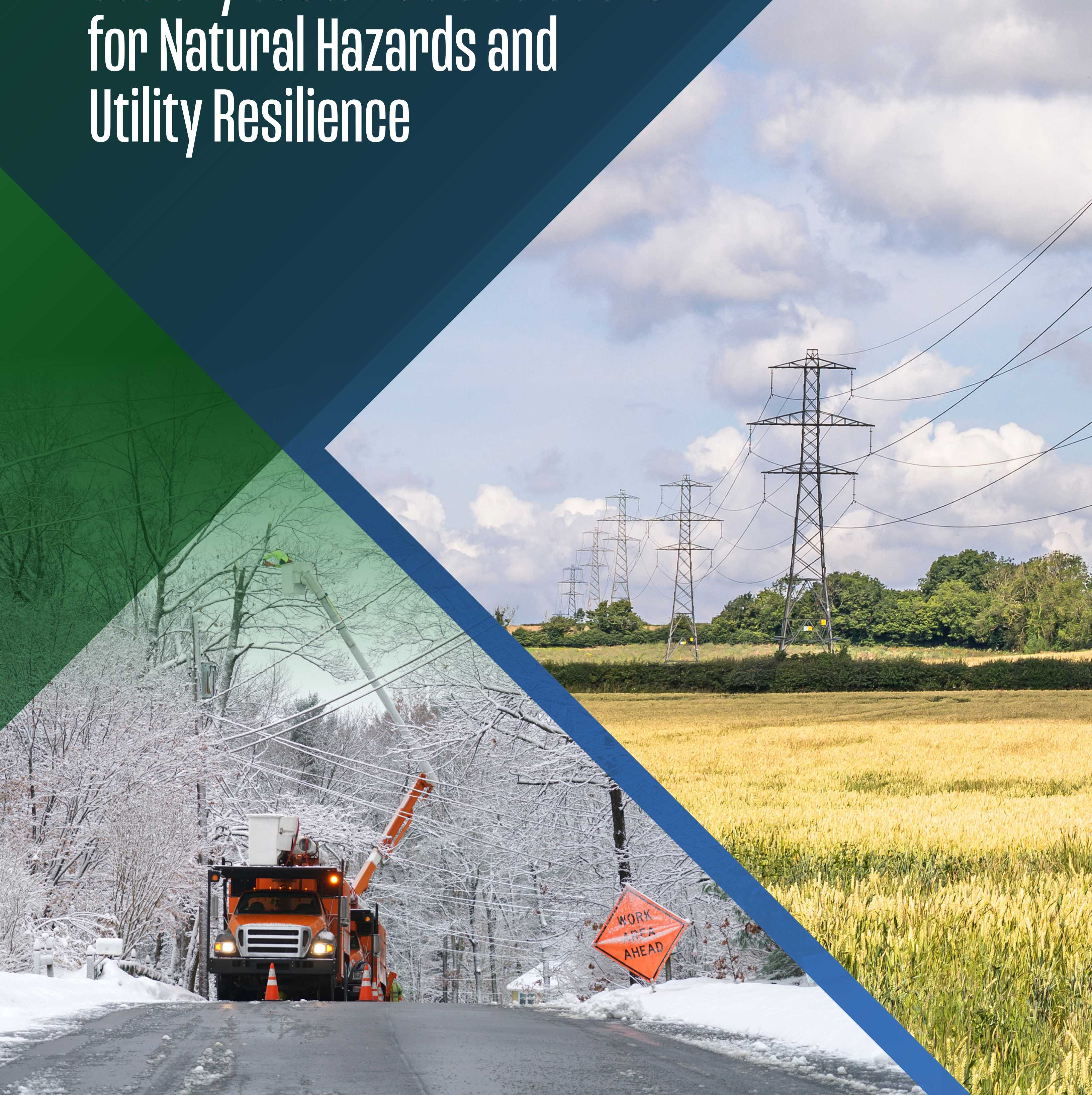
CHAPTER 9

Socially Sustainable Solutions for Natural Hazards and Utility Resilience



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*This material is based on work supported by the **National Science Foundation** under Grant No. **OIA-1946093**, through the **Established Program to Stimulate Competitive Research (EPSCoR)** and the **Oklahoma State Regents for Higher Education**.*

This work represents a collaborative effort among researchers from the University of Oklahoma, Oklahoma State University, University of Tulsa, University of Central Oklahoma, Southwestern Oklahoma State University, Langston University, and the Noble Research Institute as well as affiliated organizations within the Socially Sustainable Solutions for Water, Land Use, and Infrastructure Resilience in Oklahoma (S3OK) project.

Acknowledgements

The authors extend their sincere gratitude to the members of the Opinion Leader Advisory Network for generously sharing their time, expertise, and insight—and for taking a chance on collaborating with us for the good of Oklahoma.

We are deeply appreciative of the participants in the Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet) for contributing their time and opinions across eight surveys over the past five years. Their continued engagement provides an invaluable pulse check on the development of socially sustainable solutions to the state's most complex and "wicked" problems.

We also thank the members of the Extended Peer Science Advisory Network (EPSAN) for their expertise, insight, and commitment to advancing an empirically sound and socially relevant science.

The authors extend heartfelt gratitude to all members of the Natural Hazards and Utility Resilience working group for the time, effort, and expertise they contributed to the working group's efforts. A special note of thanks goes to Nick Shumaker at the Oklahoma Electric Cooperative, members of the National Rural Electric Cooperative Association, and Chris Myers at the Oklahoma Association of Electric Cooperatives for their willingness to collaborate, share data, and partner with us to address wicked problems related to Natural Hazards and Utility Resilience. Their partnership has been instrumental in bridging the gap between research and practice across Oklahoma's utility and resilience communities.

Last, but not least, we express our appreciation to the dedicated research staff, students, and administrative professionals whose countless hours of collaboration, coordination, and creative effort ensure that this project remains strong, cohesive, and impactful.

CHAPTER 9

Socially Sustainable Solutions for Natural Hazards and Utility Resilience

The Natural Hazards and Utility Resilience working group was established as a cornerstone of the S3OK initiative in response to the increasing complexity of extreme weather and climate-related challenges impacting Oklahoma's electrical grid. This group emerged from an iterative, three-year stakeholder engagement process (see chapter four), guided by feedback through OLAN and insights derived from EPSAN. Additionally, insights from targeted deep-dive conversations into critical issues such as Extreme Weather and Oklahoma Infrastructure Interactions with a Wildfire Focus and Implementing Land Management Strategies for Water Use Efficiency in Agricultural Systems provided initial inspiration for early discussions before specific goals were solidified. This working group was designed to bridge the gap between S3OK researchers and utility stakeholders, fostering collaborations to enhance the physical resilience of the electrical grid and the broader infrastructure systems it supports.

The impetus for this collaboration is clear: Oklahoma's power grid resilience faces risks posed by extreme weather and climate conditions, including, but not limited to, drought, cold air outbreaks, and wildfire. These challenges underscore the need to develop solutions that integrate scientific research, advanced modeling, and stakeholder expertise. Simultaneously, S3OK researchers were developing novel datasets, predictive techniques, and key scientific innovations that showed promise for utility stakeholders, but needed real-world data to provide best results. Through collaborative efforts and a trusted partnership, S3OK researchers and utility partners joined together to share data,

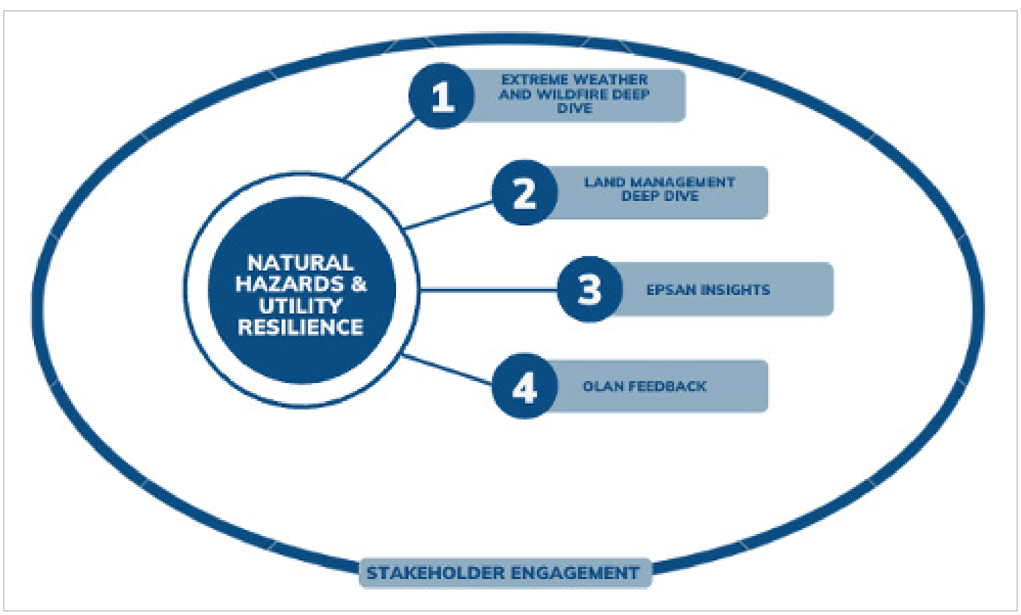

Figure 9.1: Natural Hazards and Utility Resilience Working Group Topic Identification Process Map

improve models, providing utility stakeholders with essential tools to mitigate risks to power grid resilience posed by extreme weather. Building on the significant progress made during the first four years of the S3OK project, the working group defined four primary goals for its fifth year:

1. **Foster Wider Collaboration and Opportunities to Share Tools and Knowledge between Research and Practice.**
2. **Seek Avenues to Better Incorporate Forecasting at a Specified Timescale as a Planning and Resilience Input/Tool.**
3. **Consider Impacts of Emerging Technologies and Renewable Energy Sources for Resilience Practices.**
4. **Increase the Availability and Awareness of Hazard Maps.**

This chapter outlines the collaborative research efforts undertaken by the Natural Hazards and Utility Resilience working group in pursuit of these goals and details the culmination of past achievements while charting a pathway for future efforts. Specifically, this chapter will address:

- The nature of the problems at the intersection of natural hazards and utility resilience in Oklahoma and the working group's response to these problems.
- How collaborative proposed solutions were developed through partnerships between electric utility stakeholders and S3OK researchers.
- Key scientific advances in relevant emerging technologies form the basis of proposed solutions
- How the working group's goals provide pathways forward to address these problems.
- The significance of working group products resulting from working group collaborations.

By synthesizing these elements, this chapter provides a comprehensive account of the progress made, highlights the utility of interdisciplinary collaboration, and offers actionable insights for future research and resilience-building initiatives.

Nature of the Problems: How Subseasonal to Seasonal Weather Drives Wicked Problems for Natural Hazards and Utility Resilience

The Natural Hazards and Utility Resilience working group focused on addressing the increasing vulnerabilities of Oklahoma's utility infrastructure in the face of new and intensifying natural hazards. The state's electrical grid and associated infrastructure are crucial to ensuring the security and well-being of its communities, both socially, economically, and environmentally. However, these infrastructures are deeply embedded within complex social and organizational systems. Moreover, they are under significant pressure from an evolving risk landscape characterized by quickly changing weather dynamics, increasing consumer demand, and aging infrastructure.

Events predicted at the subseasonal to seasonal (S2S) scale such as ice storms, wildfires, and extreme temperatures, challenge resilience by combining rapid onset, probabilistic forecasting uncertainties, and the compounding impacts of disrupted infrastructure. These events not only damage critical systems but also force difficult trade-offs between competing priorities for governments, utilities, and the public. Additionally, the compounding effects of climate change intensify these hazards, further complicating urban planning, disaster resilience, and environmental sustainability.

In response, the Natural Hazards and Utility Resilience working group leveraged S3OK's scientific, solutions-oriented approach to identify vulnerabilities and enhance resilience. By examining the interdependencies of infrastructure systems and addressing the societal challenges posed by extreme weather, the group worked collaboratively to develop innovative strategies that strengthen infrastructure resilience and reliability in the face of rapidly changing hazards around key problem areas.

What Is S2S Forecasting and Why Does It Matter for Infrastructure Planning?

Subseasonal to Seasonal (S2S) forecasting refers to predicting weather patterns 10 to 19 days in advance—longer than standard weather forecasts, but shorter than seasonal climate outlooks.

- **Why It Matters:** Critical hazards like ice storms, cold air outbreaks, and wildfires often develop in the S2S range and lie in a "predictability desert" where forecasting is especially difficult.
- **For Oklahoma Utilities:** Better S2S forecasts mean more lead time to prepare for peak energy loads, vegetation management, and infrastructure protection.
- **In Practice:** S3OK researchers have shown that certain critical hazards—such as cold air outbreaks—can be predicted 14—21 days in advance using jet stream and stratospheric data[1].

Investing in S2S forecasting capabilities can dramatically improve operational planning and emergency readiness.

Key Problem Areas

Throughout the S3OK project, the Natural Hazards and Utility Resilience working group identified four sets of interconnected, wicked problem areas. This section details the nature of the key problem areas identified by the working group and how the working group collaboratively responded to these problems with a scientific, solutions-oriented focus.

1) Infrastructure systems are deeply embedded within social and organizational systems.
Reliable infrastructure systems are essential for national security and the social, economic, and environmental well-being of communities. However, these infrastructure systems do not operate in isolation. Instead, they are deeply intertwined with social systems, including cultural values and organizational structures, which shape their functionality and resilience. Increasing hazards threaten physical infrastructure and expose vulnerabilities in the social and organizational systems that manage and rely on them. This presents a unique set of interconnected challenges to fostering infrastructure system resilience.

2) Ice storms pose a significant threat, but provide an opportunity to identify vulnerabilities in the utility grid.

Ice storms present a significant threat to the resilience of Oklahoma's utility grid, as evidenced by the October 2020 ice storm. Occurring from October 26th to October 28th, this unprecedented event was the earliest Oklahoma ice storm recorded in meteorological history. The combination of early-season foliage and wintry precipitation resulted in numerous ice-laden tree limbs falling onto power lines across the region. The fallen tree limbs led to traffic interruptions and delays in repairing the damage to the electric power infrastructure, further complicating the challenges faced throughout the event. Additionally, power lines and power poles were damaged by ice and accompanying wind. This event highlighted vulnerabilities in the utility grid—the storm damaged over 4,200 power poles, along with hundreds of thousands of power lines, transformers, and other specialized equipment. At its peak, over 76,300 outages were recorded, affecting more than 350,000 customers. Ice storms, particularly those occurring early in the season, highlight the compounded risks of vegetation damage and infrastructure fragility, emphasizing the need to leverage innovative resilience strategies developed through collaboration between research and practice. By integrating these approaches, Oklahoma's utility grid can become better equipped to withstand future ice storms, ensuring a more reliable utility system for Oklahomans[2,3].

3) **Extreme temperatures tax utility systems.** Extreme temperatures pose significant challenges to utility systems by disrupting production capacity, straining delivery infrastructure, and altering demand patterns in unpredictable ways. In Oklahoma, multiple extreme temperature events throughout the S3OK project highlighted these vulnerabilities. Among the numerous extreme temperature events that occurred during the project, the February 2021 North American cold air outbreak stands out for its wide-ranging impacts. This event severely disrupted the natural gas network, power grid, transit networks, and water systems, exposing critical interdependencies and cascading failures[4,5,6,7].

4) Wildfires pose an increasing threat in Oklahoma, necessitating enhanced predictive modeling and a better understanding of public risk perception.
Wildfires are an escalating threat in Oklahoma, driven by the region's vulnerability to precipitation extremes and rapid transitions between wet and dry conditions. These fluctuations, characteristic of the Southern Great Plains, significantly impact critical infrastructure systems such as electric power and potable water while straining agricultural communities and urban areas alike[8–15]. Periods of heavy rainfall foster abundant vegetation growth, which, when followed by drought, dry into highly flammable fuel for wildfires. This dynamic is further intensified by the rapid expansion of Eastern Red Cedar, a highly flammable invasive species that thrives in wet conditions and greatly increases wildfire risk when dried. Moreover, when wildfires do occur, they can dramatically alter landscape carbon balances, water quality, and infrastructure resilience.

Developing Socially Sustainable Solutions through Key Scientific Advances

Addressing the complex challenges at the intersection of natural hazards and utility resilience requires both scientific innovation and sustained collaboration. In response to key problem areas identified throughout the project, the Natural Hazards and Utility Resilience working group advanced a suite of science-informed solutions designed to address the resilience of interdependent infrastructure systems. These efforts acknowledged critical trade-offs while advancing knowledge in areas identified above. This section highlights the scientific advances that are helping to shape a more adaptive and resilient future for the utility industry within key problem areas.

Solution to Key Problem Area: Infrastructure systems are deeply embedded within social and organizational systems.

To effectively address challenges regarding the embedded nature of infrastructure and social systems, S3OK researchers adopted **An Analytic Approach to Manage Evolving Environmental Risk** to understand evolving environmental threats and made strides in **Addressing Public Concern and Willingness to Pay for Grid Resilience in Oklahoma**.

An Analytic Approach to Managing Evolving Environmental Risk

As the risk of wildfires associated with electricity transmission and distribution infrastructure increases, utilities face increasingly complex decisions about where and when to invest in measures to prevent fire ignitions. These decisions have significant economic consequences, as utility-operated equipment, while responsible for only 1–5% of fire ignitions in regions like Southern California, is responsible for a much higher proportion of the total area burned—up to 30%—and over 80% of the damages caused by wildfires[15]. These stakes are high because wildfires can damage not only the infrastructure but also the communities and ecosystems that depend on it. To manage this risk, many states have implemented regulations that hold utilities financially accountable for the damage caused by fires ignited by power lines. These regulations vary across jurisdictions, with some states requiring utilities to be fully liable for fire damages regardless of their efforts to prevent ignitions. In contrast, others offer liability limits for utilities that take specific preventative actions.

Malloy (2024)[17] investigated how utilities' strategies to prevent fire ignitions change under different regulatory environments, using data from 2018 to 2020 in California, to provide insights for parallel contexts in Oklahoma. He found that utilities are more likely to invest in fire prevention measures when they face higher financial liability, but this effort peaks when the potential cost of a fire ignition threatens the utility's overall asset value. This pattern suggests that regulations that set clear standards for fire prevention and limit utilities' financial responsibility for damages, if those standards are met, effectively incentivize action. By focusing on the economic incentives and regulatory frameworks that shape utility behavior, S3OK researchers highlight how infrastructure decisions are embedded in complex social and organizational systems. These decisions are not just driven by technological or financial factors but also by regulatory policies, organizational structures, and societal expectations. This perspective is critical for understanding how utilities make risk management decisions and how those decisions can be influenced to enhance infrastructure resilience and wildfire prevention.

Addressing Public Concern and Willingness to Pay for Grid Resilience in Oklahoma

Public concern about the reliability of Oklahoma's electrical grid and willingness-to-pay (WTP) for improvements are critical factors in shaping energy policy and investment in grid resilience. Using data from Wave 2 of the EPSCoR S3OK M-SISNet survey (n=2,108), S3OK researchers examined what factors were associated with concern for the current state of the electrical grid in Oklahoma and willingness-to-pay (WTP) for electrical grid improvements in the state using a conceptual model based on past research and theories of risk. Results from statistical modeling indicate that people who perceive higher weather-related and power outage risks hold greater concern for the state of electricity infrastructure in Oklahoma. Additionally, those with lower trust in those responsible for maintaining the grid express heightened concerns about electricity infrastructure, indicating that confidence in grid operators plays a significant role in shaping public perception[18].

Understanding what influences WTP for grid improvements is key to developing policies that garner public support. Findings suggest that people are more likely to support and pay for grid enhancements when program costs are kept low. Additionally, politically liberal and non-white residents, as well as those who demonstrated greater trust in grid maintenance efforts and who recognize the risks of outages, show a greater willingness to pay for grid improvements. These insights underscore the significance of public trust and transparent communication in energy policy decisions.

These findings highlight the need to address public concerns and build support for resilience investments effectively. Educational campaigns that emphasize the real-world benefits of grid improvements, such as reduced outage risks during severe weather events, long-term cost savings, and enhanced energy security, can help increase public buy-in. Furthermore, incorporating public input into infrastructure planning and ensuring reliable access to grid improvements can strengthen trust and encourage participation in resilience programs. **By aligning policy decisions with public concerns and financial considerations, Oklahoma can create a more secure, sustainable, and widely supported electrical grid for the future.**

Solution to Key Problem Area: Ice storms pose a significant threat, but provide an opportunity to identify vulnerabilities in the utility grid.

Recognizing that the October 2020 ice storm event provided an invaluable opportunity for S3OK stakeholders to collaborate, S3OK researchers worked with the Oklahoma Electric Cooperative (OEC) to develop a novel opportunity to study the resilience of Oklahoma's electric distribution network.

Three research efforts stemming from this collaboration have deepened understanding of the grid's vulnerabilities and informed strategies for hardening and resilience. This includes S3OK researcher efforts to develop a **Probabilistic Framework for Assessing Ice Storm Resilience**, complete a **Resilience Analysis of Electric Distribution Networks**, and explore **Strategies for Photovoltaic Expansion in Oklahoma**.

Probabilistic Framework for Assessing Ice Storm Resilience

First, Hou et al. (2023)[2] and Hou and Muraleetharan (2023)[19] developed a probabilistic framework to evaluate the resilience of power distribution systems during ice storms and to explore hardening strategies. Their work utilized detailed fragility models for power distribution systems that accounted for factors such as falling trees and limbs, ice accumulation, and wind effects, including speed and direction (Figure 9.2, 9.3). S3OK researchers used an empirical fragility function to model tree damage using satellite images from the October 2020 storm and applied it to a portion of the OEC network. By doing so, S3OK researchers were able to identify vegetation management as a cost-effective approach to improving system resilience. This finding underscores the importance of timing vegetation management practices, especially before early-season storms.

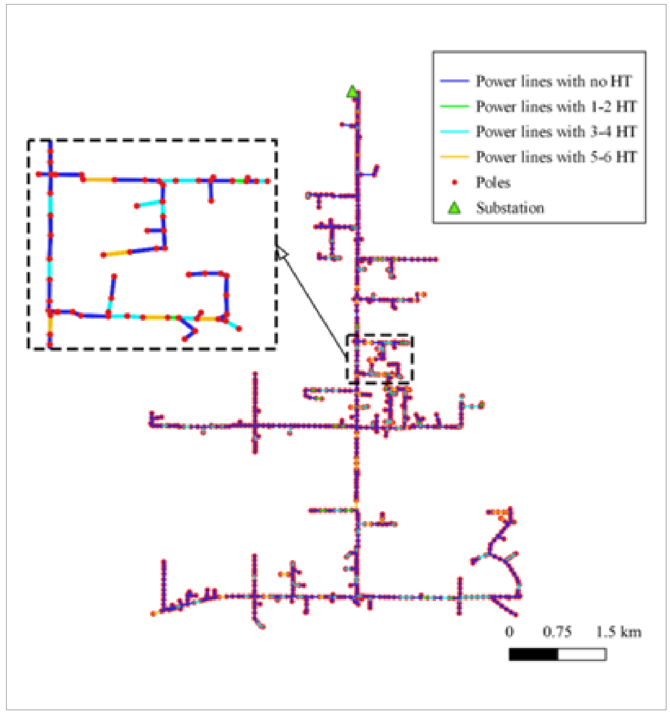

Figure 9.2. A power distribution network in Oklahoma (Note: HT refers to hazard trees) (Hou et al. 2023)[2]

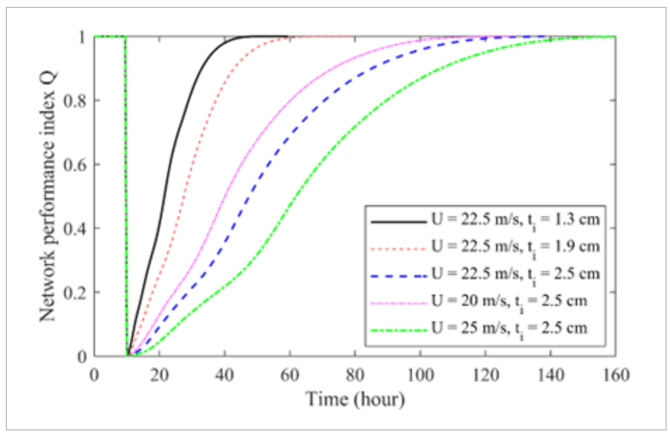

Figure 9.3. Network restoration curves for ice storms with different wind speeds (U) and ice thicknesses (ti) (wind direction perpendicular to the power lines) (Hou et al. 2023)[2]

Resilience Analysis of Electric Distribution Networks

Further, Panchalogaranjan et al. (2023)[3] examined the reliability and resilience of electric distribution networks during High Impact Low Probability (HILP) events, such as the October 2020 ice storm. They utilized OEC's network and outage data to evaluate traditional reliability indices such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) and demonstrated that these indices frequently fail to accurately capture the dynamic disruption and restoration behavior of networks during such events. Their research also showed that the traditional trapezoidal resilience curve does not fully characterize the resilience of a network undergoing dynamic restoration. Furthermore, they highlighted the potential of adaptive electrical infrastructure, such as automated switching systems, to significantly enhance network resilience by minimizing disruptions and accelerating recovery times.

Balancing Renewable Energy Integration and Grid Stability: Strategies for Photovoltaic Expansion in Oklahoma

Oklahoma's unique geography has immense potential to enhance grid resilience by leveraging its abundant solar resources, yet photovoltaic (PV) integration remains limited, with most renewable energy in the state sourced from wind power. Expanding PV generation, especially at the distribution level, offers a critical opportunity to expand energy sources, reduce dependency on centralized power, and strengthen the grid. Research has shown that PV systems, as distributed energy resources (DERs), improve grid resiliency by generating power closer to where it is consumed. However, integrating PV systems into the existing grid poses challenges, such as managing voltage stability, thermal capacity, and fault protection coordination[20].

To address these challenges, S3OK researchers conducted a locational-dependent PV hosting capacity (PVHC) analysis using a detailed test feeder provided by the OEC. This real-world 24.9 kV feeder, with 570 three-phase nodes and a peak load of 5.2 MW, served as a real-world model to evaluate how much PV generation a distribution feeder can accommodate without violating grid operational constraints. Using the Particle Swarm Optimization (PSO) method, this study efficiently identified the optimal PV sizes and locations for integration of PV systems into the Oklahoma distribution network without compromising grid reliability[20]. This approach significantly reduced simulation times while maintaining accuracy, providing a systematic method for determining safe and efficient PV penetration levels across Oklahoma's feeders. Such insights are crucial for expanding PV adoption while ensuring the grid operates reliably.

In addition, a separate study examined how integrating centralized and residential PV systems, along with electric vehicle (EV) charging stations, impacts fault currents and protection coordination in Oklahoma's grid[21], using steady-state fault analysis. In particular, this study examined symmetrical and unsymmetrical fault scenarios to explore their impact on protection device coordination. The results revealed that while residential PV systems and EV loads have minimal effects on fault levels, large-scale centralized PV systems can significantly alter fault dynamics, complicating fault clearance and protection reliability. This finding underscores the necessity for adaptive protection schemes to address these challenges and maintain grid stability as distributed energy resource (DER) penetration increases.

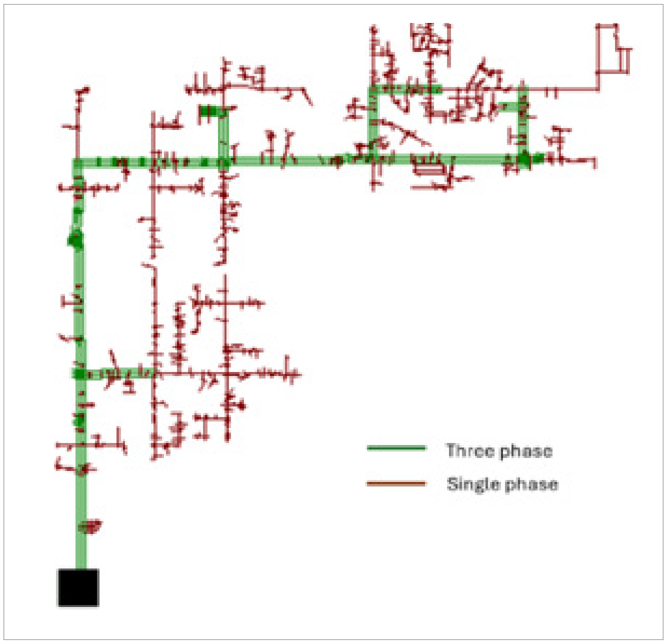

Figure 9.4: OEC distribution feeder used for PV integration studies

Together, these studies provide a clear roadmap and actionable insights for advancing Oklahoma's renewable energy integration while enhancing grid resilience. The PVHC analysis enables utilities to identify the optimal level of PV penetration for each feeder, avoiding risks such as voltage violations and thermal capacity overloads. Simultaneously, the fault analysis highlights the importance of updating protection systems to accommodate the operational complexities associated with high DER penetration. **By applying advanced modeling techniques and real-world data, these strategies offer a practical path forward for Oklahoma to capitalize on its solar potential, meet renewable energy goals, and build a more resilient and sustainable energy future.**

PV Hosting Capacity (PVHC): A Planning Tool for Distributed Solar Energy

PV Hosting Capacity is the maximum amount of solar energy (photovoltaic, or PV) a power distribution feeder can accept without causing reliability issues like voltage instability or thermal overload.

Why It's Important: As Oklahoma expands its solar footprint, utilities need to know where and how much PV can be safely integrated.

How It Works: PVHC studies use optimization algorithms and system simulations to test different scenarios for solar placement and load conditions.

In Action: S3OK researchers partnered with OEC to test PVHC using real Oklahoma feeder data and optimization tools like Particle Swarm Optimization.

Practitioners can use PVHC analysis to guide solar deployment and grid upgrades in ways that reduce risk and improve resilience.

Key Problem Area: Extreme Temperatures Tax Utility Systems

In response to challenges surrounding the impact extreme temperatures have on Oklahoma's utility systems, the Natural Hazards and Utility Resilience working group researchers dynamically adapted their research scope to address these emergent and ongoing hazards. In particular, they aimed to identify **Strategies for Enhancing Resilience Across Utility Systems** in the face of climate-exacerbated risks by focusing on the 2021 North American cold air outbreak's impact on Oklahoma and neighboring Texas. S3OK researchers also made efforts toward **Improving Prediction Skill for Cold Air Outbreaks Across the Central US** and used **Subseasonal Circulation Patterns to Predict Peak Power Demand.**

Strategies for Enhancing Resilience Across Utility Systems: Insights from the Texas Power Grid

The February 2021 North American cold air outbreak, which most notably devastated the Texas power grid, provided a critical opportunity to analyze and compare the performance of neighboring power systems, including the Southwest Power Pool (SPP) that monitors and directs the electric utility grid Oklahoma. Unlike the 2020 winter ice-storm just 4 months prior, the extreme weather in February 2021 did not cause any significant infrastructure damage in Oklahoma. Rather, because of freezing temperatures, a lack of available supply combined with surging electricity demand led to excessive forced outages that narrowly avoided a complete grid collapse. By examining publicly available historical system performance data, including load loss, generation mix, and resource adequacy, the research team identified key factors contributing to system failures[22]. This study highlighted often-overlooked dynamics that were critical to power network performance in Oklahoma, including SPP's foresight in coordinating generation dispatch across member states, which mostly mitigated impacts in Oklahoma. In contrast, the Texas grid's isolated architecture, with minimal capacity for power imports, exacerbated its crisis. Furthermore, the analysis revealed that interdependencies between electricity and natural gas infrastructure were the primary drivers of outages, stemming from a 15-year-long evolution in increased reliance on natural gas. This study also revealed that, contrary to widespread narratives, renewable energy played a minimal role in the outage. Electric Reliability Council of Texas' (ERCOT's) resource adequacy planning did not rely on wind or solar energy during winter peaks. While some 50% of wind turbines experienced icing-related failures, their actual output exceeded forecasted levels. These findings emphasize the importance of grid interconnectivity, maintaining a heterogeneous energy mix, and proactive contingency planning to enhance resilience against climate-driven hazards.

Improving Prediction Skill for Cold Air Outbreaks Across the Central US

Cold air outbreaks (CAOs) are episodes of extremely low temperatures that affect relatively large regions and are associated with the invasion of cold air out of the high latitudes from southward dips in the jet stream[23,24]. These events have substantial socioeconomic impacts; in the United States alone, cold air intrusions and associated wintry stormy weather cost an average of $4.2 billion per event between 1980 and 2024[25]. The February 2021 North American CAO, which hit Oklahoma and the Southern Plains especially hard, was particularly costly[4,6].

Prompted by these events, members of the working group focused on making key scientific advances that could be used to improve long-lead predictions of extreme climate anomalies (CAOs) in the Central United States. Millin et al. (2022)[6] developed the first-of-its-kind CAO database for the Central US, dating back to 1950. They found that despite winters rapidly warming over time, the February 2021 CAO was the second-most severe to affect the region; the most severe CAO in the Central United States occurred on December 16th, 1983. Millin et al. (2022)[6] also found that CAOs in the region occur under two specific weather regimes: (1) the Arctic High regime, featuring higher-than-normal pressure across the Arctic regions, displacing frigid air masses southward; and (2) the Alaskan Ridge Regime, featuring a blocking high pressure system over the Gulf of Alaska that forces air masses from Siberia to cross the Arctic Ocean and invade central and eastern North America. Recognizing these regimes, the team also tied their formation to subseasonal (up to 14 days ahead of the start of the CAO) predictors including overall weakness in the stratospheric polar vortex (Arctic High CAO events) and a combination of changes in tropical convection and a phenomenon known as stratospheric wave reflection (Alaskan Ridge CAO events).

Other studies quantified how well these predictors performed in forecasts. For the February 2021 CAO event, Millin and Furtado (2022)[6] demonstrated that several runs of operational subseasonal forecast models successfully captured the threat of the CAO up to 3 weeks in advance. The key difference between the best-performing and worst-performing models lay in how they handled two specific jet stream configurations, two days ahead of the event's onset: one in the East Siberian Sea and the other in the Northwest Atlantic. This result highlights a key benchmarking tool for other forecasters of extreme CAOs and a process-oriented diagnostic that modelers can use for future model enhancements. **Combined, these advances provide a scientific foundation for more reliable, longer-range forecasts, and equip utility planners and forecasters with powerful tools to better anticipate and prepare for extreme winter weather.**

Using subseasonal circulation patterns to predict peak power demand

Subseasonal large-scale circulation patterns provide a powerful and innovative tool for predicting peak power demand in the Southwest Power Pool (SPP) region. S3OK researchers[26] demonstrated that recurring large-scale weather patterns, such as the large-scale recurrent circulation patterns mentioned above, have a significant influence on temperature variations. These temperature variations, in turn, influence subseasonal temperature forecasts and peak power demand in the cold season months in the region. For example, when patterns during the fall or winter resemble the Alaskan or West Coast Ridge, the SPP is 50% to 100% more likely to exceed peak power demand. On the other hand, milder weather regimes, such as the Pacific Trough and Arctic Low, reduce the chances of peak demand spikes[26].

These findings are crucial because they provide potential for utility planners to directly connect weather patterns to the conditions that drive heating needs and energy use. Furthermore, such weather regimes are predictable with reasonable accuracy up to 14 to 20 days in advance[27]. This means energy providers could look ahead nearly three weeks to identify periods of potential stress on the power grid. By integrating these forecasts into their planning processes, utility operators can proactively manage resources, ensure grid stability, and reduce the risk of outages during high-demand periods. **Such forward-looking strategies can also lead to cost savings and more efficient energy distribution, benefiting both providers and consumers.**

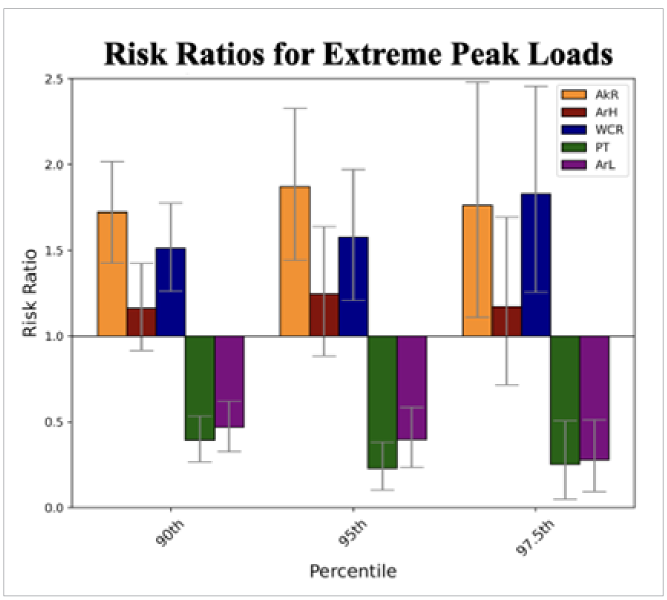

Figure 9.5 The risk of exceeding extreme peak loads in the Southwest Power Pool nearly doubles during the Alaskan Ridge and West Coast Ridge regimes. The relative risk of extreme peak load as a function of North American winter weather regimes (bars) for the 90th, 95th, and 97.5th percentile extreme thresholds as compared to all winter days. Whiskers represent the 95th percentile confidence interval for each risk ratio. Adapted from Millin et al. (2024)[26].

Key Problem Area: Wildfires pose an increasing threat in Oklahoma, necessitating enhanced predictive modeling and a better understanding of public risk perception.

In response to emergent hazards related to wildfires in Oklahoma, working group members collaborated to **Enhance Wildfire Forecasting** and **Better Understand Shifts in Public Risk Perception Following Wildfire Events,** as both are central to ensuring practitioners and the public are informed and better able to perceive and respond to wildfire threats. Recognizing these challenges, the Natural Hazards and Utility Resilience working group developed science-driven strategies to mitigate wildfire risks and their impacts on critical systems. The group leveraged insights from studies on precipitation anomalies and vegetation patterns that identify increased chances for wildfire months in advance. This predictive capability enables utility managers to optimize maintenance schedules, such as strategic vegetation management near power lines, and implement grid-hardening measures to reduce vulnerability during high-risk seasons. By integrating cutting-edge research with practical solutions, the working group has produced scientific products that have the potential to advance Oklahoma's ability to prepare for and respond to wildfire threats, protecting both community well-being and infrastructure resilience.

Enhance Wildfire Forecasting

S3OK researchers made significant strides in predicting wildfire risk in Oklahoma through advances in predictive modeling. Puxley et al. (2024)[15] have shown that "precipitation whiplash" events—sudden shifts from wet to dry conditions—play a pivotal role in driving wildfire activity in the Oklahoma and Texas Panhandles. By examining the 2017—2018 wildfire season, the researchers found that above-average spring vegetation growth, followed by a wet summer and a dry winter and spring, left vegetation dry and highly flammable. Hence, precipitation whiplash events such as wet summers followed rapidly by dry falls and winters had a strong correlation with increased wildfires and acres burned the following spring (Figure 9.6).

The 2017 season presents a striking example, where precipitation reached 137% of normal during the growing season. This increased precipitation fostered dense vegetation growth. However, this was followed by an abrupt transition to drought, with winter rainfall dropping to just 21% of normal and drought conditions intensifying to the highest severity level (D4—exceptional drought). This sequence of events culminated in an above-average wildfire season in spring 2018, underscoring the impact of rapid wet-to-dry transitions on wildfire proliferation. This research highlights how enhanced modeling and monitoring of seasonal precipitation patterns and rapid transitions can inform wildfire forecasts months in advance. By integrating these insights into predictive models, decision-makers can take proactive steps, such as improving vegetation management and fortifying infrastructure in high-risk areas. These advancements offer practical tools to strengthen resilience against wildfires, protecting Oklahoma's landscapes, communities, and critical systems.

Understanding Shifts in Public Risk Perception Following Wildfire Events

Using the March 2023 wildfire outbreak in Oklahoma as a case study, S3OK researchers led by Campos et al. (2024)[28] advanced understanding of public risk perception and awareness of wildfires. The March 31, 2023, wildfire outbreak in Oklahoma (see Figure 9.8) exposed

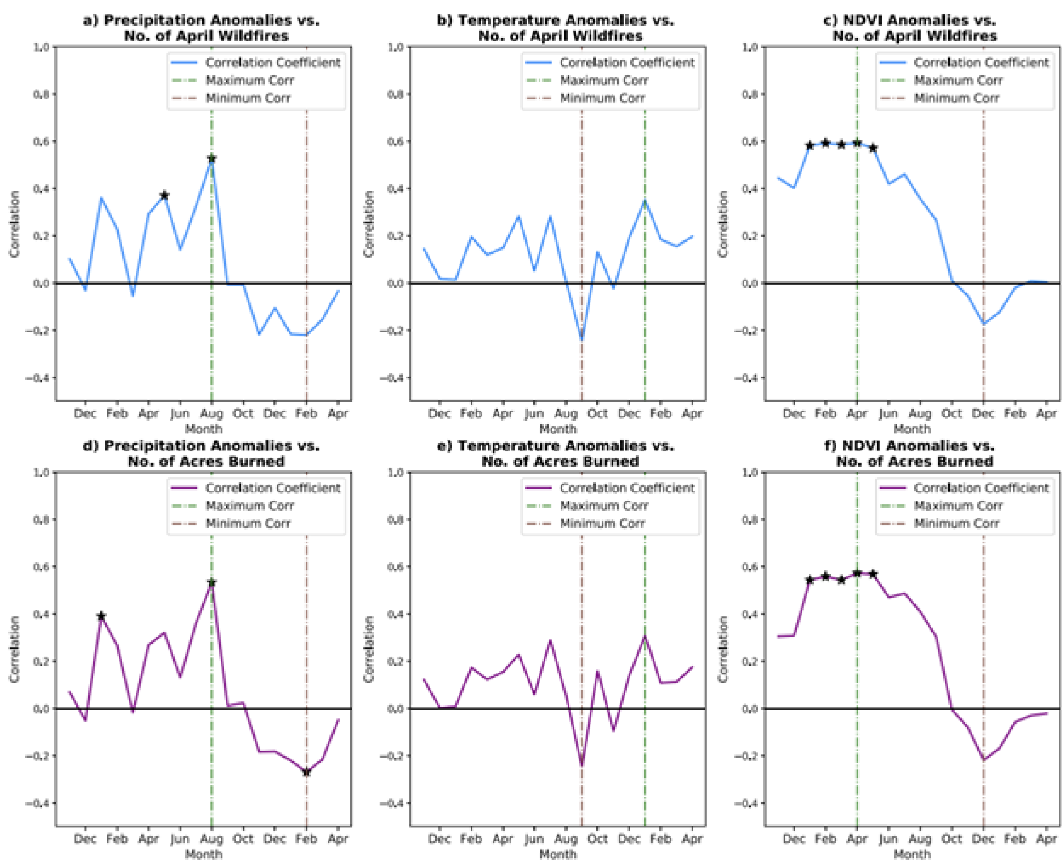

Figure 9.6: The lag correlation coefficient between the number of April wildfires and (a) precipitation anomalies, (b) temperature anomalies, (c) NDVI anomalies, and the number of acres burned by April wildfires and (d) precipitation anomalies, (e) temperature anomalies, (f) NDVI anomalies. All values are domain-averaged across the study domain (see Puxley et al. 2024 for more details). The green and brown dashed lines show the maximum and minimum correlation coefficients, respectively, and the black stars show correlations that are significant at the 95% level, calculated using Monte Carlo.

the devastating impact of extreme weather and underscored the importance of proactive wildfire risk management. The outbreak was driven by extreme meteorological conditions, including unusually high temperatures, strong winds, and a sharp drop in humidity. For example, at the Guthrie Mesonet station (see Figure 9.9), pre-wildfire temperatures soared to an average of 70.4°F—far above the typical March average of 56.5°F—while humidity levels plummeted from 80% to just 9% in a matter of hours. Winds reached speeds of 39 m/s, with gusts up to 56 m/s, accelerating the spread of the fires. Compounding these conditions, prolonged drought left soil moisture critically low, with the fractional water index at only 0.50 cm at a 5 cm depth. These factors combined to fuel wildfires that spread rapidly, impacting both urban and rural communities and exposing vulnerabilities in Oklahoma's changing biomes, particularly in areas near urban developments.

In the aftermath of the March 2023 wildfire outbreak, public awareness of wildfire risk surged. Responses to the M-SISNet survey collected before and after the fires revealed significant increases in perceived current and future wildfire risk perception, showing the psychological impact of experiencing this natural hazard. Relatedly, trust in the private sector and in policymakers before and after the firestorm eroded (see Figure 9.7).

Meanwhile, older individuals, women, and those with lower trust in policymakers and private companies or with less conservative political views reported the highest levels of concern[29]. These insights highlight how direct experiences with wildfires, individual demographic differences, and trust can shape risk perceptions. This understanding offers a valuable opportunity to improve community preparedness and resilience by offering the insight that can shape the development of tailored education and outreach efforts. By leveraging increased awareness and addressing community-specific needs, Oklahoma can better prepare for and mitigate the impact of future wildfire events.

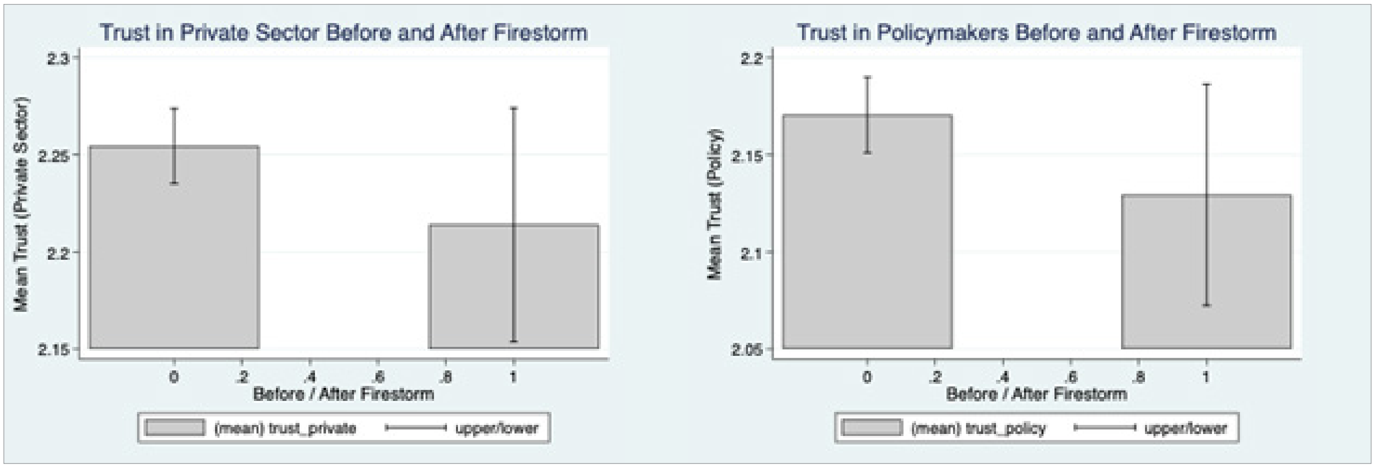

Figure 9.7 Mean trust in Private Sector and Policymakers before and after Firestorm

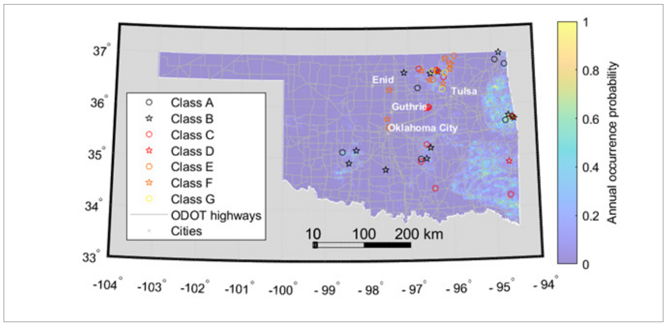

Figure 9.8. Locations of the wildfires during the outbreak (from Campos et al. 2024).

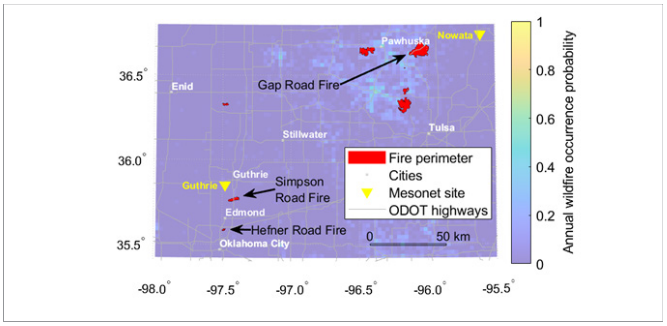

Figure 9.9. Locations of the wildfires during the outbreak (from Campos et al. 2024).

Rural Utility Cooperative Perspective on Wildfire Risk

Wildfire risk is an increasingly pressing issue for rural electric cooperatives, particularly as extreme fire events in states like California and Colorado highlight vulnerabilities in electric utility infrastructure. Though destruction at the scale seen in recent years in other regions has not been observed in Oklahoma, wildfire threats have long been a concern for rural utility cooperatives. Damage to utility infrastructure, such as burned power poles and downed lines, results in costly repairs, service disruptions, and potential liability challenges.

Challenges of Wildfire Risk for Rural Utilities

One of the biggest concerns for rural utilities is the rising cost and availability of insurance. Due to past wildfire incidents where utilities were deemed responsible for fire ignition, securing wildfire coverage has become increasingly difficult. Insurers are either excluding wildfire coverage from general liability policies or significantly raising rates due to the potential for large damage settlements. In cases where utilities are found liable, they can face lawsuits amounting to millions of dollars, costs that ultimately get passed down to consumers. Rural electric cooperatives, which aim to keep rates affordable for their members, struggle to balance financial risk mitigation with the rising cost of insurance. Additionally, legal disputes often arise over whether wildfire damage should be classified as an "act of God" or attributed to utility negligence. The burden of proof often falls on the utility, requiring them to demonstrate extensive mitigation efforts to maintain eligibility for insurance policies. This makes proactive fire prevention strategies critical not only for infrastructure protection but also for financial sustainability.

Wildfire Mitigation and Preparedness Strategies

To reduce liability exposure and improve overall grid resilience, rural cooperatives are investing in mitigation strategies, including:

Vegetation Management & Fuel Load Monitoring: Regular inspections of power line corridors and vegetation clearance efforts help reduce fire ignition risks. Advanced mapping of fuel loads and strategic maintenance of high-risk areas could enhance these efforts.

Prescribed Burns as a Risk Reduction Tool: When weather conditions permit, controlled burns can help manage excessive fuel loads, though high winds present a challenge.

Infrastructure Hardening: Metal poles offer greater fire resistance than traditional wooden poles, though they come at a higher cost, necessitating careful cost-benefit considerations.

Weather Forecasting & Fire Risk Alerts: Existing fire weather alert systems, such as the SPIA fire-spread index, help utilities monitor fire-conducive conditions (e.g., low humidity and high winds) and adjust operations accordingly. More sophisticated predictive tools, like those developed in S3OK collaborations outlined here, could further enhance preparedness.

Strategic Investment in Targeted Inspections: If utilities have access to real-time data on fuel loads and high-risk zones, they can prioritize inspections and allocate resources more efficiently. Recently, this has resulted in new grid monitoring devices for wildfires including installing artificial intelligence based cameras, additional circuit fault current indicators (CFCIs) and adaptively readjusting fault protection relay settings for wildfire prone areas.

The Role of Insurance and Risk Management

Insurance carriers are more likely to provide coverage to utilities that demonstrate strong mitigation plans, proactive vegetation management, and the use of advanced forecasting tools. Having access to better risk assessment tools, such as predictive mapping of fire-prone areas, could strengthen utilities' ability to secure coverage at reasonable rates. This, in turn, would benefit consumers by limiting cost increases while ensuring greater grid stability.

Additionally, financing mechanisms such as catastrophe bonds (CAT bonds) can help rural utilities transfer catastrophe risk to capital market investors, providing an alternative to traditional reinsurance. Such mechanisms could enhance financial resilience by providing robust risk management options and offer a competitive alternative to catastrophe insurance, depending on market conditions. Given the limited research and development budgets of many electric cooperatives, partnering with academia could help these businesses explore such solutions for resilience enhancement. As part of this working group, the S3OK team is working to advance scientific literature on CAT bonds.

While wildfires in Oklahoma may not reach the scale of those in the western U.S., their impact on rural communities, including damage to fences, homes, and livestock, remains significant. Ensuring that rural electric cooperatives have access to the necessary resources, data, and support to mitigate wildfire risks will be essential in maintaining reliable and affordable power for rural communities.

Ultimately, as one cooperative representative put it, **"This country runs on infrastructure—these lights aren't on without the grid. It's a challenge to keep it up, but whatever we can do, even if it's incremental, is worth it.**"

Goals: Pathways Forward

Recognizing the evolving challenges posed by extreme weather and climate variability, including those detailed above, the working group outlined a series of goals that build upon the foundational scientific advances completed in the initial four years of the S3OK initiative. These goals, introduced at the start of this chapter, served as a roadmap for targeted action, ensuring that research-driven insights translate into practical, scalable solutions for utility stakeholders. Below, we expand upon these goals and highlight how these goals provide pathways forward and inspire the development of select working group products described in the next section.

Recognizing the gap between researchers and industry practitioners, the working group sought to **foster wider collaboration and opportunities to share tools and knowledge between research and practice.** Throughout S3OK, this included initiatives that:

- Expanded partnerships with electric utility cooperatives, regulatory agencies, and emergency management professionals and are evident in collaborations discussed throughout this section.
- Established recurring knowledge-sharing forums through deep dive conversations and working group meetings that ensured cutting-edge research on extreme weather impacts and grid resilience reached decision-makers.
- Developed a digital repository for tools, case studies, and best practices to enhance accessibility and implementation of resilience strategies accessible to all working group members.

Given the increasing precision of climate and weather forecasting, the working group's second goal was to **seek avenues to better incorporate forecasting at a specified timescale as a planning and resilience input/tool.** In alignment with this goal, the working group:

- Strengthened collaborations across the range of scientific (e.g., social scientists, meteorologists, and engineers) and practitioner expertise to develop and refine forecast tools relevant to infrastructure planning horizons (e.g., short-term operational forecasts and long-term resilience planning).
- Piloted test predictive models with utility stakeholders to assess usability and integration into decision-making frameworks.

In line with the third goal, **members of the working group advanced analysis that considered the** expansion of renewable energy and grid modernization. In particular, this included key works described above that:

- Assessed how increased deployment of distributed energy resources (DERs), battery storage, and microgrids can enhance grid stability and reduce vulnerabilities to extreme weather events.
- Evaluated the implications of renewable energy siting and transmission and distribution network expansion on wildfire risk and grid reliability.
- Considered public concern and willingness-to-pay to gauge public support for developing resilient energy utility systems.

The fourth and final goal the working group established was to **increase the availability and awareness of hazard maps to relevant stakeholders in Oklahoma.** To advance these efforts, members of the working group collaborated across the S3OK network to:

- Expand and refine hazard mapping efforts, incorporating new data on wildfire risk, flood exposure, and extreme temperature vulnerabilities.
- Discuss the development of interactive hazard maps tailored for utility planners, emergency managers, and policymakers.
- Conduct targeted outreach and training to increase awareness of existing hazard mapping tools and ensure their integration into resilience and emergency response planning.

Working Group Products

The aforementioned goals guided the development of concrete working group products that strengthen resilience planning and facilitate long-term collaboration. The following key deliverables serve as tangible outcomes of the working group's efforts and serve as a springboard for collaborations beyond S3OK:

Hazard Mapping Resources – Expansion of hazard maps that integrate climate projections, wildfire risks, and utility infrastructure vulnerabilities.

Mutually Beneficial Collaborations – Establishment of research-practice networks that align academic expertise with real-world utility resilience challenges and meet specific needs.

By advancing these pathways, the working group will continue to serve as a vital bridge between scientific research and infrastructure resilience planning, ensuring that Oklahoma's utility stakeholders have the knowledge and tools necessary to navigate an increasingly complex risk landscape.

Hazard Mapping for Rural Utilities

In response to the need to augment rural utility capacity to identify and respond to emergent hazards, the working group conducted an evaluation of outage reliability and resiliency to **enhance power distribution system resilience** and **address the critical intersection of wildfires and electrical infrastructure.** In these instances, open collaboration and, when necessary, data sharing made the development of usable products possible.

Enhancing Power Distribution System Resilience through Data Sharing and Hazard Mapping

The collaboration between S3OK researchers and Oklahoma Electric Cooperative (OEC) described in "Solutions to Key Problem Area: Infrastructures are deeply embedded within social and organizational systems" exemplifies how data sharing can significantly enhance hazard mapping and resilience planning for rural utilities. The ability to evaluate and implement strategies to mitigate the impact of extreme weather events, such as the October 2020 ice storm, relied on access to detailed electrical infrastructure datasets provided by OEC. These datasets enabled researchers to assess system vulnerabilities, optimize restoration processes, and develop hazard maps that integrate real-world utility data to improve preparedness and response capabilities.

Leveraging Data for Resilience Analysis and Power Restoration

OEC's provision of electrical network data and storm outage records was instrumental in evaluating power system resilience. The data included detailed electrical power line configurations, customer loads, equipment specifications for transformers, fuses, switchgear, protection relays and reclosers, and outage reports, which allowed researchers to analyze the storm's impact at a granular level. Using this information, S3OK researchers:

Computed outage reliability and resiliency indices to measure system performance before, during, and after the storm.

Analyzed outage duration trends to assess vulnerabilities in power distribution.

Simulated service restoration scenarios to compare the effectiveness of different grid management strategies, including automated restoration techniques and power flow redirection.

Findings from these analyses[3] highlighted the potential of advanced restoration strategies, such as automated reconfiguration and fault isolation, to minimize service disruptions and enhance the resilience of the distribution system against future extreme weather events. The work is currently being extended to investigate on-the-horizon technologies such as wireless roadway charging of electric vehicles and how that impacts grid operations.

Data-Driven Strategies for Grid Hardening and Hazard Mitigation

Beyond outage analysis, OEC's network data provided critical insights into proactive resilience strategies. Researchers used the data to:

- Assess the effectiveness of pole upgrades and vegetation management in mitigating ice storm damage.
- Identify infrastructure vulnerabilities to prioritize investments in structural reinforcement and adaptive maintenance.
- Develop hazard maps integrating electrical infrastructure with known environmental risk factors, such as tree encroachment, icing risks, and substation exposure, to improve predictive risk modeling and preemptive response planning.

This data-driven approach demonstrated how electrical network mapping and hazard assessment can enhance rural utilities' ability to prepare for and respond to severe weather threats[2].

Advancing Renewable Energy and Grid Modernization with Feeder Data

OEC's feeder-specific data played a crucial role in evaluating the resilience of the grid under changing energy demands and evolving technology landscapes. By sharing hourly feeder load profiles, the cooperative facilitated research into:

- The integration of renewable energy sources such as photovoltaic (PV) generation, simulating how solar energy interacts with feeder demand[20].
- The impact of electric vehicle (EV) adoption on fault levels, assessing potential grid vulnerabilities under different PV-EV scenarios[21].
- The increasing electrification of transportation and resulting effects on voltage stability, consumer demand patterns correlated with driving habits and charging-station loads combined with roadway wireless charging scenarios.

This research underscores the importance of utility-academic partnerships in designing future-ready electrical systems, where real-world data enhances modeling efforts to improve renewable energy adoption, strengthen grid stability, and optimize hazard response strategies.

Building Resilience through Collaborative Hazard Mapping

By fostering a robust exchange of utility infrastructure data, S3OK researchers and OEC have laid the groundwork for usable, high-resolution hazard maps tailored to rural electric cooperatives. These hazard maps:

- Integrate real-world outage, weather, and grid vulnerability data, providing actionable insights for risk assessment.
- Enhance operational decision-making, guiding preemptive power system reinforcements.
- Support resilience planning efforts, ensuring that rural utilities can anticipate and mitigate extreme weather impacts.

This partnership demonstrates how data-driven collaborations can bridge the gap between research and practice, enabling utilities to enhance infrastructure resilience while leveraging scientific advancements in hazard forecasting and disaster mitigation. Moving forward, strengthening these data-sharing efforts will be key to equipping Oklahoma's rural electric cooperatives with the tools needed to navigate an increasingly complex climate risk landscape.

Data Sharing for Enhanced Power Distribution Resilience and Hazard Mapping

Collaborations between S3OK researchers, working group members, utilities, and wildfire risk mitigation experts has been instrumental in efforts to enhance the resilience of rural electric utilities. One such example from the working group is The AI-Enabled Proactive Resilience Enhancement of Electric Infrastructure Against Wildfire project, led by a member of the working group, Dr. Hamid Nazaripouya at Oklahoma State University. This project addresses the critical intersection of wildfires and electrical infrastructure and exemplifies how strategic data sharing and interdisciplinary partnerships are critical to developing actionable risk assessments and resilience strategies for power distribution systems.

Leveraging AI and Data for Proactive Wildfire Resilience

This initiative, initially funded through a one-year S3OK SEED grant, sought to integrate artificial intelligence (AI) and self-healing grid mechanisms to improve power infrastructure resilience under wildfire conditions. By utilizing real-world utility data provided by key partners from the Oklahoma Forestry Services and the Oklahoma Electric Cooperative, researchers were able to:

- Analyze grid vulnerabilities to wildfire ignition, identifying electrical faults that could trigger wildfires.
- Develop a proactive self-healing mechanism, enabling automated fault detection and adaptive restoration to prevent cascading failures.
- Enhance situational awareness for utilities, integrating weather, fuel conditions, and electrical system stress data to predict wildfire risks more accurately.

The project's success led to five publications and secured a $2.1 million NASA grant, which extends these resilience-focused efforts by incorporating near-real-time wildfire risk assessment and danger rating updates.

Advancing Resilience through Utility Collaboration

The NASA-funded expansion of the AI-enabled resilience project is a key step in developing enhanced products that incorporate dynamic wildfire risk factors. This initiative builds upon utility data sharing agreements, particularly with OEC, to ensure that the maps provide usable, real-time risk assessments for rural electric utilities. Through partnerships with Oklahoma Forestry Services and OEC, along with regional and national collaborators such as Southern California Edison, USDA Forest Service, and CAL FIRE, the project will ensure that hazard mapping tools are operationally viable, scientifically robust, and directly applicable to rural power grid management.

Impact on Rural Utilities and Future Directions

By leveraging utility-provided electrical infrastructure data and wildfire risk modeling, this initiative is poised to:

- Improve proactive risk assessment by incorporating real-time grid conditions into analysis.
- Enhance decision-making for rural utilities, equipping them with AI-driven insights for grid resilience planning.
- Reduce wildfire ignition risks associated with electrical faults, thereby protecting critical infrastructure and communities.

This collaborative approach underscores the importance of data-sharing agreements between researchers, utilities, and emergency response agencies. By continuing to refine hazard mapping methodologies and integrating cutting-edge AI-driven predictive analytics, the project will provide rural electric utilities with the tools needed to enhance grid resilience and mitigate the increasing wildfire threats in Oklahoma.

Mutually Beneficial Collaborations with Utility Partners

Utilities today face unprecedented challenges in building resilient and economically viable infrastructure amidst increasingly chaotic natural disasters, aging systems, and shifting consumer demands. These challenges are compounded by limited resources, including workforce and financial constraints, which often hinder access to the advanced technical expertise necessary to address long-term issues. By fostering mutually beneficial collaborations with academic institutions, utilities can unlock innovative solutions that address these challenges while also advancing research that benefits the industry and societal function as a whole. This working group demonstrates **The Value of Collaboration Between Utilities and Academia** and how such collaborations can be leveraged to enhance **Reliability in Power Grid Resilience**. Combined, these efforts underscore the critical role of utility data sharing in facilitating such partnerships and highlight how leveraging research infrastructure in academia can provide valuable insights and actionable solutions for utility stakeholders.

The Value of Collaboration Between Utilities and Academia

The S3OK project and efforts advanced under the Natural Hazards & Utility Resilience working group demonstrate the potential of such collaborations. During the severe **ice storms of late 2020 and early 2021**, which strained Oklahoma's power grid, researchers worked closely with **Oklahoma Electric Cooperative (OEC)** to analyze grid failures and recovery efforts. By sharing **critical utility data**, OEC enabled researchers to assess **infrastructure resilience, component stresses, and system recovery processes**. This partnership not only yielded **data-driven recommendations** for improving grid reliability but also provided a model for **cost-effective, mutually beneficial collaborations** between academia and utilities. These efforts demonstrate how **data sharing and joint research initiatives** can enhance **operational standards, analytical methods, and long-range infrastructure planning**, helping utilities prepare for **increasingly volatile weather patterns** and the **growing integration of renewable energy**. This collaboration also helped spur new offshoot projects funded by the NSF (e.g., CAREER and Department of Energy awards) that study other aspects of grid resiliency and reliability, such as the impacts of chaotic electromagnetic transients.

A Path Forward for Data Sharing

Building on the success of these collaborations, new opportunities exist for utilities to work with academic researchers on shared challenges in grid resilience and modernization: These include:

- **Long-range infrastructure planning** to mitigate risks from extreme weather and climate variability.
- **Performance optimization** through improved operational standards and system monitoring.
- **Event-based analysis** of grid disturbances, component failures, and service restoration strategies.

By sharing anonymized network data, historical load trends, asset management documentation, and event-specific damage reports, utilities can empower researchers to uncover actionable insights that enhance grid stability and efficiency. Access to maintenance records, Supervisory Control and Data Acquisition (SCADA) logs, and supervised site visits during significant disruptions can further strengthen this research, ensuring that academic findings translate into practical, real-world applications. The results of this project are also being promulgated through the Oklahoma Association of Electric Cooperatives (OAEC) and nationwide entities including the National Rural Electric Cooperative Association (NRECA). OEC has strong representation in these organizations and is advocating for further data sharing from members to support ongoing and offshoot projects.

Reliability in Power Grid Resilience: A Collaborative Approach

Ensuring that power distribution systems are resilient and reliable is an essential challenge for utility providers, particularly in rural communities susceptible to progressive wildfires. As part of a seed grant project funded through S3OK, working group member Dr. Hamid Nazaripouya collaborated with the Oklahoma Association of Electric Cooperatives (OAEC) to examine the distribution of power outages across multiple rural areas in Oklahoma. This partnership provided a data-driven approach to understanding how power disruptions affect different communities and how utilities can enhance resilience while addressing disparities in service reliability.

Assessing the Distribution of Power Outages

Through this collaboration, OAEC provided multi-year power outage data covering several counties within its members' service territories. Researchers analyzed power disruptions over a two-year period, focusing on both major disaster-related outages and routine daily service interruptions. The study assessed key metrics of outage distribution, including:

- Total outage duration across different counties and communities.
- The frequency of outages and their geographic distribution.
- The number of customers affected per outage event.

To identify potential disparities, these metrics were correlated with socioeconomic indicators such as poverty rates, levels of unemployment, racial and ethnic demographics, disability status, and the proportion of senior citizens within affected communities. The findings provided critical insights into how different groups experience power outages and how utilities can better prioritize resources for expedient service restoration.

Advancing Research and Practical Solutions

The results of this study were published in the *Proceedings of the IEEE Power & Energy Society General Meeting*[30] highlighting the intersection of power grid resilience and socioeconomic disadvantage. This research underscores the importance of utility-academic collaborations in advancing:

- Data-driven strategies to mitigate imbalances in power restoration efforts.
- More resilient infrastructure planning that considers community needs.
- Proactive solutions to ensure reliable access to electricity, especially in disaster-prone regions.

By fostering partnerships such as the ones described, utilities can leverage research expertise to enhance both operational efficiency and reliability, ensuring that all communities have access to a resilient and dependable power supply. Through open data exchanges and joint research initiatives, utilities and academia can work together to develop smarter, more adaptive power systems capable of withstanding future challenges. It also enables research findings to influence utility standards and update energy policies focusing on infrastructure planning and resiliency. Moreover, these collaborations not only strengthen infrastructure resilience but also create a foundation for innovative strategies that meet the demands of a rapidly changing energy landscape.

Broadening the Infrastructure Conversation Beyond S30K: Interdependencies, Emerging Technologies, and Transportation Resilience

The need for effective collaborations around natural hazards and utility resilience has never been greater. The challenges ahead demand not only technical innovation but also sustained engagement among researchers, industry professionals, policymakers, and community stakeholders. Moving forward, successful resilience efforts will require a shift from reactive responses to proactive, data-driven strategies that integrate emerging research, real-world expertise, and cross-sector partnerships.

This section delineates critical pathways for future research and engagement around natural hazards and utility resilience. In particular, we highlight the importance of integration of other infrastructure considerations, sustained stakeholder involvement, and emerging technologies and renewable energy sources. We also detail insights for future collaborations gained from our work with a broad range of stakeholders. Finally, in response to the quickly changing risk landscape and in line with utility stakeholder concerns, we address the value of future foci on adopting novel financial tools for utility resilience.

Integrating Other Infrastructure and Considering Cascading Impacts

The increasing interdependence between critical infrastructure systems, such as electricity and transportation networks, presents both opportunities and challenges for resilience planning in the face of natural and human-made disasters. As modern advancements in energy and mobility, including transportation electrification, connected and autonomous transportation, and intelligent traffic management systems, become more prevalent, their reliance on stable power grids and distribution networks grows. Simultaneously, the electric utility sector depends on transportation systems for fuel delivery, supply chain operations, and maintenance logistics. This intricate web of dependencies introduces new vulnerabilities, particularly in the face of natural hazards and extreme weather events.

A key challenge is the cascading nature of damage, where disruptions in one system ripple through interconnected infrastructure, exacerbating failures and complicating recovery efforts. Understanding how these interdependent systems respond to disasters, the nature of their coupling (tight or loose), and the influence of changing climate conditions remains a crucial research frontier. In addition, research must address the uncertainties in operations and supply-demand imbalances that emerge during extreme events, which can create unforeseen bottlenecks in both power and transportation networks. The extremely long lead times in the order of decades for planning and commissioning transmission and generation capacity to serve new consumer growth is a significant challenge. As a result, existing substations are quickly saturated beyond their capacity resulting in accelerated aging and loss of service life of vital components such as transformers. Better management of consumer loads, including coordinated EV charging, and customer demand response programs will be key in managing the limited resources, especially during extreme weather events and natural hazards.

Beyond the technical vulnerabilities of these interdependencies, the societal dimensions of infrastructure resilience must also be a focal point for future research. As new technologies are deployed, ensuring access to resources during disasters is essential. Climate-driven disruptions occur differentially across communities, raising questions about the fair distribution of energy, mobility, and emergency response capabilities. Research into the social and policy dimensions of resilience will be key to developing inclusive solutions that prioritize community needs alongside technological advancements.

Understanding these dynamics informs **future research priorities** along the lines of:

- **Cascading Infrastructure Failures**
- **Integrating Emerging Technologies**
- **Access in Disaster Response**

Regarding cascading infrastructure failures, investigating how disruptions propagate across interdependent systems and developing predictive models to mitigate widespread failures will be important. Similarly, incorporating non-stationary climate projections into power grid and transportation network planning to improve adaptability to future conditions can enhance the design of climate-resilience infrastructure. Meanwhile, assessing how advancements in electric vehicles, smart grids, and automation affect resilience and system vulnerabilities during disaster unfold will facilitate seamless integration of emerging technologies into analysis, generating relevant research well into the future.

Addressing these critical pathways will strengthen the foundation for interdisciplinary collaborations within the S3OK initiative and beyond, ensuring that research not only advances scientific understanding but also informs real-world infrastructure resilience strategies in an era of increasing climate uncertainty.

Considering Impacts of Emerging Technology and Renewable Energy Sources

As renewable energy adoption accelerates and advanced energy technologies reshape distribution grids, ensuring grid resilience amid natural hazards remains a pressing challenge. Oklahoma, with its high solar potential and significant wind energy infrastructure, is at the forefront of this transition, with over 42% of its electricity generated by wind power in 2023[31]. Additionally, the growth of Distributed Energy Resources (DERs)—such as localized photovoltaic (PV) systems and battery energy storage—is enhancing grid flexibility and reliability and helping overcome bottlenecks in generation and transmission capacity. However, these advancements introduce new technical and operational challenges that require further research to ensure a stable, climate-resilient energy system.

For example, Distributed PV systems have proven valuable during extreme weather events, such as the 2020 Oklahoma ice storm, by supporting critical loads and expediting recovery. However, their integration presents challenges related to voltage stability, thermal capacity management, and protection coordination. Research on PV Hosting Capacity (PVHC)—the maximum amount of PV a distribution feeder can accommodate without disrupting grid operations—has provided insights into grid constraints, but further investigation is needed to optimize PV placement and adaptive grid management. Future studies should explore:

- Advanced voltage regulation strategies to maintain grid reliability amid fluctuating solar generation.
- Adaptive thermal capacity management for more efficient DER integration.
- Enhanced protection coordination schemes to prevent inverter-based faults from propagating through the grid.

Moreover, the widespread deployment of EV charging stations—both stationary and dynamic wireless charging (DWC)—adds another layer of complexity to power distribution networks. While EVs and DWC technology offer a promising path toward sustainable transportation, they introduce variable loads, voltage fluctuations, and new fault current dynamics that can strain distribution grids. Research has demonstrated the importance of adaptive protection schemes to manage these impacts, but additional work is needed to:

- Develop real-time monitoring and control mechanisms to balance EV demand and grid stability.
- Enhance fault detection and response for EV-integrated networks.
- Explore the role of distributed PV and battery storage in mitigating peak demand from EV charging.

- Enable seamless DER fed microgrids serving communities when existing transmission and distribution networks are experiencing disruptions.

As climate-driven hazards such as severe storms, heatwaves, and wildfires become more frequent, leveraging DERs like PV and battery energy storage systems (BESS) for grid stabilization is crucial. Modeling efforts using real-world distribution feeder data from the Oklahoma Electric Cooperative (OEC) have shown that strategically placed PV-BESS combinations can help smooth demand spikes, optimize renewable energy use, and ensure voltage stability. Future research can support grid resilience by:

- Developing intelligent DER deployment strategies to enhance resilience across varied weather conditions.
- Improving grid flexibility through AI-driven load forecasting and real-time energy management.
- Exploring multi-sector energy coordination to enhance infrastructure resilience during disaster scenarios.

Strengthening Transportation-Grid Interdependencies

The transportation sector is undergoing a rapid transformation, driven by emerging technologies, renewable energy integration, and data-driven innovations. As electric vehicles (EVs), autonomous systems, and renewable fuels such as solar, green hydrogen, and biofuels reshape mobility, ensuring resilience in these evolving networks is critical. This transformation requires a holistic approach to infrastructure planning that considers robustness, redundancy, rapidity, and resource availability to maintain seamless operations in the face of climate change, natural disasters, and growing energy demands. The integration of EV infrastructure with renewable energy grids has the potential to create decentralized and adaptable systems that enhance energy security and reduce dependence on fossil fuels. However, the growing interdependencies between transportation and energy networks introduce new risks of cascading failures during extreme weather events or cyberattacks. Research must focus on:

- Developing adaptive energy-transportation models that account for disruptions across interlinked systems.
- Assessing cascading failure of risks and identifying strategies to minimize system-wide outages.
- Optimizing EV-grid interaction to balance charging demand with variable renewable energy generation.

Technologies such as wireless charging, autonomous vehicle systems, and predictive analytics improve transportation system efficiency and resilience. The adoption of Internet of Things (IoT) sensors and Artificial Intelligence (AI) facilitates real-time monitoring, predictive

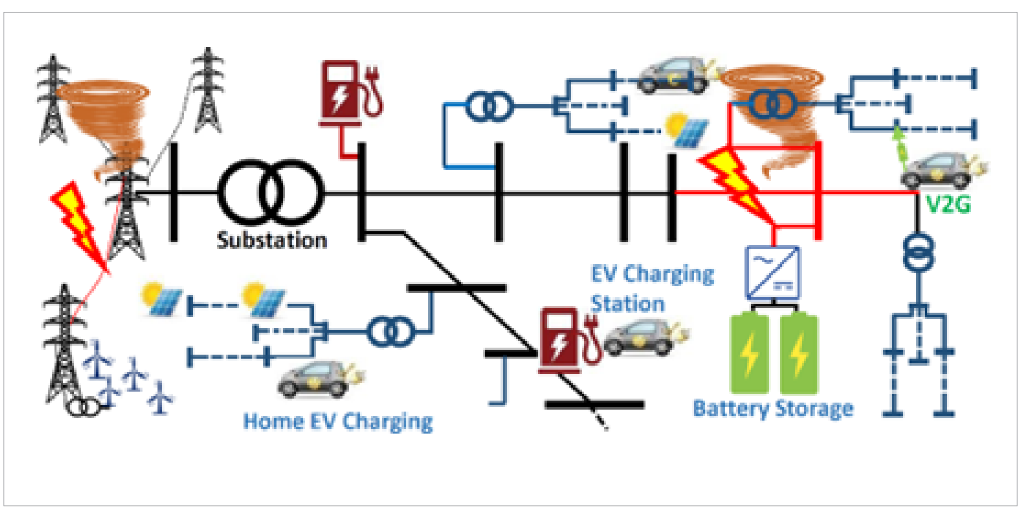

Figure 9.10: Evolving distribution system (Image Source: Panchalogaran and Moses, 2024)[21]

maintenance, and rapid response to infrastructure disruptions. However, to fully harness these advancements, future research should explore:

- Enhancing real-time mobility forecasting for disaster-prone areas using AI-driven models.
- Improving predictive maintenance systems to address infrastructure vulnerabilities preemptively.
- Integrating IoT and AI solutions to optimize traffic flow and emergency response during extreme weather.

As new transportation and energy technologies emerge, ensuring access is essential to prevent widening disparities. Underserved communities often face barriers to adopting EV infrastructure, renewable fuels, and smart mobility solutions due to high costs, geographic distribution gaps, and policy constraints. Additionally, policy and regulatory frameworks have yet to fully address the long-term resilience of these systems under evolving climate and disaster scenarios. Future research should prioritize:

- Developing deployment strategies to ensure that underserved communities benefit from emerging technologies.
- Assessing long-term performance and sustainability of renewable fuels in transportation networks.
- Creating policy frameworks that support resilient transportation-energy systems and ensure regulatory adaptability to technological advancements.

The intersection of transportation, energy, and climate resilience demands collaborative, interdisciplinary research to address emerging vulnerabilities while maximizing the benefits of technological innovation. Moving forward with lessons learned, S3OK affiliates can play a crucial role in bridging engineering and policy considerations to create resilient, sustainable, and inclusive mobility systems.

Adopting Novel Financial Tools for Utility Resilience

As climate-driven disasters become more frequent and severe, the financial burden of disaster recovery and resilience investments is growing, straining traditional public funding mechanisms. To address this challenge, novel financial tools, such as catastrophe bonds (CAT bonds), are emerging as viable alternatives for managing catastrophe risk and financing resilience projects. The integration of these financial instruments into infrastructure resilience planning presents critical opportunities for research and collaboration, particularly in leveraging private capital to support infrastructure adaptation.

Alternative Financial Tools for Disaster Risk Reduction

A key research priority for future work in this area is developing and refining financial models that effectively assess, price, and manage multi-peril catastrophe risks. As part of the S3OK project, researchers have created a high-resolution methodology for quantifying financial losses from natural hazards, with application to pricing CAT bonds, laying the groundwork for integrating financial risk assessment with engineering and climate science models[32]. Future research should build upon these efforts and focus on:

- Expanding financial risk modeling to incorporate more localized hazard data and infrastructure fragility assessments.
- Enhancing machine learning applications for predicting risk exposure and improving CAT bond pricing accuracy.
- Explore new financial instruments that align with evolving resilience and adaptation needs.

Reducing the Cost of Catastrophe Insurance for Utilities

Electric utilities across the country are facing soaring catastrophe insurance premiums, particularly for wildfire risk, making coverage increasingly unaffordable. This growing financial strain highlights the need for alternative risk transfer mechanisms that can stabilize costs while maintaining adequate protection. Future research should explore:

- The viability of CAT bonds and other financial innovations in reducing insurance costs for high-risk energy infrastructure.
- New risk-sharing models that distribute financial responsibility across utilities, private investors, and public institutions.
- Policy and regulatory adaptations that facilitate the adoption of CAT bonds and private capital solutions for utility resilience.

Integrating Financial and Engineering Models for Resilient Infrastructure

Ensuring that financial tools effectively support real-world resilience efforts requires closer integration of risk financing with infrastructure adaptation strategies. This includes developing prototypes that combine financial risk models with engineering solutions, enabling utilities to make data-driven investment decisions. Key research pathways include:

Exploring the role of AI-driven catastrophe modeling in linking financial planning with resilience strategies.

Developing frameworks for utilities to integrate financial risk management into resilience planning.

Assessing the effectiveness of CAT bonds in incentivizing long-term infrastructure investments.

A Collaborative Approach to Financing Resilience

The increasing financial risks associated with climate-driven disasters demand an interdisciplinary and multistakeholder approach that brings together financial experts, engineers, policymakers, and climate scientists. Future research collaborations within S3OK affiliates can bridge the gap between infrastructure resilience and financial innovation, ensuring that utilities, investors, and regulators have access to sustainable, scalable solutions for catastrophe risk management.

What Are Catastrophe Bonds (CAT Bonds)?

CAT bonds are a financial tool that allows utilities to transfer risk from natural disasters—like wildfires or ice storms—to investors.

How They Work: Utilities pay premiums to issue bonds. If a predefined disaster (like a wildfire exceeding a certain scale) occurs, bondholders absorb the financial loss, not the utility.

Why It's Useful: CAT bonds can reduce insurance costs and provide faster access to recovery funds.

Relevance to Oklahoma: With increasing wildfire threats and insurance challenges, CAT bonds offer a scalable, market-based resilience strategy—especially for rural co-ops facing growing liability.

Coupling financial modeling with climate science can help utilities prepare for and withstand high-impact, low-probability events.

Navigating Compound Events: Addressing Emergent Risks in Utility Resilience

Rising temperatures, shifting precipitation patterns, and increasing flash drought frequency are intensifying wildfire risks and straining Oklahoma's utility infrastructure. By 2050, the state could see up to 30 more days above 100°F annually, while the eastward migration of the climatological dry line will likely heighten drought and wildfire threats in the near term across the Central Great Plains[33]. As population growth and energy demand rise, grid resilience must move beyond historical baselines to account for non-stationary climate risks in infrastructure planning and management.

A major challenge is the predictability gap on S2S timescales, limiting early warnings for extreme weather. Improving S2S forecasting will be critical for stakeholders such as utility managers, emergency planners, and policymakers, as well as citizens who would benefit from being able to anticipate risks and allocate resources effectively. Additionally, compound events—instances in which multiple extremes such as heatwaves, wildfires, or ice storms occur back-to-back or at once—present unique grid stressors across the region. These events are expected to become more frequent in the future[34–37] and increase infrastructure vulnerabilities and disrupt response efforts beyond what is observed with individual extreme events. In particular, compound events have the potential to generate greater impacts by decreasing time for recovery and restoration efforts between events or overwhelming human and utility systems through simultaneous occurrence. In light of the unique challenges posed by compound events, future collaborations should focus on:

- **Improving S2S Forecasting** – Closing the predictability gap to support proactive decision-making.
- **Incorporating Climate Projections into Grid Planning** – Moving beyond historical trends to account for evolving risks.
- **Developing Strategies for Compound Events** – Understanding cascading impacts and refining response measures.
- **Strengthening Utility-Research Partnerships** – Co-producing solutions tailored to real-world operational needs.

By integrating advanced forecasting, climate-adaptive planning, and cross-sector collaboration, stakeholders can better prepare for future extreme weather challenges and build a more resilient energy system.

Insights for Future Collaborations

Through the research collaborations described in this chapter, we have identified key insights that can inform and strengthen future collaborations between researchers and utility practitioners.

This section distills the lessons learned from our engagements, highlighting strategies for fostering effective partnerships, addressing barriers to collaboration, and enhancing the integration of scientific research into decision-making processes. By reflecting on our experiences, we offer guidance for designing collaborative efforts that are both responsive to emerging challenges and grounded in long-term resilience planning.

Building Resilience through Collaboration: Lessons Learned for Future Partnerships

Effective resilience research requires both interdisciplinary expertise and sustained stakeholder engagement. The Seed Grant project awarded to working group member Dr. Hamid Nazaripouya exemplifies this approach. Initially focused on a technical challenge related to power grid resilience amid wildfires, the project quickly expanded beyond electrical engineering in response to the recognition that addressing wildfire risks required a broader perspective. By integrating expertise from Geography, Fire Safety & Protection, Ecology, and Industrial Engineering, the team developed a more comprehensive approach to wildfire impact mitigation.

Beyond academia, these multi-stakeholder collaborations ensure that research findings are both analytically rigorous and practically applicable. In the collaboration here, partners provided operational data while facilitating real-world implementation, bridging the gap between research and practice.

What began as a technical research project evolved into a multi-sector research network, fostering long-term academic-industry collaboration, joint proposals, and publications. This case highlights the importance of flexibility, cross-disciplinary engagement, and sustained partnerships in addressing complex environmental challenges, offering a model for future collaborations in resilience research. In particular, looking across collaborations central to the Natural Hazard and Utility Resilience working group, we suggest future collaborations:

1. **Embrace Interdisciplinary Expertise** – Complex challenges like wildfire resilience require perspectives beyond a single discipline. Integrating a range of fields such as environmental science, engineering, and public policy enhances the depth and applicability of research.
2. **Engage Stakeholders Early and Continuously** – Building relationships with industry partners, government agencies, and community organizations from the outset ensures that research is aligned with real-world needs and facilitates smoother implementation.
3. **Bridge Research and Practice** – Collaborations should prioritize not only theoretical advancements but also practical applications, leveraging operational data and real-world insights to create actionable solutions.
4. **Foster Long-Term Partnerships** – Moving beyond short-term projects to sustained collaborations strengthens institutional capacity, facilitates joint funding opportunities, and expands the impact of research efforts.
5. **Maintain Flexibility and Adaptability** – The ability to pivot in response to emerging challenges or new insights is critical for tackling complex infrastructure problems and ensuring research remains relevant and effective.

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