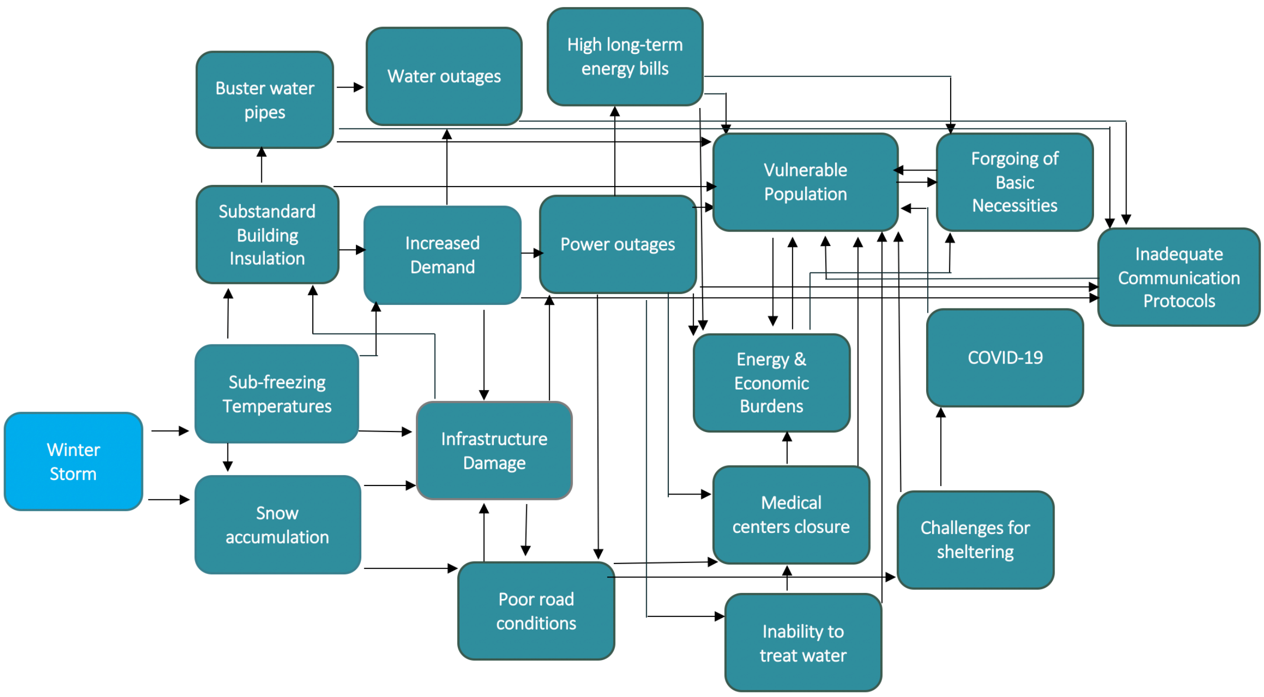

Fig. 1. System interdependency issues related to the 2021 Winter Storm and analyzed in this contribution covering the electricity, water, housing, transportation, and communication sectors.

2.2 Interdependent Systems

2.2.1 Impacts of Electricity Blackouts

The extreme cold temperatures during Winter Storm Uri caused a sudden increase in demand for electricity. The grid endured extreme load demand as temperatures dropped because 55% of households and commercial entities in Texas rely on electricity for heating [18–20]. To maintain grid (frequency) stability amidst high demand and increasingly low power generation due to power plant failures and outages, ERCOT required utilities to shed load and institute energy conservation measures in the form of rolling blackouts [3]. These blackouts were initially planned and advertised as rolling, which describes the way they are rotated from location to location over time to minimize the overall time any one customer is without power. However, some of these blackouts extended for several days, and affected customers in counties of all sizes [21,22]. Consequently, households were left without electricity for as long as five days, preventing them from satisfying their basic needs, and ultimately leading to at least 246 deaths [7].

The extended duration and wide geographic scope of the blackouts placed an additional burden on struggling demographic groups in the state [23]. Before the February 2021 storm, 1 in 3 Texans were below 300% of the Federal Poverty Line – roughly $38,640 as of 2021 [24]. The energy burden (i.e., the percentage of annual household income spent to cover energy costs) was consistently the highest for low-income and minority groups across the major urban centers in Texas [21]. Beyond the largest cities, residents of small to mid-sized counties tend to have the highest average energy cost burdens in the state, reaching up to 18% of total income [22,25]. A survey of 953 people in Texas across income levels following the Winter Storm of 2021 revealed that 77% of low-income respondents were concerned about affording their electricity bills even before the storm, with 34% of them having existing outstanding bills at the onset of the events [2]. During the storm, residents faced even higher energy costs due to the drop in supply, which led the state's Public Utility Commission to peg wholesale electricity prices for most of the event at $9000 per Megawatt-hour, which is the cap for wholesale electricity [26] and up to 70 times higher than typical clearing prices [27]. As the economic burden of this price spike was too severe to endure at once, utilities incurred billions of dollars of debt and many public officials instead raised energy bills by approving the issuance of bonds, which will be repaid over a decade or more to offset the price spike [2]. The financial consequences of this increased energy bill may further impact vulnerable groups that were experiencing high energy burden prior to the winter storm.

High energy costs place additional burdens on households that are already more likely to be dealing with financial hardships. It is common for energy-burdened individuals to already struggle to pay other essential bills, which further exacerbates their dilemma [28]. In these situations, the compounding costs force residents to make trade-offs to pay their energy bills. Most commonly, this means forgoing on basic necessities such as food, clothing, transportation, and medication [29]. The inability to meet these needs during the 2021 Winter Storm, left people vulnerable due to the foregone trade-offs to confront cold weather for an extended period [2]. People with disabilities or chronic illnesses are particularly vulnerable in these situations. These individuals in already vulnerable conditions, tend to face greater financial hardships, forcing them to make additional trade-offs, and a loss of power has the potential to deprive them of life-sustaining services [28].

Beyond the costs of the blackouts, other effects of the storm were multiplied and propagated across multiple facets of people's lives. Sudden electricity loss caused medical centers to close, forcing patients suffering from chronic medical conditions to rush to and overwhelm emergency rooms, thereby limiting the bandwidth to operate and accommodate further patients in need of emergency care; all happening during the COVID-19 pandemic [30]. The story was similar–if not worse– for people receiving medical treatment at home, who were left unprepared to sustain electricity losses as the power outages affected refrigerators (critical for some medicines), dialysis machines or other devices at the same time that care providers might not have been able to visit the patients because they were dealing with their own power losses or were unable to travel the icy roads, thus causing the vulnerable to endure lack of care [31]. Many businesses were also unable to operate without power and were forced to shut. Grocery stores, in particular, faced significant losses due to food and perishable products spoiling [23,32].

The enforcement of blackouts avoided a total power grid collapse, which would have resulted in even more damage to the Texas electric system. Nevertheless, nearly 80% of Texans do not believe the power outages in their area were carried out in an equitable manner [23]. While Texans across the socioeconomic spectrum were hit with blackouts, initial assessments revealed that the majority of the blackouts occurred in census block groups that were dominated by minority groups [33]. In addition, while the lowest income group in this study was the most likely to experience outages, analysis by Watson et al. [23] also reveals that the racial inequities of these outages were consistent across all income categories. Some utilities claim that they had difficulty rotating and distributing blackouts during the storm due to the large amount of critical infrastructure, such as oil and gas infrastructure, hospitals and water treatment plants to which they are required to continue supplying power during load shed events [9]. However, work published by the Rockefeller Foundation [33] notes that the presence of critical infrastructure in a census block group only reduced the likelihood of a blackout by up to 6%.

The uneven impact of the blackouts was also seen as a function of income and time, where surveyed respondents corresponding to the lowest-income group were the highest share in terms of longest time sustained without electricity (either "4+ days", or "still without") [23]. The same group also constituted the lowest share in the category of "never lost" electricity in the same survey.

Also, the economic nature of low supply and high fuel and electricity demand had repercussions beyond state borders. Mexico, one of the main consumers of Texas natural gas for a large share of their power plants, could not afford supply costs and left more than 4.7 million users from the states of Chihuahua, Coahuila, Durango, Tamaulipas and Nuevo León without electricity, many of them already living in poverty [33]. Within the US, even months after the storm, other states such as Colorado and as far away as Minnesota also face higher bills because of gas price spikes from the storm [35,36].

2.2.2 Water Disruptions

In the days prior to the 2021 Winter Storm, the Texas Section of the American Society of Civil Engineers (ASCE) released their 2021 report card where they gave the Texas water system a C- grade after assessing the already dilapidated state of water infrastructure [37]. These existing vulnerabilities and the fragility of the provision of water service were exposed by the onset of freezing temperatures and electrical grid failures. On the distribution side, many water treatment plants lost electricity and were unable to adequately treat water to remove potentially harmful contaminants. In addition, pressure in the water system dropped significantly due to a combination of burst water pipes and millions of dripping faucets across the state because many people intentionally slightly opened their faucets to prevent freezing. The power failures resulted in 43% of community public water systems across the state issuing boil water notices [38], likely rendering this the largest boil water incident in U.S. history. Many systems were on boil water notices for weeks after the winter storm while repairs were underway. Residents with electrical appliances and no power had no means to boil potable water, while many turned to unsafe practices of using outdoor stoves or other improper heating sources that introduce fire risks or elevate exposure to criteria air pollutants from the fumes [39]. During the storm, approximately half of Texans lost water access at some point, with estimates showing that Texans had to endure, on average, 40 hours without access to potable water [23,38]. Further, failures in the electrical system impacted wastewater operations, leading to additional public health risks. For instance, in Austin, while the wastewater system generally fared better than the water system, nine sanitary sewer overflows occurred as a result of lost power at lift stations [40].

At the distribution level, many water service lines were buried often only 12 inches below the historic frost lines. This practice put the water system at risk of damage due to freezing temperatures and power failures. Many buildings that lost power and heat suffered on-premises plumbing breaks, leading to loss of water service and water damage [41–43]. Water utility crews have anecdotally discussed the need to respond to a high influx of water shutoff requests from customers due to private-side breaks during the storm. Further, utilities have identified the need to better equip residents and business owners with the knowledge to perform their own shutoffs using meter keys as a result of the storm [11,42].

While an exhaustive description of the water system impacts during the Winter Storm of 2021 are summarized by Glazer, et al. [6] and other sources [43–45], some of the connections drawn to the energy space take prominence in low-income communities, which are associated with a higher percentage of renters in addition to older housing that tends to be characterized by "substandard insulation, inefficient appliances, and older windows" [2]. That is, newer homes in richer communities with better insulation and tighter envelopes maintained safer temperatures more readily after a power outage than older homes with leakier building envelopes. Furthermore, renters and apartment complex residents suffered disproportionately from damage to plumbing, with many apartment complexes remaining without water for weeks after water utilities restored service to the distribution system due to shortages of plumbers and property managers delaying repairs [44,45].

2.2.3 Housing and Living Conditions

The 2021 Winter Storm caused significant property damage across the state. In the aftermath of the storm, individuals in 126 counties received over $200 million in federal assistance in the form of 60,329 grants, loans, and other programs to cover home repairs, reimburse property losses, and recover business operations [46]. These efforts complemented other resources made available for the community by both state and county offices, which provided food assistance, healthcare, mental health services, medical trips, and unemployment benefits. Psychological trauma continues to prevail and affect underserved communities, as shared through conversations between co-authors and community members in the Austin area.

During the storm, many people were trapped in their homes without aid and struggled to keep themselves warm. As gathered by TEPRI [24], low-income groups in Texas are more likely than high-income groups to live in homes built with less insulation and improperly weatherized infrastructure [47]. The lack of proper insulation during this extreme weather event made it difficult for many homes to retain heat, which forced people to seek heat from non-traditional sources such as gas-fired stoves or vehicle engines. These heat sources were often operated in enclosed spaces, increasing the risk of carbon monoxide poisoning [2,48,49]. Despite these risks, over 27% of survey respondents, across all income levels, used unconventional methods of heat generation during the storm [2]. In all, at least 18 deaths from carbon monoxide exposure during the storm have been reported [7].

Failures in the healthcare system further impacted health and well-being throughout the event. Power and water outages limited hospitals' ability to provide care for patients and forced many non-emergency facilities, such as urgent care, pharmacies, and dialysis centers, to close entirely [50]. Roughly 10% of recorded deaths during the storm were due to the exacerbation of pre-existing conditions, which may have been avoided had the necessary healthcare facilities been able to operate at normal capacity [7]. Moreover, the reduced access to healthcare likely contributed to the death rates due to other circumstances such as hypothermia (64%), motor vehicle accidents (9%). These outcomes are particularly problematic for low-income households, who are already more likely to live further away from healthcare facilities [51].

The prevalence of homelessness was another factor that contributed to the storm-related deaths [31]. During the storm, shelters and warming stations were established by a combination of local governments and volunteer organizations [41]. Anecdotal evidence points towards an initial reluctance from people to seek shelter as they were hoping to avoid crowded spaces during the COVID-19 pandemic and expected to be able to manage the unexpectedly low temperatures on their own [52]. Studies of previous disasters, like the 2018 Camp Fire in California, suggest that additional factors like the rules imposed by government-organized shelters, a shelter's sense of community, and the proximity of shelters might have also factored into people's sheltering decisions during the winter storm [53]. Fortunately, the number of people seeking shelter eventually increased over time due to the sustained low temperatures and the efforts of sheltering volunteers. However, many shelters were ill-prepared. Some lost power and water and could not provide proper accommodations [52], while others lacked the supplies and space needed to meet the high demand during the storm. This confluence of failures led to an increased reliance on local businesses, volunteers, and community organizers to distribute supplies and support local communities [41,42].

2.2.4 Road Transportation

Studies have shown that low-income, immigrant, and Black, Indigenous and People of Color (BIPOC) are less likely to own private vehicles and depend more on public transportation than those that are US-born and white [54]. When this fact is considered alongside the lack of accessible services such as grocery stores [55–58], any disruptions to these services quickly become life-threatening. When the snow cover from the February 2021 storm rendered roads and railways impassable, low-

DOI: 10.1088/2516-1083/aca9b4

income and rural communities were especially isolated as many public transit options shut down ahead of the storm [59]. Transportation authorities, like Capital Metro in Austin, attempted to sustain some level of service during the storm. However, a lack of coordination and resources limited the efficacy of these services and placed their employees at risk [60].

However, low-income communities were not the only ones impacted by road closures and service disruptions: 75% of Texans reported difficulty obtaining food or groceries [23] – whether due to inaccessibility, business and service closures, or disrupted supply chains and altered transportation logistics is not obvious. Despite the lack of mobility, around 18% of Texans left their homes during the storm, with the highest share heading to a local relative's homes in the nearby areas, followed by friends' homes and local hotels or motels [23].

Poor road conditions also negatively impacted the recovery efforts of the electricity and water sectors. Multiple reports indicate that unsafe road conditions led to significant delays in response time and rendered some facilities completely inaccessible to repair workers [5,9,10].

2.2.5 Communication Systems and Practices

The City of Austin developed its own Winter Storm Review [11], with many of the findings in that report critiquing their response and acknowledging areas for improvement that resemble prior best practices on disasters, crises, and communication. For example, the city used some social media, including holding Facebook meetings by city departments, but they predominantly followed a pattern of one-way, outgoing communication [11]. Prior research suggests that more dialogic, two-way communication, along with frequent updates are important to build trust [61]. During the 2021 freeze, many people relied on a device that required electricity or the internet to access information during the storm [23]. Other studies have identified that power is a foundational communication need. As such, without power people cannot use their mobile phones as consistently to send or receive information or to coordinate with others sending them help [62].

The communication efforts by public officials were at times inconsistent and sometimes included incorrect information [11], potentially leading to distrust of authorities [61,63]. Best practices for communicating during weather emergencies include communicating with honesty, candor, openness, compassion, and empathy and acknowledging and accounting for cultural differences [61,64]. Communication around power outages was particularly inadequate. For example, one energy company had outage maps and text alerts available to their customers, yet the scale of the event meant they could not accurately predict the duration of outages, and they did not proactively provide status updates [9].

Utilities also largely excluded non-English speaking communities from their outreach efforts. This problem is especially impactful in Texas, which has a diverse population and millions of households whose primary language is something other than English. One tally estimated that nearly two-thirds of Texas households speak English at home, but the remaining third speak one of more than 160 other languages, predominantly Spanish but also Vietnamese, Tagalog, German, among others [65]. In many cases, information concerning how to prepare and respond to the winter storm was not translated into languages other than English [11].

Communication platforms also lacked diversity. While some local governments tried to communicate using social media (e.g., Twitter and Facebook), they rarely included multiple platforms (e.g., WeChat, WhatsApp, TikTok, Instagram) that have been shown to be more relevant for reaching different cultural groups, some of which are marginalized during disasters [66]. To compensate for these communication gaps and needs for basic preparedness and recovery materials, non-profit organizations took a leading role [11]. This is a common practice in disasters when the public needs help and the official organizations are not meeting those dire needs [67].

2.2.6 COVID-19 Compounded Impacts

The ongoing COVID-19 pandemic had already disrupted the status quo prior to the storm. In January 2021, a month before the state-wide freeze, Texas unemployment rate was 6.8%, nearly double the unemployment a year prior, just before the pandemic began [68]. That same month, approximately 563,000 Texans were subscribed to the Federal Pandemic Unemployment Compensation program, which provided $600 per week in addition to the standard unemployment payments to ensure recipients could meet their basic needs. Over the course of the pandemic, energy poverty in the state increased; 25% of the low-income survey respondents reported by TEPRI (Texas Energy Poverty Research Institute) [2] had sought electricity bill assistance or enrolled in electricity bill payment deferral programs due to the financial strain caused by the pandemic. This level of participation in assistance programs may have been exacerbated by an increase in residential electricity usage as a result of ongoing safety measures that included work-from-home, quarantining, and so forth. A study of the impact of safety measured in other states found that residential electricity consumption increased by 4-5% during the pandemic, with low-income and minority populations experiencing a larger increase [69].

DOI: 10.1088/2516-1083/aca9b4

During the parallel events of the storm and the pandemic, the ongoing safety measures aimed at reducing SARS-CoV-2 transmissibility, such as social distancing, are hypothesized to have reduced the ability or willingness of those impacted by the electricity blackouts to seek alternative sheltering options. During the storm, about 60% of people continued to follow social distancing recommendations, with an additional 15% practicing higher levels of distancing than usual [23]. Among other factors, this high adherence to social distancing policies may have led people to stay in their homes despite losing power. Additionally, communities shared their hesitation in opening their homes to one another if they did not lose power; people were forced to choose between potential exposure to COVID or having friends and family continue to be exposed to the freezing temperatures [11].

Further, the ongoing COVID-19 pandemic might have impacted the recovery of infrastructure systems across the state with emergency response resources already strained from a year of pandemic response [16]. In an effort to prevent outbreaks, some utilities had field crews operating atypically during the winter storm event (e.g., limiting crews to one worker per vehicle, not mixing sub-crews, requiring workers to use personal vehicles), potentially slowing response times. In many municipalities, utilities' non-field crew staff such as management and administrative support, were working from home and coordinating event response via digital platforms. Such social distancing and work-from-home practices varied among municipalities across the state, making their impact on response and recovery times difficult to measure.

3. A Need for Equitable Long-Term Infrastructure Planning and Recovery

To prevent hazards from turning into disasters – and disasters from turning into catastrophes – requires cross-sectoral coordinated proactive efforts, and robust long-term strategies that can systematically address the climate crisis risk in terms of disaster preparedness, response, and recovery – especially in disadvantaged communities [39]. A foreseen challenge is one where energy insecurity will continue to grow for vulnerable populations as infrastructure and societal shocks from natural disasters – whether in the form of winter storms, fires, droughts, or floods –increase over time in both magnitude and frequency [70,71].

Energy insecurity, which is the inability to adequately meet basic household energy needs [25,29], was observed across low-income groups before COVID-19 and the February 2021 Winter Storm. The additional costs to repair the property damage (e.g., burst pipes, fallen trees, damaged appliances, home structural damage, etc.) only further reduces the amount of disposable income left to cover energy and other basic needs. This energy burden could likely increase over time as climate crisis-related events continue to occur.

Even if rapid disaster aid is provided, care must be taken in the way it is administered to avoid exacerbating income inequality and other types of inequities that have been documented in areas affected by disasters and receiving high FEMA aid [72].

To provide a basis for future equitable and resilient emergency response planning, the following section outlines some of the long-term needs made evident by Winter Storm Uri and suggests potential solutions for them based on existing literature (e.g., reports, news articles, academic publications) and perspectives formed through conversations with different groups and entities.

3.1 Electricity Sector

A common belief is that thermal power plants (such as those that use nuclear, coal, or natural gas as fuel) provide higher reliability for the grid as the power units tend to be dispatchable (i.e., can adjust their power output) and can accommodate large demand variations much more easily. The February 2021 winter storm disproved this conventional wisdom as considerable thermal power capacity failed to dispatch electricity when required, revealing their vulnerability to extreme weather when inadequately conditioned or if dependent on gas supplies or pipelines that themselves were not winterized [3]. A lack of enforcement to ensure power plants were weatherized, coupled with a significant number of gas suppliers being ineligible for critical load designation in many utilities (e.g., due to improper paperwork filing), led to significant unplanned outages [73] and an inability to restore proper grid working conditions (i.e., decreased system resilience). In fact, all power plants have reliability challenges in one way or another [74]. It is possible to retrofit existing generators (fossil and non-fossil fuel based) to withstand cold weather and provide a degree of resilience to the system, but the process is much more expensive and ends up costing ratepayers more than building weatherized generators in the first place [75].

In regard to power plants operations, a clear nexus can be drawn between the existing fossil-fueled thermal plants and the uneven distribution of pollutant emissions across the state. Figure 2 compares the aggregated SO2 pollutants exposure across counties from operational coal plants in Texas against the average energy burden from low-income households. Similarly, natural gas plants in the state –including those that reported problems during the winter storm– have increased their emissions during the 2022 winter due to weather-related operating issues [76].

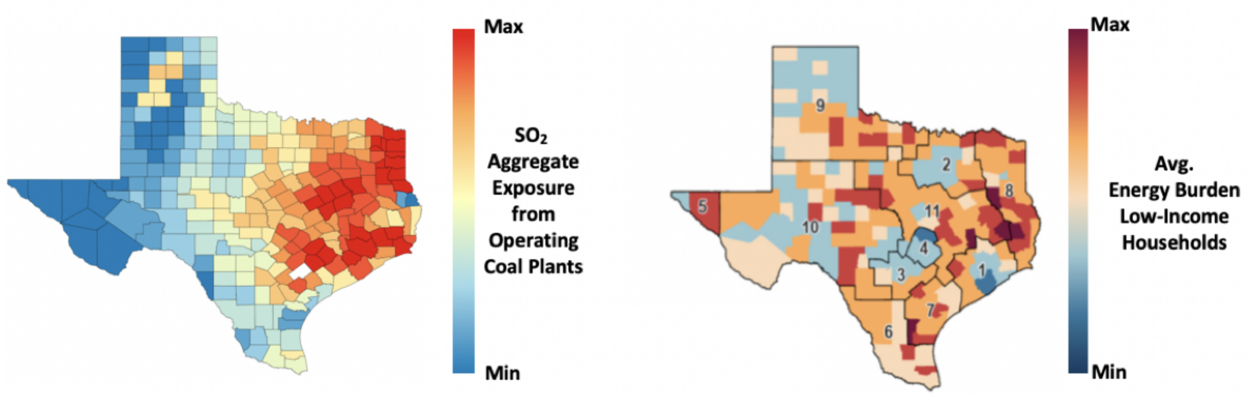

Fig. 2. (a) SO2 aggregate exposure from operating coal plants in Texas during 2020, and (b) the average energy burden from low-income households prior to the February 2021 Winter Storm. Sources: Authors and TEPRI [22].

The evident lack of guaranteed reliability from multiple thermal plants and the disparate exposure of burdened communities to power plants pollutants provides an opportunity to re-think the grid planning process for the future. Approaches that assess accelerated decommissioning of unreliable and polluting grid assets while improving system resilience (e.g., withstanding and rapidly recovering from disruptions) in the face of extreme weather should be favored to address both reliability concerns and inequity issues early on.

Distributed energy resources (DER) also provide unique clean electricity generation opportunities and should be considered in the strategic planning of grid development, especially as means of diversifying the electricity generation sources – an approach that would isolate transmission and (to an extent) distribution-level challenges and add resiliency. Therefore, acknowledging DER as a grid-resilience tool, efforts should be geared towards providing affordable access to this tool. However, evidence from other states and across the US suggests that the concentration of DER, such as rooftop solar, are disproportionately located in higher income neighborhoods [77,78]. The proliferation of these technologies is also underrepresented in Black and Hispanic communities, even after controlling for income and homeownership [79]. When paired with storage, the prospect of improving home resiliency to disasters and power outages further increases dramatically. The importance of storage cannot be understated, particular for underserved communities; storage provides energy independence, generates wealth, and, by consequence, reduces social inequities [75]. These technologies require supportive utility pricing structures that avoid exacerbating disparities in energy burden across race and income [81].

Downstream, the end uses for electricity are expanding as is the need to ensure the electric grid can reliably accommodate these loads in an economy poised to be electrified. The transportation sector is seeing an increased conversion and adoption rate for electric vehicles (EV), which can be thought of as an extension of additional storage units that can provide home resiliency in the event of disasters. The increased electricity demand from electric vehicle charging also has direct implications in the grid, its fuel mix, and the need for a comprehensive planning process. As an example, studies show how switching from combustion engines to EVs moves pollution from urban, daytime, nose-level tailpipes to rural, night-time, tall smokestacks. This change in behavior alters the formation of photochemical smog and pollution dispersion [82], highlighting the need for an integrated planning process that addresses time and spatial domains for both generation and demand coordination [83] capable of operating during peacetime, and respond during disasters. In addition, access to EVs requires expanded incentives to make them accessible across income levels [84,85]. The distribution of charging infrastructure has also been demonstrated to have unequal placement along racial or income lines in different parts of the United States [86,87].

Beyond the planning process, an equally important need is to ensure a resilient coordinated dispatch at all times. With an increased risk of more frequent and severe natural disasters, the protocols used to determine rolling blackout schedules and maintain grid stability need to be evaluated. The Winter Storm of 2021 demonstrated both that low income and minority households were at a far greater risk of experiencing blackouts [33] and that the current procedures for extreme weather events are still insufficient for mitigating disasters. It is critical to identify where the protocols fall short and what actions can be taken by local and state regulators to avoid racial and economic inequities. Additionally, there is a clear need to understand the degree to which these problems are a result of implicit bias within the tools and procedures used by system operators, and/or pre-existing inequities in civil infrastructure.

Equity should be at the forefront when deciding where and how to cut power during rolling blackout events [88]. Other studies have found that it is possible to drastically reduce the impacts of blackouts by creating an electricity rationing plan based on the social cost that end users experience when they lose power [89]. A method for distributing blackouts in this way would mitigate the burdens placed on low-income communities by cutting power to businesses and households that either need

DOI: 10.1088/2516-1083/aca9b4

the electricity less or are more prepared for an outage thanks to backup electricity sources [90]. While these types of rationing programs would minimize impacts, it may also require a level of granularity and control over the system that is not currently present in some areas [9]. Lastly, beyond the technical and procedural aspects described here, studies have also identified a specific regulations, rules, and market mechanisms to provide a reliable and resilient grid that ERCOT should review and respond to in future rule-making and market design [91].

3.2 Water Systems

In response to the Winter Storm of 2021, Glazer et al. [6] offer a comprehensive set of state-wide communication, policy, and research recommendations for improving resilience to natural disasters in the water infrastructure system. On the water utility side, after-action reports published by public agencies identify short- and long-term infrastructure improvements aimed at better preparing Texas' water systems for future extreme weather events. Key among these provisions are establishing back-up power generation at critical water and wastewater facilities (e.g., water treatment plants, pump stations, lift stations), ensuring ample back-up fuel supply for generators, winterizing facilities, and updating Emergency Response Plans [41,42]. Utilities may also consider long-term plans that include the construction of additional water storage facilities and increasing water transmission redundancies in vulnerable portions of distribution systems. In the housing sector, code changes related to water line depth of cover requirements and building insulation have the potential to improve resiliency of both energy and water systems, while addressing long-standing inequities.

Water utilities' after-action reports, like those of energy companies seen so far, reveal an awareness of the severe communication challenges faced during this winter storm. Procedural changes planned by utilities include efforts to clarify roles for communication staff, increasing the frequency and consistency of releasing information to the public, and increasing the utilization of the Warn Central Texas mobile app system [10]. There are, however, additional communication planning and execution gaps that still exist. The rise in use of mobile warning apps and social media, as well as back-up communication plans if power is lost, warrant increased attention if a two-way communication channel between the utilities and public is sought [11,61].

Examples can be illustrated by an identified need by communities to have Homeland Security Emergency Management and water utilities working together to send information to residents, and training and outreach to register residents on the Warn Central Texas mobile app.

The breakdown in water infrastructure systems and cascading impacts into the social system that occurred during the Winter Storm Uri were particularly evident in the lack of knowledge transfer. Emphasis must be placed on both decentralizing knowledge among utility providers (e.g., empowering operators to make critical decisions) and disseminating knowledge among the community (e.g., teaching residents how and where to shut off water supply in case of a premise-side break). Limited initiatives to educate the public on winter storm preparedness, weatherization practices, and residential valve shutoffs, have already begun [92–94]. However, such programs must be accelerated with greater efforts and funding put towards distributing free winterization supplies (e.g. meter keys, hose bib covers, tip sheets), sharing accessible information via multiple channels and mediums (e.g., videos, social media, local news, utility websites), providing information in multiple languages, and conducting active outreach to vulnerable communities.

3.3 Housing and Living Conditions

There is a clear need to address the disparity in energy burden across income levels and their primary causes. Programs such as bill assistance help to alleviate energy costs in the short-term, but do not attempt to eliminate root causes for the disparities. A combination of weatherization, energy efficiency, and demand response programs to subsidize upgrades of low-income homes can help reduce household energy costs while making homes and the broader grid more resilient in the event of extreme weather events and blackouts, helping maintain comfortable temperatures for longer periods.

Implementing weatherization and energy efficiency programs requires multiple types of incentive structures. The Weatherization Assistance Program (WAP) funded by the U.S. Department of Energy [95] has documented successes in this effort, having provided funding to weatherize hundreds of thousands of low-income homes and generating billions of dollars in energy savings [96]. While this program has been successful in distributing billions of dollars of funds, the program is not without its shortcomings [97,98]. Benefits of this program, however, go almost exclusively to homeowners, which made up 87% of WAP's clients in 2014 [99]. Programs like WAP require approval from landlords, who may have little incentive to weatherize or upgrade their units since they are not paying the energy bills. These programs also often prevent landlords from raising rent once the unit is upgraded. Alternative and complementary incentives [100] are needed to provide benefits to landlords as well as tenants to encourage them to invest in or approve weatherization and energy efficiency programs in their units, particularly in lower-income housing.

The pitfalls of the WAP program highlight a broader need to assess the distribution of government funding to ensure it is equitably distributed across different demographics. Otherwise, disproportionate distributions of this aid during the recovery response will further exacerbate the inequities that existed prior to the disaster. For example, while government aid after disasters is crucial for providing immediate relief to households in need, studies evaluating Federal Emergency Management Authority (FEMA) aid allotments [101] have shown that misguided assistance has led to exacerbated wealth inequalities between White and Black communities [72].

Regarding shelters, insufficient preparation during Uri indicated that there is a need for additional measures to ensure shelters are reliably stocked [41]. Authorities could have pre-emptively ensured that shelter locations had supplies on-hand in case disasters strike or could have developed a resilient supply chain that would be able to continue supplying goods during disaster scenarios. In addition, studies of previous disasters and local reports assessing these events show there is a need for a more coordinated effort between the formal shelters operated by local governments and the unofficial shelters of volunteer groups [53]. These groups should be in active communication during disasters to coordinate their efforts and provide accurate information to the public. In addition, given the reliance on unofficial shelters, local governments should take efforts to ensure volunteer organizations have the resources needed to meet higher demand. One approach being developed in Austin, Texas, is the establishment of "Resilience Hubs", which are local facilities such as schools and community centers that are outfitted with resources and infrastructure to support the needs of the local community during disasters [102]. These hubs are community-led and, with the support of the local government and additional partners, are intended to meet the unique needs of the communities where they are established.

3.4 Road Transportation

Effective planning and disaster response in the transportation sector will also expedite recovery efforts in other sectors. An ASCE Texas Section report suggested that the road prioritization system used by the Texas Department of Transportation (TxDOT) should be revisited and expanded [91]. Prioritizing road maintenance and clearing to provide connections to critical electricity, gas, and water infrastructure alongside local and regional infrastructure in emergency maintenance procedures will aid greater response efforts. In addition, the ASCE Texas Section suggested efforts to reduce the interdependencies with the transportation sector to ensure facilities remain operational when they are needed most. The report also notes the high impact of poor road conditions on supply chain logistics and personal mobility and recommends a more comprehensive emergency response plan that outlines how to best leverage existing resources and keep drivers safe. Investments are needed to improve roads, bridges and other old and poorly maintained infrastructure. Texas received a D+ rating from the ASCE, highlighting the dire state of critical transportation infrastructure. Improving our infrastructure will improve public safety, improve normal operations, and make the transportation infrastructure more resilient and easier to maintain in an emergency [103], while simultaneously improving physical and economic mobility, particularly for disadvantaged communities.

The breadth of documented experiences reveals the links between insufficient planning and resource management during disaster scenarios [60], the vital provision of limited services during recovery efforts [104], and the need for improved procedures to determine when to suspend transportation service. Similarly, guidance on how to act and distribute vehicles and resources as part of the relief effort, and how and when to begin service restoration, especially prioritizing services for low-income and minority neighbourhoods who rely more heavily on public transportation have been identified [105]. These identified actions can support a resilient response in this sector against future extreme weather events.

3.5 Communication Systems and Practices

Communication systems and processes broke down during the winter storm because of workforce and bandwidth limits, power outages, and downed lines, and utilities recognize many of these issues [9,10]. The impacts of the storm demonstrated that it is vital for communication plans to be in place and be ready to activate quickly during emergency events [61]. In the wake of the extreme weather events, it became clear that vital preparatory actions like hardening telecommunication facilities, building out infrastructure redundancies for these facilities (e.g., duplicate communication assets), developing reliable two-way communication methods, and educating communication staff are vital to increase public awareness and help prevent negative side effects [91]. Newer wireless emergency alert technologies, combined with best-practice communication strategies, have the potential to improve public receptiveness to messaging [106]. These lower-bandwidth communication options can work better than resource-intensive channels like social media and even television (a widely trusted source). Policymakers also must better understand how social media is being used both publicly and privately when people need help [37]. While using that social media data comes with some privacy concerns, ignoring the prevalence of social media communication could present an even bigger threat when disasters occur [62,67]. In addition, it was evident that a significant portion of the population do not use social media platforms or have access to smartphones with apps. Communication strategies should consider the needs of all population segments, particularly with respect to digital accessibility.

4. Conclusion

The deadly winter storm of February 2021 exposed many issues in our existing infrastructure and systems that led to inequitable outcomes whose impacts continue to manifest. Furthermore, the systems' interdependence (e.g., electricity, water, transportation, housing, communications) revealed multiple compounded challenges arising from poor initial infrastructure conditions and preparedness.

While the majority of the discussion in this work revolves around a single winter weather event, different natural disasters, such as hurricanes, heat waves, tornadoes, droughts, and floods, will continue to strain the fragile interconnection between our multiple systems and amplify harmful inequitable impacts on minority and disadvantaged communities. This extreme weather event has highlighted the need to design our systems in a more reliable, resilient, and equitable manner.

Beyond the summarized systems' interdependence challenges, we propose a list of actions that could provide a long-term planning and recovery process for different sectors while prioritizing equitable outcomes.

The non-exhaustive list of impacts and mitigation strategies synthesized in this manuscript summarize salient needs identified by the research group through expertise and ongoing conversations with community members.

While we recognize that many of the outcomes discussed rely on non-academic sources (e.g., local journalistic pieces), the impacts documented here reflect local narratives that need to be addressed in a timely manner to induce change and that might not need to be quantified through academic venues prior to be disseminated. Moreover, our research into this topic did not uncover any glaring inconsistencies, which suggests a consistent narrative between academic and non-academic sources.

The outcomes identified from the interdependent electricity, water, housing, transportation and communication sectors require a critical focus and an empathic response in terms of planning to prepare our communities in an equitable way for the more frequent and extreme weather events we expect in the coming decades.

Acknowledgments

The contributions by Castellanos, Potts, Tiedmann, Alverson, Stephens and Faust were based upon work supported by the National Science Foundation under Grant No. 2129801. The contributions by Glazer and Webber were partially supported by the Texas State Energy Conservation Office, the U.S. Army Corps of Engineers' Engineer R&D Center (ERDC) under a subcontract with Artesion, and the Energy Foundation. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. In addition to the research work on topics generally related to energy systems at the University of Texas at Austin, one of the authors (Webber) has an affiliation with Energy Impact Partners (a venture investment firm) and IdeaSmiths LLC (an engineering consulting firm). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors, Energy Impact Partners, or IdeaSmiths LLC. The terms of this arrangement have been reviewed and approved by the University of Texas at Austin in accordance with its policy on objectivity in research.

References

[1] "More than 100 insurance companies sue ERCOT, power generators over winter storm losses," *KXAN Austin*, Jan. 05, 2022. https://www.kxan.com/news/texas/more-than-100-insurance-companies-sue-ercot-power-generators-over-winter-storm-losses/ (accessed Feb. 07, 2022).

[2] (TEPRI) Texas Energy Poverty Research Institute, "When the Lone Star Froze Over," Jul. 2021.

[3] J. W. Busby *et al.*, "Cascading risks: Understanding the 2021 winter blackout in Texas," *Energy Research & Social Science*, vol. 77, p. 102106, Jul. 2021, doi: 10.1016/j.erss.2021.102106.

[4] C. W. King *et al.*, "The timeline and events of the February 2021 Texas electric grid blackouts," *The University of Texas Energy Institute*, 2021.

[5] "The February 2021 Cold Weather Outages in Texas and the South Central United States | FERC, NERC and Regional Entity Staff Report | Federal Energy Regulatory Commission." https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and (accessed Feb. 07, 2022).

[6] Y. R. Glazer *et al.*, "Winter Storm Uri: A Test of Texas' Water Infrastructure and Water Resource Resilience to Extreme Winter Weather Events," *J. of Extr. Even.*, p. 2150022, Dec. 2021, doi: 10.1142/S2345737621500226.

[7] T. D. of S. H. S. Texas Health and Human Services, "February 2021 Winter Storm-Related Deaths – Texas," Dec. 2021. Accessed: Feb. 07, 2022. [Online]. Available: https://dshs.texas.gov/news/updates/SMOC_FebWinterStorm_MortalitySurvReport_12-30-21.pdf

[8] "The Texas Winter Storm And Power Outages Killed Hundreds More People Than The State Says," *BuzzFeed News*. https://www.buzzfeednews.com/article/peteraldhous/texas-winter-storm-power-outage-death-toll (accessed Sep. 09, 2021).

[9] Austin Energy, "Austin Energy - February winter Storms After-Action Report 2021," Oct. 2021. https://austinenergy.com/wcm/connect/482f26ba-7c94-465a-8a00-59bd65f33967/Feb2021-WinterStormsAfterActionReport.pdf (accessed Feb. 07, 2022).

[10] Austin Water, "Austin Water: Winter Storm Uri After Action Report," Nov. 2021. Accessed: Feb. 07, 2022. [Online]. Available: https://www.austintexas.gov/sites/default/files/files/Water/AW_WinterStorm_Report.pdf

[11] City of Austin, "Austin Winter Storm Review Task Force Report," Jul. 2021. Accessed: Feb. 07, 2022. [Online]. Available: https://www.austintexas.gov/edims/document.cfm?id=366445

[12] S. B. Billings, E. Gallagher, and L. Ricketts, "Let the Rich Be Flooded: The Distribution of Financial Aid and Distress after Hurricane Harvey," Social Science Research Network, Rochester, NY, SSRN Scholarly Paper ID 3396611, May 2019. doi: 10.2139/ssrn.3396611.

[13] C. E. Willison, P. M. Singer, M. S. Creary, and S. L. Greer, "Quantifying inequities in US federal response to hurricane disaster in Texas and Florida compared with Puerto Rico," *BMJ Global Health*, vol. 4, no. 1, p. e001191, Jan. 2019, doi: 10.1136/bmjgh-2018-001191.

[14] "Report on outages and curtailments during the Southwest cold weather event," p. 357.

[15] A. P. and B. Sechler, "Winter storm blackouts plagued Texas in 2011, too. Recommendations made afterward went unenforced.," *USA TODAY*. https://www.usatoday.com/story/news/nation/2021/02/18/state-energy-winter-protections-lacking-reports-have-suggested/4490501001/ (accessed Feb. 07, 2022).

[16] C. of A. Office of the City Auditor, "Audit Report: Disaster Preparedness - The City Was Unprepared to Respond to Winter Storm Uri," Nov. 2021. Accessed: Feb. 07, 2022. [Online]. Available: https://www.austintexas.gov/edims/document.cfm?id=371190

[17] N. US Department of Commerce, "Valentine's Week Winter Outbreak 2021: Snow, Ice, & Record Cold." https://www.weather.gov/hgx/2021ValentineStorm (accessed Nov. 12, 2022).

[18] J. Doss-Gollin, D. J. Farnham, U. Lall, and V. Modi, "How unprecedented was the February 2021 Texas cold snap?," *Environ. Res. Lett.*, vol. 16, no. 6, p. 064056, Jun. 2021, doi: 10.1088/1748-9326/ac0278.

[19] M. Waite and V. Modi, "Electricity Load Implications of Space Heating Decarbonization Pathways," *Joule*, vol. 4, no. 2, pp. 376–394, Feb. 2020, doi: 10.1016/j.joule.2019.11.011.

[20] P. R. White, J. D. Rhodes, E. J. H. Wilson, and M. E. Webber, "Quantifying the impact of residential space heating electrification on the Texas electric grid," *Applied Energy*, vol. 298, p. 117113, Sep. 2021, doi: 10.1016/j.apenergy.2021.117113.

[21] "Addressing Energy Poverty Issue Brief," *Texas Energy Poverty Research Institute*, Oct. 16, 2018. https://txenergypoverty.org/2018/10/addressing-energy-poverty-issue-brief/ (accessed Sep. 09, 2021).

[22] "Texas Low-Income Community Profile (LICP) Series Part 1: Texas Overview," *Texas Energy Poverty Research Institute*, Jun. 26, 2019. https://txenergypoverty.org/2019/06/licp-texas-overview/ (accessed Sep. 09, 2021).

[23] K. P. Watson, R. Cross, and M. P. Jones, "The Winter Storm of 2021," Hobby School of Public Affairs, University of Houston.

[24] "2021 Poverty Guidelines," *ASPE*. https://aspe.hhs.gov/topics/poverty-economic-mobility/poverty-guidelines/prior-hhs-poverty-guidelines-federal-register-references/2021-poverty-guidelines (accessed May 31, 2022).

[25] "Energy Insecurity: Why It Matters Infographic," *Texas Energy Poverty Research Institute*, Apr. 28, 2020. https://txenergypoverty.org/2020/04/energy-insecurity-why-it-matters-infographic/ (accessed Sep. 09, 2021).

[26] J. Adams, "Winter Storm Uri Market Update - March 5, 2021," *Energy Edge Consulting, LLC*, Mar. 05, 2021. https://energyedge.com/winter-storm-uri-market-update-march-5-2021/ (accessed Jun. 13, 2022).

[27] G. M. N. del Rio, N. Bogel-Burroughs, and I. Penn, "His Lights Stayed on During Texas' Storm. Now He Owes $16,752.," *The New York Times*, Feb. 21, 2021. Accessed: Feb. 07, 2022. [Online]. Available: https://www.nytimes.com/2021/02/20/us/texas-storm-electric-bills.html

[28] C. Agbim, F. Araya, K. M. Faust, and D. Harmon, "Subjective versus objective energy burden: A look at drivers of different metrics and regional variation of energy poor populations," *Energy Policy*, vol. 144, p. 111616, 2020.

[29] D. Hernández, "Understanding 'energy insecurity' and why it matters to health," *Social Science & Medicine*, vol. 167, pp. 1–10, Oct. 2016, doi: 10.1016/j.socscimed.2016.08.029.

[30] Z. D. Serrano Alejandro and S. Lamm, "Analysis reveals nearly 200 died in Texas cold storm and blackouts, almost double the official count," *Houston Chronicle*, Apr. 01, 2021. https://www.houstonchronicle.com/news/houston-texas/houston/article/texas-cold-storm-200-died-analysis-winter-freeze-16070470.php (accessed Sep. 10, 2021).

[31] "Feed the Soul Foundation Launches Emergency Restaurant Relief Fund," *Black Restaurant Week*, Feb. 24, 2021. https://blackrestaurantweeks.com/feed-the-soul-foundation-launches-emergency-restaurant-relief-fund/ (accessed Sep. 10, 2021).

[32] K. Yentch, "Texas Coffee Shops Endure Winter Storm Uri," *Barista Magazine Online*, Feb. 23, 2021. https://www.baristamagazine.com/texas-coffee-shops-endure-through-winter-storm-uri/ (accessed Sep. 10, 2021).

[33] "Frozen Out in Texas: Blackouts and Inequity," *The Rockefeller Foundation*, Aug. 10, 2021. https://www.rockefellerfoundation.org/case-study/frozen-out-in-texas-blackouts-and-inequity/ (accessed Aug. 10, 2021).

[34] "¿Por qué hace tanto frío en Texas?: la histórica tormenta invernal en Texas que ha causado apagones en la mitad de México," *BBC News Mundo*. Accessed: Feb. 08, 2022. [Online]. Available: https://www.bbc.com/mundo/noticias-internacional-56078326

[35] "Coloradans starting to see double-digit hikes in their gas utility bills," *The Colorado Sun*, Nov. 05, 2021. https://coloradosun.com/2021/11/05/colorado-utility-bill-gas-hikes/ (accessed Feb. 08, 2022).

[36] "2021 Winter Storm Uri Repercussions Still Felt – in Minnesota." https://www.publicnewsservice.org/index.php?/content/article/77810-2 (accessed Jun. 13, 2022).

[37] "Texas Infrastructure Report Card - ASCE Texas Section," *American Society of Civil Engineers - Texas Section*, Oct. 11, 2021. https://www.texasce.org/our-programs/infrastructure-report-card/ (accessed Oct. 10, 2021).

[38] "After-Action Review of Public Water Systems and Winter Storm Uri," *Texas Commission on Environmental Quality*, Sep. 10, 2021. https://www.tceq.texas.gov/drinkingwater/after-action-review (accessed Sep. 10, 2021).

[39] B. Booker and V. Romo, "Winter Storm Leaves Many In Texas Without Power And Water," *NPR*, Feb. 17, 2021. Accessed: Feb. 08, 2022. [Online]. Available: https://www.npr.org/2021/02/17/968665266/millions-still-without-power-as-winter-storm-wallops-texas

[40] Freese and Nichols, Inc, "Winter Storm Uri After Action Technical Review," Austin, Texas, Nov. 2021. Accessed: Feb. 08, 2022. [Online]. Available: https://www.austintexas.gov/sites/default/files/files/Water/FNI%20Technical%20Review%20-%20Supporting%20Document.pdf

[41] Austin-Travis County, "Winter-Storm Uri After-Action Report & Improvement Plan- Technical Report," Austin, Texas, Oct. 2021. Accessed: Feb. 08, 2022. [Online]. Available:

https://www.austintexas.gov/sites/default/files/files/HSEM/Winter-Storm-Uri-AAR-and-Improvement-Plan-Technical-Report.pdf

[42] "City of San Antonio – Community Emergency Preparedness Committee Report: A Response to the February 2021 Winter Storm," San Antonio, Texas, Jun. 2021. Accessed: Feb. 08, 2022. [Online]. Available: https://www.sanantonio.gov/Portals/5/files/CEP%20Report%20Final.pdf

[43] N. Bogel-Burroughs, G. M. N. del Rio, and A. Paybarah, "Texas Winter Storm: What to Know," *The New York Times*, Feb. 20, 2021. Accessed: Mar. 09, 2022. [Online]. Available: https://www.nytimes.com/2021/02/20/us/texas-winter-storm-explainer.html

[44] L. Fisher, FRI., March 19, and 2021, "Campaigners, Firefighters Help Residents With Burst Pipes." https://www.austinchronicle.com/news/2021-03-19/campaigners-firefighters-help-residents-with-burst-pipes/ (accessed Feb. 08, 2022).

[45] R. O. and J. P. Garnham, "Over a million Texans are still without drinking water. Smaller communities and apartments are facing the biggest challenges.," *The Texas Tribune*, Feb. 25, 2021. https://www.texastribune.org/2021/02/24/texas-water-winter-storm/ (accessed Feb. 08, 2022).

[46] "President Joseph R. Biden, Jr. Approves Major Disaster Declaration for Texas | FEMA.gov," Aug. 10, 2021. https://www.fema.gov/press-release/20210220/president-joseph-r-biden-jr-approves-major-disaster-declaration-texas (accessed Aug. 10, 2021).

[47] "Low-Income Texans Already Face Frigid Temperatures at Home. Then the Winter Storm Hit.," *The Texas Observer*, Feb. 24, 2021. https://www.texasobserver.org/low-income-texans-already-face-frigid-temperatures-at-home-then-the-winter-storm-hit/ (accessed Sep. 10, 2021).

[48] G. M. N. del Rio, R. Fausset, and J. Diaz, "Extreme Cold Killed Texans in Their Bedrooms, Vehicles and Backyards," *The New York Times*, Feb. 19, 2021. Accessed: Sep. 10, 2021. [Online]. Available: https://www.nytimes.com/2021/02/19/us/texas-deaths-winter-storm.html

[49] K. Griffith, "CO poisoning, fire kill six near Houston as residents try to stay warm," *Mail Online*, Feb. 16, 2021. https://www.dailymail.co.uk/news/article-9267557/CO-poisoning-house-fire-kill-six-near-Houston-residents-try-stay-warm.html (accessed Sep. 10, 2021).

[50] K. B. Harper, "'An emergency on top of a pandemic': Texas hospital workers scramble as winter storm hampered operations," *The Texas Tribune*, Feb. 19, 2021. https://www.texastribune.org/2021/02/18/texas-hospitals-power-outages-winter-storm/ (accessed Nov. 12, 2022).

[51] "Extreme Winter Storms: Environmental Impacts of - ProQuest." https://www.proquest.com/docview/2631687463 (accessed Nov. 12, 2022).

[52] J. P. Garnham, "At least six people experiencing homelessness died during the winter storm. That number could rise.," *The Texas Tribune*, Feb. 22, 2021. https://www.texastribune.org/2021/02/22/texas-winter-storm-homeless-deaths/ (accessed Sep. 10, 2021).

[53] L. A. Spearing, K. K. Stephens, and K. M. Faust, "Shelter shopping: Where the built environment and social systems meet," *International Journal of Disaster Risk Reduction*, vol. 58, p. 102161, May 2021, doi: 10.1016/j.ijdrr.2021.102161.

[54] N. J. Klein and M. J. Smart, "Car today, gone tomorrow: The ephemeral car in low-income, immigrant and minority families," *Transportation*, vol. 44, no. 3, Art. no. 3, May 2017, doi: 10.1007/s11116-015-9664-4.

[55] "Winter Storm Uri Spread Snow, Damaging Ice From Coast-to Coast, Including the Deep South (Recap) | The Weather Channel - Articles from The Weather Channel | weather.com," *The Weather Channel*, Sep. 10, 2021. https://weather.com/safety/winter/news/2021-02-14-winter-storm-uri-south-midwest-northeast-snow-ice (accessed Sep. 10, 2021).

[56] T. C. Blanchard and T. L. Matthews, "Retail concentration, food deserts, and food-disadvantaged communities in rural America," *Remaking the North American food system: Strategies for sustainability*, pp. 201–215, 2007.

[57] L. W. Morton and T. C. Blanchard, “Starved for access: life in rural America’s food deserts,” *Rural Realities*, vol. 1, no. 4, Art. no. 4, 2007.

[58] M. N. Mead, “Urban Issues: The Sprawl of Food Deserts,” *Environ Health Perspect*, vol. 116, no. 8, p. A335, Aug. 2008.

[59] “Winter weather triggers transit changes in Dallas-Fort Worth, shutdown in Houston,” *Trains*. https://www.trains.com/trn/news-reviews/news-wire/winter-weather-triggers-transit-changes-in-dallas-fort-worth-shutdown-in-houston/ (accessed Feb. 08, 2022).

[60] Capital Metro, “Capital Metro – February 2021 Winter Weather After Action Report,” Aug. 2021. Accessed: Feb. 08, 2022. [Online]. Available: https://www.documentcloud.org/documents/21176453-capital-metro-aar-7-26-021-final-report

[61] S. R. Veil, T. Buehner, and M. J. Palenchar, “A Work-In-Process Literature Review: Incorporating Social Media in Risk and Crisis Communication,” *Journal of Contingencies and Crisis Management*, vol. 19, no. 2, pp. 110–122, 2011, doi: 10.1111/j.1468-5973.2011.00639.x.

[62] K. K. Stephens, B. W. Robertson, and D. Murthy, “Throw me a lifeline: Articulating mobile social network dispersion and the social construction of risk in rescue communication,” *Mobile Media & Communication*, vol. 8, no. 2, pp. 149–169, May 2020, doi: 10.1177/2050157919846522.

[63] K. K. Stephens, *New media in times of crisis*. Routledge, 2019.

[64] T. L. Sellnow, R. R. Ulmer, M. W. Seeger, and R. Littlefield, *Effective Risk Communication: A Message-Centered Approach*. Springer Science & Business Media, 2008.

[65] A. U. and J. McCullough, “As Texas Population Grows, More Languages are Spoken at Home,” *The Texas Tribune*, Nov. 26, 2015. https://www.texastribune.org/2015/11/26/languages-spoken-texas-homes/ (accessed Jun. 01, 2022).

[66] J. Li, K. K. Stephens, Y. Zhu, and D. Murthy, “Using social media to call for help in Hurricane Harvey: Bonding emotion, culture, and community relationships,” *International Journal of Disaster Risk Reduction*, vol. 38, p. 101212, Aug. 2019, doi: 10.1016/j.ijdrr.2019.101212.

[67] W. R. Smith, B. W. Robertson, K. K. Stephens, and D. Murthy, “A different type of disaster response digital volunteer: Looking behind the scenes to reveal coordinating actions of disaster knowledge workers,” *Journal of Contingencies and Crisis Management*, vol. 29, no. 2, Art. no. 2, 2021, doi: 10.1111/1468-5973.12352.

[68] “Bureau of Labor Statistics Data.” https://data.bls.gov/timeseries/LASST480000000000003?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true (accessed Feb. 08, 2022).

[69] J. Lou, Y. (Lucy) Qiu, A. L. Ku, D. Nock, and B. Xing, “Inequitable and heterogeneous impacts on electricity consumption from COVID-19 mitigation measures,” *iScience*, vol. 24, no. 11, p. 103231, Nov. 2021, doi: 10.1016/j.isci.2021.103231.

[70] M. Graff, D. M. Konisky, S. Carley, and T. Memmott, “Climate Change and Energy Insecurity: A Growing Need for Policy Intervention,” *Environmental Justice*, vol. 15, no. 2, pp. 76–82, Apr. 2022, doi: 10.1089/env.2021.0032.

[71] A. Maxim and E. Grubert, “Anticipating Climate-Related Changes to Residential Energy Burden in the United States: Advance Planning for Equity and Resilience,” *Environmental Justice*, vol. 15, no. 3, pp. 139–148, Jun. 2022, doi: 10.1089/env.2021.0056.

[72] J. Howell and J. R. Elliott, “As Disaster Costs Rise, So Does Inequality,” *Socius*, vol. 4, p. 2378023118816795, Jan. 2018, doi: 10.1177/2378023118816795.

[73] “Texas Steps Up Oversight of ‘Critical’ Natural Gas Infrastructure in Wake of Winter Storm Uri,” *Natural Gas Intelligence*, Dec. 02, 2021. https://www.naturalgasintel.com/texas-steps-up-oversight-of-critical-natural-gas-infrastructure-in-wake-of-winter-storm-uri/ (accessed Jun. 01, 2022).

[74] K. Ramirez-Meyers, W. N. Mann, T. A. Deetjen, S. C. Johnson, J. D. Rhodes, and M. E. Webber, "How different power plant types contribute to electric grid reliability, resilience, and vulnerability: a comparative analytical framework," *Prog. Energy*, vol. 3, no. 3, p. 033001, Apr. 2021, doi: 10.1088/2516-1083/abf636.

[75] E. Douglas, "Gov. Greg Abbott wants power companies to 'winterize.' Texas' track record won't make that easy.," *The Texas Tribune*, Feb. 20, 2021. https://www.texastribune.org/2021/02/20/texas-power-grid-winterize/ (accessed Feb. 08, 2022).

[76] "Plunging Natural Gas Supply Shows Texas Still Not Ready for Cold," *Bloomberg.com*, Jan. 03, 2022. Accessed: Feb. 08, 2022. [Online]. Available: https://www.bloomberg.com/news/articles/2022-01-03/plunging-gas-supplies-show-texas-still-hasn-t-prepared-for-cold

[77] E. O'Shaughnessy, G. Barbose, R. Wiser, S. Forrester, and N. Darghouth, "The impact of policies and business models on income equity in rooftop solar adoption," *Nat Energy*, vol. 6, no. 1, Art. no. 1, Jan. 2021, doi: 10.1038/s41560-020-00724-2.

[78] A. M. Brockway, J. Conde, and D. Callaway, "Inequitable access to distributed energy resources due to grid infrastructure limits in California," *Nat Energy*, vol. 6, no. 9, Art. no. 9, Sep. 2021, doi: 10.1038/s41560-021-00887-6.

[79] D. A. Sunter, S. Castellanos, and D. M. Kammen, "Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity," *Nature Sustainability*, vol. 2, no. 1, pp. 71–76, Jan. 2019, doi: 10.1038/s41893-018-0204-z.

[80] S. Michener, R. O'Neil, S. Atcitty, B. Jeffers, and B. Tarekegne, "Energy Storage for Social Equity Roundtable Report," p. 49.

[81] J. Lewis, D. Hernández, and A. T. Geronimus, "Energy Efficiency as Energy Justice: Addressing Racial Inequities through Investments in People and Places," *Energy Effic*, vol. 13, no. 3, pp. 419–432, Mar. 2019, doi: 10.1007/s12053-019-09820-z.

[82] T. Thompson, M. Webber, and D. T. Allen, "Air quality impacts of using overnight electricity generation to charge plug-in hybrid electric vehicles for daytime use," *Environ. Res. Lett.*, vol. 4, no. 1, p. 014002, Jan. 2009, doi: 10.1088/1748-9326/4/1/014002.

[83] R. Sioshansi and P. Denholm, "Emissions Impacts and Benefits of Plug-In Hybrid Electric Vehicles and Vehicle-to-Grid Services," *Environ. Sci. Technol.*, vol. 43, no. 4, pp. 1199–1204, Feb. 2009, doi: 10.1021/es802324j.

[84] G. Bauer, C.-W. Hsu, and N. Lutsey, "When might lower-income drivers benefit from electric vehicles? Quantifying the economic equity implications of electric vehicle adoption," *Work. Pap*, vol. 6, 2021.

[85] A. Ku, D. M. Kammen, and S. Castellanos, "A quantitative, equitable framework for urban transportation electrification: Oakland, California as a mobility model of climate justice," *Sustainable Cities and Society*, vol. 74, p. 103179, Nov. 2021, doi: 10.1016/j.scs.2021.103179.

[86] C.-W. Hsu and K. Fingerman, "Public electric vehicle charger access disparities across race and income in California," *Transport Policy*, vol. 100, pp. 59–67, 2021.

[87] J. A. Mahady, C. Octaviano, O. S. Araiza Bolaños, E. R. López, D. M. Kammen, and S. Castellanos, "Mapping Opportunities for Transportation Electrification to Address Social Marginalization and Air Pollution Challenges in Greater Mexico City," *Environ. Sci. Technol.*, vol. 54, no. 4, pp. 2103–2111, Feb. 2020, doi: 10.1021/acs.est.9b06148.

[88] A. Nejat, "Equitable Community Resilience: The Case of Winter Storm Uri in Texas," p. 11.

[89] "Optimal blackouts: Empirical results on reducing the social cost of electricity outages through efficient regional rationing | Elsevier Enhanced Reader." https://reader.elsevier.com/reader/sd/pii/S0140988308001692?token=C8D3FE9FF09053267A8387B267C06E8CCD728E3BD5F0CDFAD4C0303A182C43E7A9EF0EB97747C29572336097C332485E&originRegion=us-east-1&originCreation=20220209035245 (accessed Feb. 08, 2022).

[90] "California power outages highlight economic disparity," *AP NEWS*, Apr. 28, 2021. https://apnews.com/article/california-us-news-ap-top-news-income-disparity-ca-state-wire-abf6aa6a271447c1a2a3c1303f2b7884 (accessed Feb. 08, 2022).

[91] "Texas Beyond Storms Report - ASCE Texas Section," *American Society of Civil Engineers - Texas Section*. https://www.texasce.org/our-programs/beyond-storms/ (accessed Feb. 08, 2022).

[92] "Prepare Your Home for Winter Weather | AustinTexas.gov." https://www.austintexas.gov/news/prepare-your-home-winter-weather (accessed Feb. 08, 2022).

[93] "Austin Water offers supplies to help customers prepare for winter weather," *KUT Radio, Austin's NPR Station*, Dec. 15, 2021. https://www.kut.org/energy-environment/2021-12-15/austin-water-offers-supplies-to-help-customers-prepare-for-winter-weather (accessed Feb. 08, 2022).

[94] "Be Ready," *San Antonio Water System*. https://www.saws.org/beready/ (accessed Feb. 08, 2022).

[95] "Weatherization Assistance Program," *Energy.gov*. https://www.energy.gov/eere/wap/weatherization-assistance-program (accessed Feb. 08, 2022).

[96] B. Tonn, E. Rose, and B. Hawkins, "Evaluation of the U.S. department of energy's weatherization assistance program: Impact results," *Energy Policy*, vol. 118, pp. 279–290, Jul. 2018, doi: 10.1016/j.enpol.2018.03.051.

[97] D. J. Bednar and T. G. Reames, "Recognition of and response to energy poverty in the United States," *Nature Energy*, vol. 5, no. 6, pp. 432–439, 2020.

[98] T. G. Reames, "A community-based approach to low-income residential energy efficiency participation barriers," *Local Environment*, vol. 21, no. 12, pp. 1449–1466, 2016.

[99] D. Carroll, J. Berger, C. Miller, and C. Driscoll, "National Weatherization Assistance Program Impact Evaluation - Baseline Occupant Survey: Assessment of Client Status and Needs," ORNL/TM--2015/22, 1223650, Oct. 2015. doi: 10.2172/1223650.

[100] S. Bird and D. Hernández, "Policy options for the split incentive: Increasing energy efficiency for low-income renters," *Energy Policy*, vol. 48, pp. 506–514, Sep. 2012, doi: 10.1016/j.enpol.2012.05.053.

[101] "4586 | FEMA.gov." https://www.fema.gov/disaster/4586 (accessed Feb. 08, 2022).

[102] U. S. D. Network, "Urban Sustainability Directors Network." https://www.usdn.org/resilience-hubs.html (accessed Feb. 08, 2022).

[103] "Failure to Act: Economic Impacts of Status Quo Investment Across Infrastructure Systems (2021) | EBP | US." https://www.ebp-us.com/en/projects/failure-act-economic-impacts-status-quo-investment-across-infrastructure-systems-2021 (accessed Feb. 08, 2022).

[104] "Texas Transit Providers – Providing Vital Service Through Winter Storm Uri." https://www.txdot.gov/inside-txdot/division/public-transportation/transit-providers-response.html (accessed Feb. 08, 2022).

[105] "Racism has shaped public transit, and it's riddled with inequities," *The Kinder Institute for Urban Research*. https://kinder.rice.edu/urbanedge/2020/08/24/transportation-racism-has-shaped-public-transit-america-inequalities (accessed Feb. 08, 2022).

[106] H. Bean, A. M. Cruz, M. Shimizu, K. K. Stephens, M. McGlone, and S. Strover, "Mobile Alert and Warning in the United States and Japan: Confronting the Challenges of International Harmonization," *International Journal of Disaster Risk Science*, vol. 12, no. 6, pp. 928–934, 2021