PNNL-34091

Grid Resilience to Extreme Events – Connecting Science to Investments and Policy

Workshop Report

April 2023

Juliet Homer
David Judi
Jason Fuller
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

A workshop co-hosted by Pacific Northwest National Laboratory and Seattle City Light was held at the Seattle Municipal Tower on November 8–10, 2022. Participants from research organizations, utilities, professional associations, consultants, and government organizations attended. The purpose of the workshop was to develop a vision for addressing climate extremes that include improving forecasting and characterization, infrastructure resilience modeling, and investment planning and decision support. The workshop also aimed to provide a platform for sharing approaches and information and identifying possible collaborations.

Key insights

Some key insights from the workshop are summarized below.

- **We must focus on and enhance the "research to planning and policy pipeline" to improve implementation and resilience**. Researchers and scientists need utility data to connect observations to research, and utility planners need research-supported forecasts to know what to plan for. In addition, people downstream in the pipeline need to be aware of the research and be using it. Regulators and policymakers can support critical research and data development and access, as well as provide guidelines for resilience planning that support utility prioritization. They can also contribute to the demand for the research.
- **There is a need for an updated common language** across all stakeholders (scientists, planners, and regulators/policymakers) in climate preparedness. The terms "100-year event" or "1000-year event" are now out of date. When people talk of weather extremes, there are many different interpretations (e.g., extremes of 2022 or extremes of 2040, and extreme relative to what). Therefore, a new taxonomy and language are needed (such as the Richter magnitude scale for earthquakes). There is currently a significant gap in language and priorities between climate scientists and investment decision-makers. **Climate translators** are also necessary, with people playing specific roles to fill the gaps.
- **More work is needed to translate climate science into investment planning that supports resilience.** We need to be planning for the weather of the future rather than the weather of the past. Climate science needs to provide guideposts for energy planning and adaptation. From a climate science perspective, the risks the utilities must plan for are the result of a wide variety of inputs—these inputs need to be brought together to create something meaningful. Engineers typically plan according to the expected peak conditions with an added safety factor. Long-term trends or averages are less helpful for engineers and investment decision-makers. We need a simplified way to translate climate impacts into equipment and grid planning decisions. Significant data and information are currently available but are not known and therefore not used—we need to make both more widely available and widely known.
- **Utilities and policymakers would benefit from vetted, standardized, and accessible data about climate variability and risks.** California has a good example of this with its Cal-Adapt data portal, which is a web-based climate adaptation tool that provides information and current high-resolution data on a variety of climate-related risks (temperature, precipitation, snowpack, sea level rise, and wildfire). California utilities were directed by the California Public Utilities Commission to use Cal-Adapt emissions scenarios in their Climate Change Vulnerability Assessments. Other states could benefit

from a similar resource so each utility (particularly smaller and under-resourced utilities) can benefit from it and do not have to develop their own climate risk forecasts. A national version of Cal-Adapt that provides vetted, easy-to-use, granular climate data sources for the entire United States would be extremely helpful.

- **We need to lean into decision-making under uncertainty**. Energy system decision-making needs to better address and respond to uncertainties in climate science. One approach to this is designing ductile systems (i.e., the ability of a material or system to be compromised or deformed without fracture). An example of this planning for ductility is Seattle City Light's transmission poles in landslide areas, which are being designed to break away to avoid cascading impacts on other transmission towers. The Infrastructure Investment and Jobs Act represents a unique opportunity to make significant investments in the near term. These investments should be ductile and robust in the face of climate uncertainty.
- **Importance of storyline approach**. A storyline approach can be useful for holistic preparedness for future climate-related events, especially those that are highly uncertain (high impact, low probability). This technique evaluates the potential impact on systems of physically self-consistent unfolding of past events or plausible future events. An event in the past, such as a hurricane, would be adjusted to account for projected future climate conditions and used as analysis inputs. By leveraging storyline events, stakeholders can consider climate events they have already experienced and gain perspective on anticipated changes to the series of impacts from those events should they occur again in the future.
- **We need to go beyond existing codes and standards**. Standards include Institute of Electrical and Electronics Engineers standards, North American Electric Reliability Corporation (NERC) standards, individual utility engineering standards, equipment standards, and other industry-based standards. Updating standards is an important topic that came up throughout the workshop. There's a need for common communicable standards for generating future time series of environmental variables of interest.
- **We need communication and coordination** across utilities, emergency response, communities, and land planners. Achievable and effective power system climate resilience will also require partnerships between researchers, businesses, utilities, and government organizations.
- **"Directionally correct" may be a useful concept in planning for climate variability.** It would be good to think more about when "directionally correct" is appropriate and useful versus when precision is needed and achievable. Different aspects of forecasting, modeling, and investments may require precision, where in other cases "directionally correct" is sufficient. No model is perfect, and we need to avoid analysis paralysis.
- **Climate migration** is something that needs to be considered.
- **Smaller utilities need support understanding data, needs, and how to apply available climate science information**. Human capital constraints exist at co-ops and other smaller utilities that may limit their ability to understand and plan for climate risks, and also to apply for and use infrastructure dollars. Larger and more advanced utilities can help smaller ones. **A mechanism for information and capability sharing between utilities, especially smaller utilities, is needed.** In addition to making the data available, guides are needed to help utilities understand and apply climate science to their applications. This is especially true for smaller utilities who are not aware of

available data and tools, and/or perhaps those utilities that cannot afford to make resilience investments.

- **Utility regulators play an important role in resilience planning and investments.** Regulators can set important guidelines for utilities to follow during resilience planning that can help utilities focus on and prioritize resilience activities. Regulatory guidelines can include what climate variables to consider, risk severity levels and time horizons to plan for, and community engagement requirements. For example, the California Public Utilities Commission (CPUC) requires that utilities file climate vulnerability assessments every four years that address specific risks over specified timeframes and are developed with input from a structured stakeholder engagement process. CPUC requires that relevant climate projections be consistently incorporated across all key long-term energy planning processes. Cost recovery principles and practices for long-term, proactive resilience investments may need to be considered separately from traditional investments.
- **Standardization and customization are both needed.** Standardization is needed for risk profiles and equipment standards, and a customization approach is necessary that is responsive to local threats and conditions. For example, Seattle City Light is planning for liquefaction risks in addition to temperatures, precipitation, and sea level rise. We need a framework for a hybrid global/local and standardized/customized approach.
- **Equity, community engagement, and public involvement are important parts of resilience.** The public and communities should be meaningfully involved in resilience planning. Seattle City Light has mapped vulnerable communities to better understand needs and potential solutions. CPUC requires community engagement plans be developed and tracked by CA's investor-owned utilities as part of Climate Adaptation Vulnerability Assessments. Community-based organizations are a new and important part of the picture.

Specific recommendations for next steps include the following:

- Organize a working group to develop a climate-to-energy lexicon and taxonomy that includes standard metrics and definitions for extreme events and can be used by research, utilities, NGOs, and government (note: even the research realm does not seem to agree on many things).
- Develop better guidance for use of larger climate model ensembles.
- **Assemble continuous working groups** between researchers, regulators, utilities, and other planners with appropriate staffing for continued collaboration.
- Make this event (or an expanded version of this event) an **annual event**.
- **Form regional partnerships** that openly/transparently share information and data.
- Assess the viability of rolling out a **Cal-Adapt approach nationwide**.
- **Keep in communication** about our individual organizations' efforts, plans, challenges, and hopes for grid resilience.
- **Develop guidance for regulators** so they can help utilities prioritize and plan for resilience. Potentially work with the National Association of Regulatory Utility Commissioners.

Recommended actions

Specific actions that were recommended relative to (1) climate-extreme characterization, (2) infrastructure resilience modeling, and (3) investment planning and decision support are listed below.

Climate-extreme characterization

- Develop validated and consensus dynamical downscaling methods for extreme events and evaluate statistical downscaled data for extreme events.
- Fund open-source public data and tools.
- Develop data accountability and model bias quantification methods.
- Develop an **ensemble model approach** within a Representative Concentration Pathway climate scenario and develop **bands of outcomes** with **focus on extremes** and key thresholds.
- Develop and agree upon a **methodology for defining climate-informed extreme events** that includes the use of historical analogs with climate predictions.
- **Adopt storyline approaches** to connect research with utilities and stakeholders.
- Develop **automated data mining techniques for finding storylines** and extremes in climate ensemble data and develop **generative machine learning for downscaling extreme weather generation**, potentially in combination with satellite data if utility data is not available.
- Develop and share additional guidelines on use of climate datasets.

Infrastructure resilience modeling

- **Fill data gaps and develop methods for linking diverse datasets**. There are available approaches, but they are case specific and thus not usable across a wide set of use cases.
- **Develop synthetic grid system models for resilience, similar to what we have for reliability**. These need to be multidisciplinary, forward-looking, and longer than a 5-year planning horizon. Use these for tool development solutions.
- **Update and evolve existing metrics and standards**. Standards are currently being updated in Washington. Standards need to be created at a national scale—individual states can then look to these standards and adopt them rather than making/designing standards themselves. The Federal Emergency Management Agency may be a good route for developing standards that could then be adopted under building codes.
- **Institute a collaborative spares program** to tackle supply chain shortages as well.
- **Institute multi-hazard modeling** that is highly regionally specific.
- **Institute multiagency collaboration and modeling**. Integrate modeling with other planning entities and infrastructure sectors for evaluation of interdependencies and co-benefits.
- **Conduct asset sensitivity characterization**. Start from understanding vulnerabilities today. Work with the manufacturers on ways to mitigate emerging fragilities.

- **Upgrade existing supervisory control and data acquisition systems and environmental management systems** to improve information availability and reporting.

Investment planning and decision support

- Develop and share **a guide to best practices or a standardized framework** for long-term resilience assessments, planning, and investments under climate change. Include an assessment of the cost of doing nothing.
- Get **agreement on definitions** for baseline and extremes for technical standards.
- Develop **updated standards**, including:
  - **Risk-informed engineering design standards** for different stress levels, including peak and acute extremes.
  - **Updated bulk systems reliability standards** with data about risks and criteria about probabilities and consequences. Note: NERC is developing a cold weather standard that has recently been transitioned to an extreme weather standard.
  - **Reporting standards for utilities** so that assumptions, analyses, and costs are more transparent, potentially something like California's Risk Assessment Mitigation Phase process reporting.
- Designate a state-level entity **to develop and share centralized datasets and risk maps** for fire, flood, wind gusts, and temperature extremes, like Cal-Adapt. Potentially develop a national dataset that can be used in this way and that can be adapted to the needs of individual states.
- **Develop a widely disseminated menu of risk mitigation solutions/strategies** that can be applied to different risks. Include plans for how to address extremes. Strategies could be organized into something like a food pyramid of resilience/climate change planning.
- **Revisit regulatory prudence for long-term climate change planning**. It may not be appropriate to use the same prudence determination basis for multidecadal investments that specifically target resilience as that used for traditional investments. Find best practice examples of how prudence can be best applied to resilience investments.
- Establish **regional coordination of pathways and strategies** that go beyond state-by-state pathways and include interstate dynamics for weather, renewable energy, and emergency response.

Partnerships and coordination

Workshop participants identified partnerships and coordination actions that will support grid resilience to extreme events. Figure ES. 1 illustrates the needed partnerships and coordination actions identified.

Figure ES. 1. Necessary Partnerships and Coordination for Resilience

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Acronyms and Abbreviations

CPUC	California Public Utilities Commission
DOE	Department of Energy
EGRASS	Electrical Grid Resilience and Assessment System
EPRI	Electric Power Research Institute
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
IIJA	Infrastructure Investment and Jobs Act
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OPUC	Oregon Public Utilities Commission
PG&E	Pacific Gas & Electric
PNNL	Pacific Northwest National Laboratory
SCE	Southern California Edison

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1.0 Introduction

A workshop funded by Pacific Northwest National Laboratory (PNNL) and co-hosted by Seattle City Light and PNNL was held at Seattle's Municipal Tower on November 8–10, 2022. The purpose of the workshop was to develop a vision for addressing climate extremes that include improving forecasting and characterization, infrastructure resilience modeling, and investment planning and decision support. The workshop also aimed to provide a platform for sharing approaches and information and identifying possible collaborations.

The workshop brought together a diverse set of stakeholders, including utilities, industry, policymakers and regulators, and researchers to discuss gaps and explore approaches for resilience to climate extremes. More than 45 people from the organizations listed in Table 1 joined in person.

Table 1. Workshop Participant Organizations

Participant Type	Participants
Utilities	Bonneville Power Administration Pacific Gas & Electric Seattle City Light Southern California Edison
Consultants	CollinsWoerman Converge Strategies Electric Power Research Institute RMI
Professional Associations	National Rural Electric Cooperative Association Northwest Energy Coalition
State Organizations	California Public Utilities Commission Oregon Public Utilities Commission Washington Department of Commerce
National Laboratories	Lawrence Livermore National Laboratory National Renewable Energy Laboratory Pacific Northwest National Laboratory
Universities	University of California, Los Angeles University of Washington

This report summarizes the workshop motivation, topics of focus, and key workshop themes and findings.

2.0 Workshop Motivation

One of PNNL's strategic objectives is Decarbonization and Human–Earth Systems Interactions. This objective aims to develop and analyze portfolios of decarbonization approaches that meet emissions reduction goals, are resilient to future climate and other global changes, and minimize negative impacts on human and natural systems.

To move toward this objective, PNNL organized the Grid Resilience to Extreme Events workshop to pull together a diverse set of stakeholders and provide a venue from dynamic exchange of ideas. The goal was for attendees to share approaches and information, identify possible collaborations, and walk away having identified gaps, specifically where more research is needed vs. where translation is needed. Through collective review and group discussions, attendees were charged with formulating a vision to advance grid resilience to extreme events.

The workshop prioritized three topical areas with corresponding breakout groups.

Climate-Extreme Characterization for Energy Systems

Climate change is accelerating the frequency and intensity of extreme weather events, such as hurricanes, fires, and heat waves. This breakout group set out to focus on the current state of science for characterization of these extreme events and discussed the needs and developments necessary to enhance understanding, availability, and utilization (analysis, visualization, etc.) of these data in energy system resilience planning. Special attention was given to how the most cutting-edge science can be designed and translated to inform engineering decisions and policymaking.

Infrastructure Resilience Modeling

Achieving grid resilience in the face of extreme weather events—including planning, response, and recovery—can be strengthened and accelerated through the development of an assortment of grid modeling and simulation tools that can represent the behaviors of interconnected energy systems with Earth system models. This breakout group set out to focus on defining the analysis and development needs surrounding high-fidelity modeling of the power system's increasingly complex interdependencies in the face of extreme climate events and how those events can be characterized in power system models to reduce system outage risk.

Investment Planning and Decision Support in an Uncertain Climate

Utilities, grid operators, and community planners must deliver a safe and reliable electricity supply to businesses and consumers. This is becoming more and more challenging in the face of extreme weather events. Regulators and policymakers also have an important role to play in planning and investment decision-making. Characterizing and allocating costs and benefits is particularly challenging for resilience investments and high-impact, low-frequency events. This breakout group set out to focus on needs and developments specific to understanding risks, opportunities, costs, and benefits to inform important planning, investments, and policymaking.

During an initial session at the summit, participants were asked about their desired outcomes for the summit. Many participants said they wanted to better understand the needs of electric utilities for climate change data and planning and investment prioritization for resilience. There was also an expressed desire for understanding the latest in climate change and extreme weather science and how that can be used for grid planning instead of historical data. Some wanted to walk away with a better sense of good metrics for grid vulnerability and resilience with respect to weather and climate variability. Many expressed an interest in learning more about the current state of the connection and gaps between climate modeling and utility planning. There was an expressed desire to better understand grid risks and the policies needed to address them. Others said they wanted to ensure that policy goals are supported by solid engineering analysis. Some wanted to walk away from the summit with future research directions, and many wanted to establish new relationships, connections, and paths for future collaborations and partnerships. One participant summarized that they wanted to better connect research to policy to practice.

3.0 Workshop Presentations and Panels

Several presentations and four panels over the three-day period provided context for the breakout sessions and discussions. The sections below describe information covered during these presentations and panels.

3.1 Overview of Workshop Topics

The workshop opened with presentations from the three co-organizers on topics of focus, which were revisited throughout the workshop.

David Judi from PNNL presented on Climate-Extreme Characterization for Energy Systems, opening by providing an overview of the current environment in which the United States is experiencing climate-driven temperature changes that lead to extreme events—which are increasing in frequency—and that affect our energy systems. He provided an overview for a conceptual framework that connects climate risks with infrastructure resilience, offering specific examples of capabilities that exist to investigate many of the relevant extreme events, including extreme heat/cold, drought, hurricanes/floods, and wildfires. David asked the attendees what gaps exist in connecting climate infrastructure models to enhance energy resilience.

Jason Fuller from PNNL presented on Infrastructure Resilience Modeling, including the engineering basics of the power grid and what it means to have a climate-resilient power grid. He also covered prior blackouts and lessons learned gleaned by engineers and summarized steps being taken—such as the development of tools like the Dynamic Contingency Analysis Tool, RADR-Fire, and the Electrical Grid Resilience and Assessment System (EGRASS)—to understand and enhance power system resilience in the future. Jason asked attendees to consider if we currently have end-to-end tools that address climate challenges while also achieving decarbonization goals equitably and sustainably.

Juliet Homer from PNNL presented on Investment Planning and Decision Support in an Uncertain Climate, highlighting a review of 30 electric integrated resource plans that summarized best practices for analyzing and reporting on potential waster-based and climate change risks. She also covered asset planning and operations and how utility assumptions lead to risk, which regulators can help address. Juliet asked the attendees to consider what is the responsibility of ratepayers compared to society/taxpayers when it comes to investments in disaster preparedness.

3.2 Climate Change Landscape

Two university researchers provided an overview of the change our climate is facing and introduced various climate modeling tools that can be leveraged for planning.

Guillaume Mauger from the University of Washington (UW) reviewed past and future temperature changes for the northwest and projected changes in snowpack, streamflow, heavy rainfall, and sea level rise. He also discussed considerations for supporting climate-resilient decision-making based on 25 years of experience at UW's Climate Impact Group.

Naomi Goldenson from the University of California, Los Angeles discussed the reasons for simulating climate—to better understand regional processes, to evaluate and improve simulations, and to plan via data applied to climate impact assessments. She reviewed process-based rankings of global climate models for the western United States and shared that even with better-performing global climate models, there are still a range of possibilities (e.g., uncertainty). Naomi also shared a tool called the Cal-Adapt Analytics Engine, which provides climate analysis tools for the state of California.

3.3 Industry Panel: Resilience Activities and Needs

The first panel during the workshop featured three industry experts, moderated by **Uzma Siddiqi** from Seattle City Light. Each of the experts shared resilience activities that they/their organizations are involved in and needs regarding advancing/improving their resilience to climate change.

Andrea Staid from the Electric Power Research Institute (EPRI) provided an overview of the Climate Resilience and Adaptation Initiative (Climate READi). She shared that immediate action toward addressing climate change was warranted because it can significantly reduce damages and avoid rapid increase of costs. She reviewed the three Climate READi workstreams and activities taking place within each and highlighted Climate READi members and the Climate READi affinity group. Andrea also highlighted EPRI's Physical Climate Data 101 training, the first training in the Climate 101 series, which can be used as a resource for all workshop attendees.

Patti Metro from the National Rural Electric Cooperative Association (NRECA) highlighted NRECA's Natural Hazards Consortium and their work to integrate technology, people, and process upgrades to better recover from and respond to events. She highlighted the assistance provided to members during such events, such as meals, tent cities, laundry service, and mobile showers. Patti shared that the Natural Hazards Consortium is seeking solutions that enable information sharing and collaboration to address common problems across all-hazards planning, risk assessment, and damage mitigation projects.

Heide Caswell, representing her role on the Institute of Electrical and Electronics Engineers (IEEE) Distribution Reliability and Distribution Resilience working groups, shared plans for an IEEE 1366/1782 equivalent that is focused on resilience metrics and approaches, similar to the reliability of standard and guide support distribution. She noted that the resilience guide should be utility, vendor, and technology agnostic so that it can be adopted broadly.

3.4 Infrastructure Investment and Jobs Act

A summit session was held on incorporating climate change into funding decisions that focused on federal resilience funding.

As part of the IIJA, the Department of Energy Grid Deployment Office is administering $13 billion in grid resilience and innovation partnership grants over the next five years. These include grid resilience utility and industry grants, state formula resilience infrastructure grants, smart grid grants, and grid innovation program grants. Each of these grant funds target different sectors or actors and are focused on a variety of funding opportunities. These opportunities range from direct investment in transmission and distribution technology solutions that mitigate extreme weather events, to smart grid technologies that increase the flexibility, efficiency, and reliability of the power system, to deployment of projects that use innovative storage and distribution infrastructure approaches to enhance grid resilience. These funding opportunities are found in Sections 40101, 40103, and 40107 of the IIJA.

In particular, Section 40101d describes $2.5 billion over five years in state formula grants that states and tribes can use for investment in many aspects of system resilience, such as hardening of power lines, undergrounding equipment, weatherization technologies, fire prevention systems, monitoring, vegetation management, and modeling technologies. Because many state agencies and commissions are implementing new policy directives, this resilience grant funding can be used to augment existing state resources to find new innovative approaches to electricity system modernization and responses to climate change threats. These programs raise questions about how to optimize use of this funding either by each state individually or by partnering with other states to address regional threats to the electricity system and interstate resilience investment opportunities.

Participants discussed the pros and cons of multi-state or regional cooperation in both applying for grants and deploying grant resources. Some state agency participants suggested that the agencies are currently stressed with workload and did not have the internal resources to develop partnerships during either the application or deployment planning phases. Others found the idea of partnering to be a useful conversation because risks to the system do not necessarily recognize utility system or state boundaries and regional risks might be best addressed by regional solutions.

3.5 Utility Panel: Resilience Activities and Needs

The second panel, which kicked off Day 2, featured four utilities and was moderated by **Jeff Dagle** from PNNL. Each presenter shared resilience-specific activities at their utility and barriers that they are facing.

David Logsdon from Seattle City Light highlighted what the utility is doing to tackle inequity and injustice in their communities, noting disproportionate climate harms that disadvantaged communities face. He highlighted their Climate Change Adaptation Program, which issued Seattle City Light's first comprehensive adaptation plan in 2015. Their vulnerability assessment tied climate stressors to utility functions, demonstrating that most stressors affected transmission and distribution. Finally, David shared some of the resilience projects that Seattle City Light is undertaking or considering undertaking.

Dmitry Kosterev from the Bonneville Power Administration discussed the multiple horizons they are considering: planning, operational planning, and real time. He discussed a few recent extreme events, such as the June 2021 heat dome, the 2021 Bootleg Fire, and the 2020 Beachie Creek Fire. Finally, Dmitry highlighted how decarbonization and electrification will require higher reliability of electric power service going forward.

Eric Kuhle, on behalf of **Brenna Mahoney**, from Pacific Gas & Electric (PG&E) discussed how more frequent and severe natural hazards driven by climate change are affecting PG&E and their customers. He described their need for a robust strategy to address risks while further developing the energy system of tomorrow in a way that will be affordable to their rate payers. He shared progress on PG&E's Climate Vulnerability Assessment and Community Engagement Plan, and highlighted Menlo Park as a case study for demonstrating how utilities can participate in regional climate resilience planning.

Stephen Torres from Southern California Edison (SCE) shared their three-pronged approach to climate-informed energy system planning. This included regulatory compliance with Climate Adaptation Vulnerability requirements, reflecting climate projections in electric sector planning, and community/local jurisdiction collaboration to arrive at a common understanding of climate change impacts. He shared the progress and key findings from SCE's Climate Adaptation Vulnerability Assessment, the first of its kind in California. SCE found that the cost to invest in climate adaptation now is far less than the cost of inaction, so they have established a plan for proposing a set of near-term adaptations in their next General Rate Case. Finally, Stephen shared SCE's next steps, which include incorporating climate projections into design standards for equipment and key planning processes.

3.6 Climate Research for Resilience to Hurricanes

Two PNNL researchers provided an overview of hurricanes, related challenges, and research advances and tools to better project and prepare for hurricanes.

Karthik Balaguru indicated that hurricanes are among the deadliest and costliest natural hazards that affect the North and Central American regions. He highlighted the observed increase in hurricane intensification near the U.S. coast, and that models simulate ocean warming, more moisture in the atmosphere, and changing winds as contributing factors to that intensification. Karthik explained how PNNL's Risk Analysis Framework for Tropical Cyclones can generate large ensembles of synthetic hurricanes, coupled with climate models, to project hurricane risk into the future.

Marcelo Elizondo focused on the challenges faced in Puerto Rico, where the electric grid needs significant work to become more resilient and cleaner. He highlighted a tool developed by PNNL specifically for Puerto Rico, called EGRASS. The analytical, web-based geospatial tool enables real-time decision support and identification of critical facilities at risk and probability of failure, as well as of critical electrical infrastructure at risk. Marcelo noted that LUMA Energy, the utility in Puerto Rico, has validated and adopted EGRASS.

3.7 Research Panel: Climate and Weather Extremes for Resilience

The third panel of the workshop, also on Day 2, featured four climate researchers and was moderated by **Ronda Strauch** from Seattle City Light. The panelists each shared ongoing research activities at their respective organizations.

Ruby Leung from PNNL highlighted the Energy Exascale Earth System Model (E3SM), which couples Earth system science with computational science to provide high-resolution modeling of extreme weather events in a changing climate. It addresses three science drivers: water cycle changes and impacts, human–Earth system feedbacks, and polar processes, sea level rise, and coastal impacts. Ruby also highlighted how decarbonization (emissions reduction) can limit extreme weather events, and how coupled human–Earth system models can explore decarbonization scenarios and their regional impacts. PNNL is, for example, coupling E3SM with the Global Change Analysis Model (GCAM) to simulate the interactions between the energy system, water, agriculture and land use, the economy, and the climate.

Jean-Paul Watson from Lawrence Livermore National Laboratory discussed infrastructure modeling for system resilience and how the goal is to enable decision-making for infrastructure operations and planning to obtain defensible resilience improvements. He highlighted stochastic programming as a multi-stage investment planning model and reviewed why consideration of uncertainty is critical when planning for resilience. Jean-Paul identified the grand challenge as "data," and noted the need and challenges associated with feeding capacity expansion models with climate data. He reviewed the climate-to-infrastructure data pipeline, where climate models lead to bias correction and downscaling models, which leads to impact models, then to infrastructure models, and ultimately to informing decisions.

Grant Buster from the National Renewable Energy Laboratory (NREL) focused on renewable energy integration studies, such as LA100 and the National Transmission Planning Study, and how they fit together with climate change data to inform the renewable energy transition. He discussed how downscaling with generative adversarial networks (GANs, a form of machine learning) produces high-quality wind and solar data at a fraction of the cost of traditional dynamical methods. He highlighted NREL's Super Resolution for Renewable Resource Data (sup3r) software, which uses GANs to create high-resolution spatiotemporal data from coarse low-resolution global climate model inputs.

Daniel Kirk-Davidoff from EPRI highlighted that correlations between renewable generation and extreme heat/cold exist, but that they are generally weak enough that the accumulated load is not much different from what would occur with an equivalent amount of baseload generation. Daniel also highlighted EPRI's climate data repository.

3.8 Incorporating Climate Change into Investment Decisions

A special session on Day 1 focused on incorporating climate change into investment decisions. Current climate investments in the energy area are targeting the transition of today's system to a clean energy infrastructure. Although today's investments have reached high deployment numbers for wind and solar deployment, even higher rates of deployment must be reached and sustained to achieve net-zero emissions by mid-century.

The majority of current climate investments go toward mitigation (90–95%), with only 5–10% going toward adaptation to make our energy infrastructure, homes, and buildings more resilient. With increasing climate investments in wind/solar/storage technologies and in electrifying transportation, buildings, and industry, we have unique opportunities to build more clean infrastructure, homes, and buildings that are inherently more flexible and resilient. There will be copious opportunities for win/win situations in which distributed generation technologies provide not only a replacement for fossil-based technologies but also additional flexibility for end users to respond to extreme climate conditions. The opportunities lie not only in matching the right technologies for improving resilience but also in looking for institutional opportunities to work across local–regional jurisdictional boundaries for more overall operational coordination and market flexibilities.

3.9 Policy and Government Panel

The final panel, occurring on Day 3, consisted of three representatives from state organizations and was moderated by **Alan Cooke** from PNNL. Each representative provided an overview of resilience efforts their organizations are involved in and highlighted key challenges in the states they represent.

Heide Caswell from the Oregon Public Utilities Commission (OPUC) shared details on OPUC's investigation into resilience. She noted that House Bill 2021 required OPUC to establish resilience standards guidelines. OPUC engaged with the national labs via the Department of Energy's Grid Modernization Laboratory Consortium to evaluate the landscape toward establishing these guidelines. They found that no standards for resilience currently exist and that many approaches are being explored in a wide variety of venues. Heide noted the greatest challenge faced is balancing cost with resilience.

Jessica Tse from the California Public Utilities Commission (CPUC) presented on California's grid resilience and microgrid regulatory opportunities. She noted that in 2018, Senate Bill 1339 required that CPUC undertake activities to develop policies related to microgrids by December 2021. She discussed activities in California, including tariff and rule changes, incentive programs, and utility process improvements. She noted that the anticipated $200M Microgrid Incentive Program is intended to fund clean energy microgrids to support the critical needs of vulnerable populations affected by a grid outage to support resilience.

Eli King from the Washington State Department of Commerce (WA DOC) shared that the mission of WA DOC's Energy Resilience and Emergency Management Office is to deliver comprehensive and sustainable emergency management, resilience development, and cybersecurity services for the energy sector and Washington State's residents. She noted that their first strategic priority is building energy-resilient communities and that their resilience planning starts with a hazard-risk assessment and ends with prioritization resilience solutions. Eli noted the criticality of funding sources in implementing these solutions.

4.0 Current Grid Resilience to Climate Landscape

The workshop participants were asked to identify what is currently working well in terms of resilience to climate extremes and what the biggest challenges are that our country, or their organization, faces today.

4.1 Resilience to Climate: What is Working Well?

At the start of the workshop, participants were asked to identify what is working well regarding grid resilience to extreme events and climate change. Below is a summary of their responses.

- People are beginning to pay attention
- Risks and needs are becoming clearer
- In general, we have a very reliable grid with high resilience to today's events
- There is an increasing focus on equity in dockets, planning, and conversations on power system resilience
- There are many dedicated individuals wanting to do the right thing
- More resources are becoming available to support grid resilience
- Some utilities are making significant progress in climate adaptation planning
- There is a significant amount of data available
- Researchers/scientists and engineers/utilities are starting to talk
- Existing utility mutual aid agreements are working well
- Some collaboration and information sharing is starting to happen.

4.2 Resilience to Climate: What are the Biggest Challenges?

Workshop participants were asked to identify the biggest challenges when it comes to planning for grid resilience. Below is a summary of their responses.

- **Many things are changing simultaneously**, which increases complexity and difficulty. There is a type of coevolution happening with changes to the power grid (more weather-based, intermittent, inverter-based resources), electric vehicles, and climate.
- **Managing the interdisciplinary nature of the problem** requires communicating and working across siloes, including the climate scientists and grid resilience planners and engineers meaningfully integrating climate data into the planning process.
- Developing **fresh thinking and approaches on cost-benefit analysis** and valuing resilience in a holistic manner.
- The overall **complexity of the planning process** including prioritizing resilience approaches and investments.
- **Standards are needed** to guide the appropriate selection and use of data for grid resilience.
- **Funding is needed for resilience investments** at utilities. There are many competing funding needs at utilities.

- **Catalyzing decision-making and trying new things**; moving beyond talking to adoption and investments.
- Meaningfully **addressing social equity** to make sure no communities are left behind.
- Skilled and experienced **human resources** are needed that can actively address resilience holistically.

5.0 Vision of an Electric System that is Resilient to Climate Extremes

The workshop participants were asked to envision an electric system that is resilient to climate extremes while discussing the time horizon of resilience, how future threats will be different, and the characteristics of a truly resilient electric system. The sections below summarize their input.

5.1 Time Horizon of Resilience

Summit participants discussed the time horizons for resilience. Time horizons included same-day concerns, the next fire season, the next 2–5 years (of particular interest due to federal infrastructure dollars), the next 10–20 years (typical planning cycle for utilities), a 40-year horizon for Federal Energy Regulatory Commission (FERC) licenses, the nest 20–50 years to evaluate impacts of sea level rise, and finally the next seven generations for long-term sustainability and potentially for things like habitat recovery. Time horizons for resilience can vary based on whether the asset horizon or the threat horizon is being considered. Sometimes these will line up, and other times they will not. Different time horizons need to be considered together. For example, many investments are being made now based on decarbonization goals and the need to achieve short-term reliability. However, investments made now must outlast decarbonization goals and provide longer-term resilience 40 to 60 years in the future. In summary, the time horizon for resilience depends on many things, including how resilience is defined, whether the asset or threat time horizon is being considered, and the perspective being taken. It was also noted that in a practical sense for investments, the time horizon for making resilience investments is “as fast as you can afford it.”

5.2 Future Threats

Workshop participants discussed that there will be more extreme events and that threats will be less predictable. Impacts will become multidimensional across sectors, and more facets of life will be affected (e.g., electricity, water, and transportation). There may also be an increase in **cascading, compounded, and sequential threats with overlapping impacts that could be happening faster**. Categories discussed include impacts to essential services that keep people alive, impacts to commercial benefits and operations, and impacts to convenience. From an insurance company or financial investor perspective, significant customer impacts are a future threat.

Specific threat categories mentioned include cyber; earthquakes; loss of snowpack; temperature extremes; wildfires; landslides and sediment issues; fish and wildlife issues, including loss of fisheries; droughts, including increasing probability of back-to-back droughts; flooding and intense rain events; smoke; and demographic shocks. Some suggested that there may be threats, such as volcanoes and major earthquakes, that we cannot build for.

Other perspectives shared include the idea that our solutions of today may be a threat for tomorrow due to unintended consequences. Another concern is that people may take things into their own hands, with personal generators and battery systems. This could lead to nonuniform reliability and equity challenges. It was also suggested that if the grid is updated with flexibility and adaptability, it could be that threats today may not be threats tomorrow, and there could be less vulnerability to certain threats.

Finally, future threats could include competition for money and resources. If climate change creates major disruptions in multiple areas or sectors, it could be difficult to obtain funding needed to increase the resilience of the power system. This points to the importance of acting now or in the near future to increase grid resilience, particularly given the availability of federal infrastructure dollars.

5.3 Characteristics of a Resilient Electric System

Workshop participants brainstormed the characteristics of a resilient electric system. Key points developed are summarized below.

- **Diversity of resources**, including the types of resources and technologies and the location of resources.
- **Redundancy in supply, assets, and provision of services.** Redundancy will support robustness to both rare climate events and supply chain disruptions.
- **Adaptable, flexible, reconfigurable/self-healing, and modular** systems that can bring/send emergency resources to where they are needed and that can possibly fly batteries or generators to those locations. The system should also adapt to and learn from trends, be adaptable and flexible in both power supply and delivery, and be adaptable to changing conditions.
- Clear and regular **communications with customers** and **clear expectations** as a community about what resilience should be and what key thresholds are. Strategic communications should be well established, including education and transparency.
- Understanding of **customers with specific needs** for reliability and resilience and mechanisms for providing both.
- **Coordination** between utilities, local government, land agencies, and first responders to mitigate impacts. Recognition that resilient communities are needed and not just a resilient grid. Utilities can be a good avenue for collaboration. Clear roles are established for different participants in times of emergency events and mechanisms are put in place to prioritize where power goes. Account for risks due to social unrest.
- **Equitable and affordable.** Social impact—“bounce back for all.” A system that considers social impact as part of resilience, with metrics such as affordability, “bounce back for all,” and back up for critical societal services.
- Ability to deal with and **accommodate uncertainty.** The system should be ready for surprises and have flexible and adaptive approaches. It can prioritize in the face of uncertainty. System infrastructure is robust to many different potential futures, and probabilistic planning should be used across broad areas of uncertainties. Mechanisms are in place to prioritize where power goes, particularly during events.
- **Employee preparedness and redundancy—experienced people run the system.**
- **Rapid recovery and failsafe modes of operation**. The system is able to recover quickly. Access to necessary equipment during events is prioritized (such as wildfires, where heavy equipment access may be limited due to fire risk).
- Clear **definitions and metrics**.
- **Oversee ability, observability, and visibility**—individuals running the system can see what is happening and what is needed.

6.0 Moving Toward the Vision

With a clearer picture of the landscape and vision, workshop participants broke into groups to both share and discuss how we get to the vision. They shared existing approaches and information, determined what was missing, and identified approaches for filling the gaps.

6.1 Climate-Extreme Characterization for Energy Systems

Breakout Group 1 discussed existing approaches for climate-extreme characterization for energy systems, as well as what is missing and approaches for filling gaps. Results from these discussions are summarized in the sections below.

6.1.1 Existing Approaches and Information

Existing datasets for characterizing different types of hazards were summarized as follows.

Wildfire: Cal-Adapt, Technosylva, the Climate Toolbox (Oregon State), land surface models, the Fire Weather Index, the National Oceanic and Atmospheric Administration (NOAA) High-Resolution Rapid Refresh, machine-learning approaches using environmental parameters from reanalysis and models (currently too coarse for utilities, but can be used for burned areas as well as smoke), and LENS for shorter-term projections (e.g., decadal scale).

Flood: Hydrological modeling, national-scale models, Fathom (data), next-generation intensity-duration frequency curves, dynamically downscaled Weather Research and Forecasting Model, Delta Stewardship Council, probable maximum precipitation, and probable maximum flood.

Hurricane: High-resolution climate models, hybrid/surrogate models.

Drought: Reservoir operations models, water scarcity maps and grid impact factors, the National Integrated Drought Information System, and basin-scale water management models.

Temperature: National Aeronautics and Space Administration Earth Exchange data (bias-corrected global climate model data).

General: ERA5, the Coupled Model Intercomparison Project, the Energy Exascale Earth System Model (E3SM; available from the Earth System Grid Federation), the Federal Emergency Management Agency (FEMA) National Risk Assessment, and statistical–dynamical models.

6.1.2 What is Missing?

The following were identified as missing relative to climate-extreme characterization.

Improvements in characterization of climate events were identified during the discussion. These gaps included:

- The need to better understand the potential for **sequential extremes,** such as floods after floods or drought followed by flooding, in future climates.
- Improved approaches to **characterize snowpack** information for use in determining flood modeling.

- Development of **detailed wind data at regional scales** and appropriate vertical scales to support renewable resource adequacy studies, but also to **ensure physical consistency** across multiple climate variables (e.g., wind and temperature).
- Methods and mechanisms for continuously or regularly **monitoring initial conditions** that are necessary to develop accurate forward projections at both weather and climate time scales, in addition to more continuously updating **decadal predictions** to provide information relevant at infrastructure planning time scales.
- Standards for the **validation of datasets**, including providing potential users an understanding of strengths and weaknesses of available climate datasets and appropriateness for use in climate-energy studies.
- Quantification of model biases and robust **characterization of climate model uncertainties** to better inform stakeholders in decision-making processes**.** This also includes developing deeper confidence in and understanding of surrogate model use in the development of climate-extreme information.
- Broad utilization of **storyline approaches** to enhance researcher–stakeholder collaboration and exploration of combined climate and human behavior uncertainty.

Improvements in the ability to quantify the impacts to human systems, and specifically energy systems, were identified. The gaps discussed included:

- Partnerships with utilities to **train impact assessment models**. Models that address impacts to human systems are based on past observations. For example, fragility estimates of the electric power systems are based on observations of damage from past events. Partnership with utilities and access to utility-based observations will improve the ability to improve impacts and enhance resilience.
- **High-resolution, high-quality** renewable resource, land-use bio-carbon capture, and public **load-growth data** to facilitate development of future decarbonization strategies.
- Research on potential climate-extreme **mitigation solutions** (engineered mitigation, operational mitigation, etc.) for a range of extreme events, including a deeper understanding of the unintended consequences of mitigation strategies.
- Understanding and **characterization of human behavior** relative to weather extremes. For example, how will human response to climate extremes influence infrastructure resilience?
- Mechanisms to **monitor urbanization** and improve the ability to capture current and future impacts from extremes, in addition to quantifying the contribution of urbanization to changes in extreme events.

6.1.3 Approaches for Filling the Gap

- Breakout Group 1 identified the following approaches for filling gaps identified in Section 6.1.2.
- Develop validated and consensus dynamical downscaling methods for extreme events.
- Fund open-source public data and tools.
- Develop data accountability methods.
- Develop **bands of outcomes** with a **focus on extremes** and key thresholds.

- Develop and agree upon a **methodology for defining climate-informed extreme events** that leverages historical analogs with climate predictions for scientifically sound storylines.
- Develop automated data-mining techniques for finding storylines and extremes in climate ensemble data.
- Develop **generative machine learning for downscaling extreme weather generation**, potentially in combination with satellite data, if utility data is not available.
- Advance and refine storyline research with utilities and stakeholders.
- Develop and share additional guidelines on use of climate datasets.

6.2 Infrastructure Resilience Modeling

Breakout Group 2 discussed existing approaches for infrastructure resilience modeling, as well as what is missing and approaches for filling gaps. Results from these discussions are summarized in the sections below.

6.2.1 Existing Approaches and Information

Existing approaches identified for infrastructure resilience modeling include, but are not limited to, the following:

1. **Process downscaling and mapping** – An example of this is understanding how decadal wildfire problems shifted and were overlayed on GIS maps of transmission lines. They were then converted to N-k contingency events. Some utilities have looked at three different generation plant retirement scenarios and combined those with wildfire scenarios and checked the risk. Firm capacity was then added to the system to mitigate risk.
2. **Use of fragility data** – Using fragility data was identified as an existing process but was also identified as a gap. Performance degradation assessment approaches are currently developed based on expert opinions, and assumptions may change with changes in weather patterns.
3. **Use of an investment tool** – Washington State energy commission has developed a Washington State energy assessment tool. Although the tool is not publicly available, the maps are available to the public. Three public utilities are working on the tool and the maps.
4. **Considering social burden in resilience models** – Some utilities are looking at social burden as part of their resilience analysis. An example tool is ReNCAT (the Resilient Node Cluster Analysis Tool) by Sandia National Laboratories. Other utilities have tools they have developed for this purpose. One metric in these tools is proximity to services.

6.2.2 What is Missing?

Breakout Group 2 identified the following gaps.

1. **More science-based fragility curves** – It was noted that infrastructure impact data from climate change is nearly impossible to obtain.
2. **Representing impacts across fields**, such as impacts of wildfire smoke on reduction of solar production.

3. **Access to existing data** – The lack of widespread availability of model data for the community hampers innovation. For example, the North American Energy Resilience Model (NAERM) has aggregated a tremendous amount of data, but no one outside of the NAERM team can use it.
4. **Consistency across modeling of uncertainties** – Subject-matter-expert-based scenario modeling is one way to address this, but scenario modeling includes many assumptions that can limit applicability. As an example, there are 39 worst-case scenarios for the Cascadia subduction zone earthquake event. The choice of scenario will affect results and decisions. Conversely, large-scale Monte Carlo style runs are impractical.
5. **Standards around asset designs and the codes** – Resilience standards are needed. However, standards and codes are developed by many different organizations, and consolidation is a time-consuming and evolving process. Therefore, people do not know which ones to follow. There has also been a lack of progress in legislation or regulation related to standardization in the energy sector.
6. **Understanding and assigning value to resilience**, considering financial and non-financial aspects, consumer needs, and regulatory applications.
7. **Restoration models** – Most existing restoration models are based on historical representations of how long it took to restore power. Traditional metrics are very difficult to use for climate change resilience planning.
8. **Ways to characterize, forecast, or model supply chain shortages.**
9. **Forecasting upcoming technologies** and their capabilities.
10. **Granular load** forecasting – Load forecasting is increasingly needed at the feeder-by-feeder or substation-by-substation level, particularly when considering deep electrification scenarios. This needs to be developed in a bottom-up way as opposed to top-down way, the latter approach being the one that utilities have usually taken. Granular forecasts are needed from a GIS standpoint.
11. **A comparative assessment framework** to identify which mitigation is better than the others.

6.2.3 Approaches for Filling the Gap

1. Fill data gaps and develop methods for linking diverse datasets—there are approaches, but they are not very case specific.
2. **Develop synthetic grid system models for resilience as we have for reliability.** These need to be multidisciplinary, forward-looking, and longer than a 5-year planning horizon. Use these for tool development solutions.
3. **Update and evolve existing metrics and standards**. Standards are currently being updated in Washington. Standards need to be created at a national scale that can then be referenced and adopted by individual states rather than making/designing standards themselves. FEMA may be a good route for developing standards that could then be adopted under building codes.
4. Institute a collaborative spares program to tackle supply chain shortages.
5. **Institute multi-hazard modeling** that is highly regionally specific.
6. **Institute multiagency collaboration and modeling**. Integrate modeling with other planning entities and infrastructure sectors for evaluation of interdependencies and co-benefits.

7. **Conduct asset sensitivity characterization**. Start from understanding vulnerabilities today. Work with the manufacturers on ways to mitigate emerging fragilities.
8. **Upgrade existing supervisory control and data acquisition systems and environmental management systems** to improve information availability and reporting.

6.3 Investment Planning and Decision Support

Breakout Group 3 discussed existing approaches and information for investment planning and decisions support, as well as what is missing and approaches for filling gaps. Results from these discussions are summarized in the sections below.

6.3.1 Existing Approaches and Information

Existing approaches and information sources for investment planning and decision support in an uncertain climate include, but are not limited to, the following.

- **Electric utility Integrated Resource Planning (IRP) processes** allow for analyzing different risk scenarios. A public process is frequently required and allows stakeholders and members of the project to test utility assumptions and provide input.
- Investor-owned utilities **file rate cases** to recover capital costs associated with utility investments.
- **Electric distribution system plans (DSPs)** are used for planning distribution system investments. It is likely that resilience will become increasingly important in these plans, and many states are adding increased requirements for scenario analysis and transparency.
- **Legislation and regulatory directives to address a certain threat**. In some states, legislatures or regulators require utilities to plan for certain threats such as wildfires or hurricanes. In some cases, favorable cost recovery (outside of a general rate case) is associated with these plans.
- **Transmission planning** starts with load forecast and looks at resources and additions needed to achieve a particular performance. NERC reliability standards are used here. FERC identifies three types of transmission projects: reliability, economic, and policy-driven projects. Projects that support resilience may fit into the reliability category.
- **Regulator- or legislature-required climate vulnerability assessment**. Plans must be filed to address climate risks and vulnerability. Regulator requirements specify which risks must be considered.
- **Centralized datasets to use as the basis for climate vulnerability planning** - In California, utilities must plan their Climate Adaptation and Vulnerability Assessment to an established set of criteria. Centralized data is available on what utilities are planning for, in terms of fire, flooding risks, wind gusts, and temperatures. All utilities have the same data and direction and a common vocabulary that can be used to communicate to non-energy partners like land-use agencies.
- **After-event reviews**. In many cases, there is a technical review of past occurrences where a root cause analysis is conducted that examines how facilities performed during an extreme event.

6.3.2 What is Missing?

Breakout Group 3 identified the following items that are missing relative to investment planning and decision support in an uncertain climate.

- **Standards and datasets.** Climate is not integrated into technical standards, including design standards that are typically developed utility by utility. The exception to this may be California, where Cal-Adapt includes common data and risk profiles. There is no agreement on baseline and extreme standards.
- **No common definitions and language**. In most cases, there is no common language, including for extremes and acute disruption events. There are no local community definitions of risk.
- **Regulator guidance**. In most jurisdictions, there is no regulatory guidance on how utilities must or should plan for climate variability. Regulators are not clear on how to manage increasing risks and long-term resilience investments.
- **Understanding coming climate extremes**. Engineers at utilities do not understand the climate extremes that are coming. There is no education or training about the wave of investments needed or the increasing operations challenges of increasing penetration of variable renewable resources.
- **Money and human resources.** Both money and human resources are stretched. There are issues of aging infrastructure and questions of how to make all the investments at the same time. There are also utility human resource issues with lack of experience, high turnover, and high staff vacancy rates.
- **Supply chain certainty.** Uncertainty exists around the equipment supply chain.
- **Input from customers and communities**. There is a lack of input from customers and communities about what is important to them on resilience.

6.3.3 Approaches for Filling the Gap

Breakout Group 3 identified the following approaches for filling gaps relative to investment planning and decision support in an uncertain climate.

- Develop and share **a guide to best practices or a standardized framework** for long-term resilience assessments, planning, and investments under climate change. Include an assessment of the cost of doing nothing.
- Get **agreement on definitions** for baselines and extremes for technical standards.
- **Develop updated standards**, including:
  - **Risk-informed engineering design standards** for different stress levels including peak and acute extremes. Develop a framework for how to update design standards.
  - **Bulk system reliability standards** with data about risks and criteria about probabilities and consequences. NERC is developing a cold weather standard that they have recently transitioned to an extreme weather standard.
  - **Reporting standards for utilities** so that assumptions, analyses, and costs are more transparent, possibly through IRPs and DSPs. Could be something like California's Risk Assessment Mitigation Phase process reporting.

- Designate a state-level entity **to develop and share centralized datasets and risk maps** for fire, flood, wind gusts, and temperature extremes, like Cal-Adapt. Potentially develop a national dataset that can be used in this way and that can be adapted to needs of individual states.
- **Develop a menu of risk mitigation solutions/strategies** that can be applied to different risks. Include plans for how to address extremes. Strategies could be organized into something like a food pyramid of resilience/climate change planning.
- **Revisit regulatory prudence for long-term climate change planning.** It may not be appropriate to use the same prudence determination basis for multidecadal investments that specifically target resilience, as used for traditional investments. Find best practice examples of how prudence can be best applied for resilience investments.
- Establish **regional coordination of pathways and strategies** that go beyond state-by-state pathways and include interstate dynamics for weather, renewable energy, emergency response, etc.

7.0 Partnerships

In this section, participants discussed communication channels and partnerships that could be established or expanded to advance electric system resilience with climate uncertainty. The primary categories of organizations discussed include utilities, vendors/financing, research, government, and other. The subsections below describe coordination actions associated with each entity type. Figure 1 illustrates needed partnerships and coordination pathways to support electric system resilience to extreme events.

Figure 1. Necessary Partnerships and Coordination for Resilience.

7.1 Utility

Partnerships and communications related to utilities that could be instituted or expanded include the following.

- Utilities **communicate to customers** what the utility is doing for grid resilience. The utility should also be getting input and suggestions from customers on resilience needs and investments.
- Utilities **communicate to researchers/scientists** about how research can support data needs. Researchers can communicate the availability of datasets and resources and advise on their applicability and how they might be used.
- **Utilities (and researchers and government/academia) engage with students** and future workforce members to tell them about opportunities in meaningful work in power and climate science and work with educators to create new education opportunities.
- **Utilities share info with manufacturers and venture capital** about problems utilities are trying to solve regarding grid resilience to extreme events.
- **Departments within utilities** coordinate more about climate needs and solutions.
- **Utilities work with investors and insurers** to align on the risk measurement framework and how to direct capital to reduce climate change risk.
- **Utilities work with state government, NERC, and researchers** to create standardized prescriptions for natural disaster risk mitigation (like a McKinsey greenhouse gas reduction curve of resilience investments for different risks).
- Utilities share data (potentially under nondisclosure agreements) with researchers to help them develop better infrastructure assessment models.
- **Utilities talk to government entities** about the meaningful legislation and regulation to provide needed climate data and information and to guide and prioritize resilience investments.
- **Utilities work with tribes** to codevelop energy solutions that benefit tribes and the environment.

7.2 Research

Summit participants brainstormed the following researcher/scientist-led partnerships or communications that could be instituted or advanced.

- **Researchers coordinate with utilities** to better understand data needs, including:
  - Risk categories/climate change topics and spatial and temporal granularity for needed data and information.
  - Needs for representing operations and operational changes in modeling.
  - Climate models and electrification data needed.
- Researchers consider developing a climate modeling forum with utilities.
- **Utilities provide researchers feedback** on datasets, metrics, and their applicability so that researchers can better support decision-making, infrastructure planning, and investments.

- Researchers and infrastructure modelers coordinate with regulators to better represent policy in future modeling.
- Researchers share results with governments for specific regions, including talking to city governments about best practices for urban heat mitigation. For example, in Washington, researchers present to the Joint Energy Supply Committee about climate impacts on utilities and supply chain challenges.
- **Researchers publish climate change datasets for renewables** that can be useful for utilities and government entities.
- **Cross-research team collaborations** build on each other's research and prevent duplication.

7.3 Policy/Government

Summit participants brainstormed the following policy/government-led partnerships or communications that could be instituted or advanced.

- **Federal government** entities, including Department of Energy (DOE) and **state government entities, provide research funding** to support energy resilience.
- **National labs present information to DOE and FEMA** about the need for creating national standards.
- **National labs communicate needs,** opportunity space, and best practices **to the policymakers.**
- **Labs coordinate with utilities** on new metrics and standards and then go to **policymakers** to implement in states.
- **Public utility commissions connect with each other** and relevant Canadian regulators.
- **Utilities talk to government entities** about needs, financing, cost-sharing opportunities, the need for requiring and creating clear standards, and realistic challenges of implementing policy goals.
- **Different government and policy organizations collaborate** to ensure that everyone's swim lanes are clearly articulated and "deconflicted" and, where possible, to identify mutually beneficial partnering opportunities. Specific ideas include:
  - Coordinating across state agencies
  - Conducting interagency coordination at the federal level and identify who does what (DOE, Department of the Interior, the Environmental Protection Agency, NOAA, USDA)
  - Making presentations and sharing information between DOE offices
  - Coordinating various city and utility upgrades and investments. For example, coordinate road construction/reconstruction with water system upgrades and undergrounding powerlines.
- **FEMA, NOAA, and state governments align** to create risk maps and framework for natural disasters.

- **Government entities and policy makers** coordinate with utilities on regional development.
- **Utilities share their needs with DOE** and other government offices.

7.4 Vendors/Financing

Summit participants brainstormed the following vendor/financing-led partnerships or communications that could be instituted or advanced.

- Researchers and utilities talk to component manufacturers about changing design needs and building in flexibility.
- Innovative **utilities tell vendors** what they need.
- **Vendors coordinate with government** and policymaking bodies to understand and address policies around global supply chain issues. How can government help with supply chain issues?
- **Researchers talk to investment communities** about spin-off companies in tool development for risk assessment.
- Vendors and financing organizations help utilities better understand project cycles.
- **Consultants can lend expertise to utilities** on how to incorporate climate projections into planning processes effectively.
- **Bring insurance companies** into conversation with researchers/government.

7.5 Other Organizations

In discussing partnerships and coordination for resilience to extreme events, summit participants identified the following other organizations who could be important parts of resilience solutions.

- Communities and community-based organizations
- Media for transparence, education, and expectations
- Credit-rating agencies
- Health departments
- Communications specialists
- Churches.

8.0 Conclusions

The Grid Resilience to Extreme Events workshop was held to develop a vision for addressing climate extremes that includes improved forecasting and characterization, infrastructure resilience modeling, and investment planning and decision support.

Participants joined the workshop hoping to walk away with, among other things, a better understanding of the latest climate change and extreme weather science and how it can be used for grid planning; the needs of electric utilities for climate change data; the latest metrics for grid vulnerability and resilience; policies needed to address climate change and extreme events; and future potential research directions. Participants also hoped to walk away with new relationships, connections, and paths for future collaborations and partnerships.

Key takeaways from the workshop include:

- The need for new/more research and utility partnerships centered around climate dataset availability. Utilities need to understand from researchers what datasets are available, and they need guidance about how to use these datasets for planning.
- Regional “sandboxes” are key and are needed to support utility and researcher partnerships. These sandboxes could offer a platform where stakeholders can come together to share models and data and to coordinate support for future planning.
- Policymakers and regulators can help utilities prioritize their resilience efforts. Despite the natural friction that exists between regulators and utilities, regulators can be a key differentiator by supporting and guiding utilities on their resilience investments and priorities.
- There is a strong need and opportunity for multifaceted partnerships and collaborations between utilities, researchers, policy and government entities, vendors and equipment manufacturers, and communities/customers, as illustrated in Figure 1. Figure 1 can be used as a road map for future work and engagements in this space.

Finally, workshop attendees expressed a clear desire for more workshops, forums, and engagements where they can continue to learn from one another and collaborate on resilience practices.

9.0 References

Summit participants shared the following resources with other attendees.

Seattle City Light

- Seattle City Light's Increased Electrification Assessment: https://powerlines.seattle.gov/2022/01/20/planning-for-an-electrified-future/
- Seattle City Light's Climate Change Vulnerability Assessment and Adaptation Plan: https://www.seattle.gov/city-light/energy-and-environment/environmental-stewardship/climate-change-response (scroll to bottom of page)

NREL

- Overcoming the disconnect between energy system and climate modeling: https://www.sciencedirect.com/science/article/pii/S2542435122002379
- NREL's The Evolving Role of Extreme Weather Events in the U.S. Power System with High Levels of Variable Renewable Energy: https://www.nrel.gov/docs/fy22osti/78394.pdf

RMI

- RMI's Utility Transition Hub Financials: https://utilitytransitionhub.rmi.org/finances/ (this has financial data pulled from FERC/EIA on how much each utility is investing in CapEx, especially in T&D relative to renewables)
- RMI's Utility Transition Hub Map: https://utilitytransitionhub.rmi.org/map/ (shows capacity and emissions by fuel type, utility, and state)
- RMI's Utility Transition Hub Policies & Regulation: https://utilitytransitionhub.rmi.org/policies-regulations/ (compares how utility-relevant policies differ across states)
- RMI's Electricity Innovation Lab (eLab): https://rmi.org/our-work/electricity/elab-electricity-innovation-lab/ (facilitation team that helps accelerate conversations across stakeholders on hard-to-tackle topics)

PNNL

- PNNL's Grid Resilience Webinar Series recordings: https://www.youtube.com/playlist?list=PLdW5J6qhxuwBPk3aAvm9Mc_iQmI5x4LIM
- PNNL's Grid Resilience and Decarbonization webpage: https://www.pnnl.gov/grid-resilience-and-decarbonization (subpages include two collections of tools/resources for energy system and Earth system modeling)
- PNNL's Review of Water and Climate Change Analysis in Utility Integrated Resource Plans: https://epe.pnnl.gov/pdfs/Water_in_IRP_whitepaper_PNNL-30910.pdf
- Con Edison's Climate Change Vulnerability Study: https://www.coned.com/-/media/files/coned/documents/our-energy-future/our-energy-projects/climate-change-resiliency-plan/climate-change-vulnerability-study.pdf

- Con Edison's Climate Change Resilience and Adaptation – Summary of 2020 Activities: https://www.coned.com/-/media/files/coned/documents/our-energy-future/our-energy-projects/climate-change-resiliency-plan/climate-change-resilience-adaptation-2020.pdf
- CPUC's order setting out requirements for California Utilities' Climate Change Vulnerability Assessments and Climate Adaption in Disadvantaged Communities: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M346/K285/346285534.PDF
- PNNL's Considerations for Resilience Guidelines for Clean Energy Plans For the Oregon Public Utility Commission and Oregon Electricity Stakeholders [click to view PDF] (Note: this is the same report that is now part of the Oregon docket for HB2021).

EPRI

- EPRI's Climate READi initiative website: https://www.epri.com/research/sectors/readi

Oregon Public Utility Commission

- OPUC's Docket for Clean Energy Plans: https://apps.puc.state.or.us/edockets/DocketNoLayout.asp?DocketID=23160
- OPUC's recordings for Resilience/Community Benefits Webinars:
  - June 2 Intro to Community Benefits Methods Workshop https://oregonpuc.granicus.com/player/clip/962?view_id=2&redirect=true&h=656d9ab2dbb408c7512828e2b9e44de1
  - June 15 Intro to Resiliency – PNNL basics https://oregonpuc.granicus.com/player/clip/967?view_id=2&redirect=true&h=da10ca0edc33d8a501a2c2d615f633c9
  - September 29 Resiliency Landscape Workshop (facilitated session by RMI) PNNL report https://oregonpuc.granicus.com/player/clip/1028?view_id=2&redirect=true&h=f955a5bd5ce8b622d46d8cb4b0dfbd35
- Work on resilience supported by the IEEE Distribution Reliability Working Group: https://cmte.ieee.org/pes-drwg/wp-content/uploads/sites/61/DRWG-and-Resilience-Collaboration.pdf

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