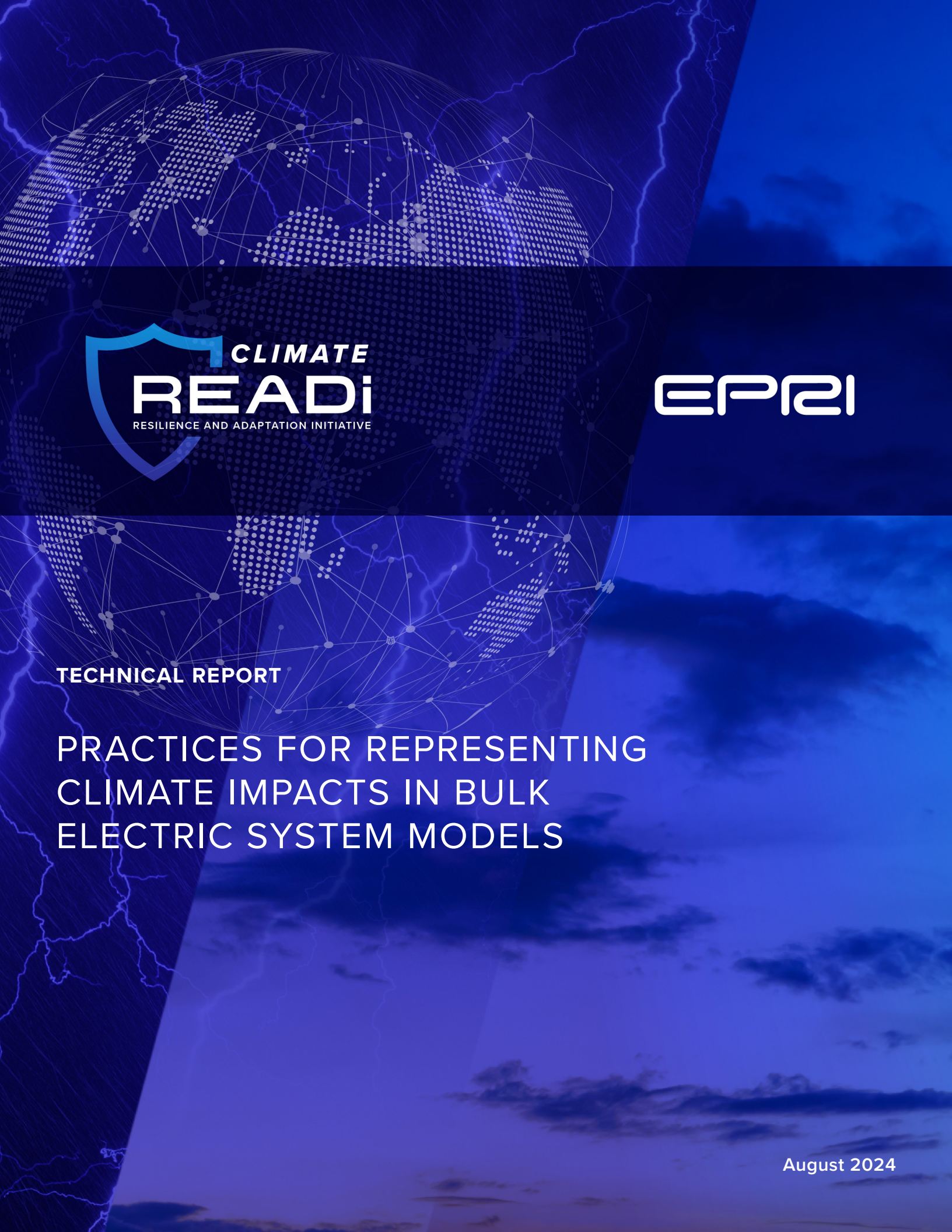


TECHNICAL REPORT

# PRACTICES FOR REPRESENTING CLIMATE IMPACTS IN BULK ELECTRIC SYSTEM MODELS

August 2024

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## EXECUTIVE SUMMARY

Changing climate conditions present new risks to electric generation and transmission infrastructure. Minimizing potential consequences from climate and weather hazards requires a change to traditional modeling practices through the accurate representation of climate impacts on power system operational and planning models. However, methods for considering climate risk within existing bulk electric system planning tools are not well established; models may have differing capabilities or limited interconnections to consistently use climate data. This report provides guidance to address these needs through the selection, processing, and interlinking of climate data across modeling stages, herein referred to as the Climate Data Pipeline.

The Climate Data Pipeline is one effort within EPRI's Climate REsilience and ADaptation initiative (Climate READi) to provide a framework for integrated modeling that supports climate resilience. At a basic level, integrated planning for climate resilience requires organizing vast amounts of data and modeling assumptions to support valuable insights and outcomes. The broader Climate READi Framework will be designed to guide electric power companies and stakeholders through practices that support climate resilience across the power system.

To emphasize agnostic tool guidance, this document outlines planning framework concepts and linkages, rather than specific tools. Still, to highlight practical examples, several tools that EPRI has used to build, demonstrate, and refine the Climate READi framework are mentioned alongside short examples of how the Climate Data Pipeline is applied to a synthetic model of the Texas electricity system. Planners may find it useful to leverage these modeling considerations in their own climate-resilient bulk electric system planning efforts.

The Climate Data Pipeline is presented across three chapters in this report, which address how planning practices can evolve to make sense of the bulk electric system climate risk landscape. The primary audience for this report is electric company staff engaged in bulk electric system planning, climate resilience assessment, and/or corporate risk management. An integrated framework is presented that enables consistent climate data inputs across bulk system planning models. Climate datasets and considerations for bulk system planning applications are discussed within this framework context. Categories of bulk electric system specific climate data inputs are documented, and sample research results summarize modeling tools used, linkages between them, and how each conveys climate risks within bulk electric system planning. Figure 1 provides a visual summary of the Climate Data Pipeline for the Climate READi integrated planning framework. What follows are short descriptions of the various modeling stages discussed within each chapter in the report.

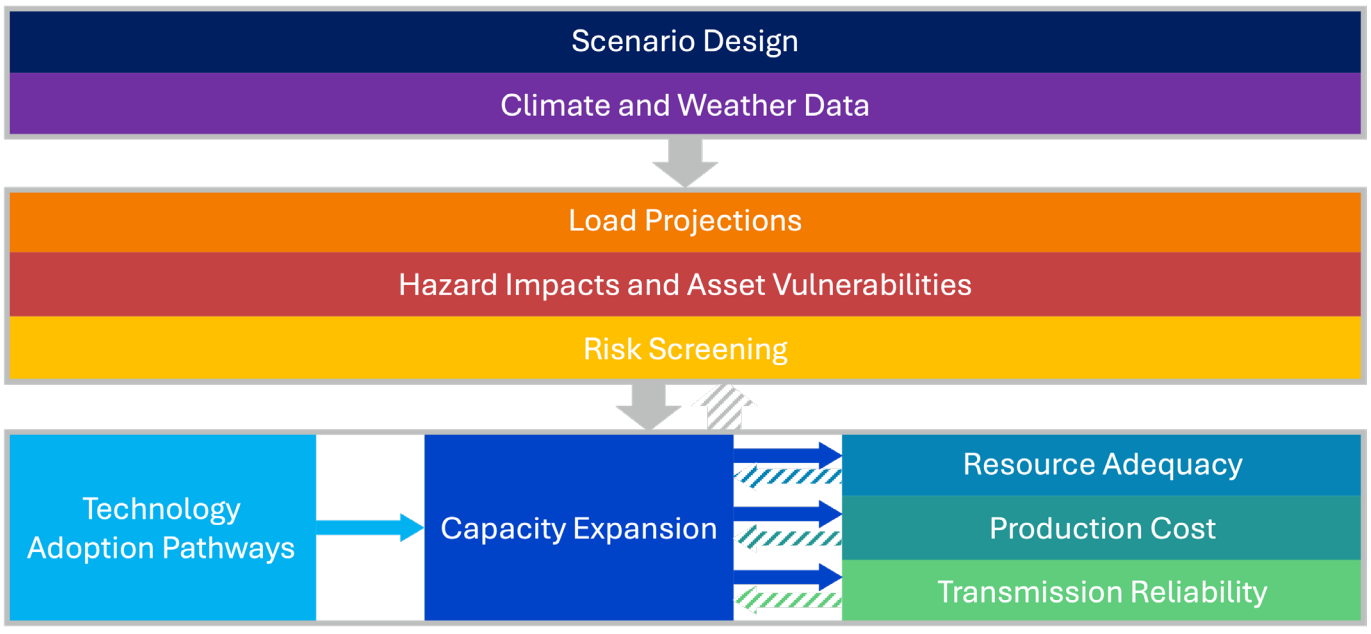


***Figure 1.*** *A high-level summary of the Climate READi Framework shows that the modeling itself depends on the proper consideration of climate risk and the many ways it might impact system operations. Solid arrows between major planning stages and individual modeling tools depict the flow of information within the framework, while dashed arrows designate data flows which may occur given feedback between models.*

## Scenario Design and Climate Data for Bulk Electric System Planning

In Chapter 2: Scenario Design and Climate Data for Bulk Electric System Planning, the "Scenario Design" and "Climate and Weather Data" modeling stages are discussed. Scenario design involves defining assumptions about how key uncertainties may evolve over the future. Climate data describes aspects of meteorological and climatological conditions such as temperature, precipitation, humidity, wind, solar irradiance, and others. It can encompass both historical and future periods. Future data include weather forecasts, extrapolated historical trends, and projection data sources derived from global climate models (GCMs), which can include statistical, dynamical, and hybrid downscaled products. Downscaling can be useful for integrating climate data into planning models by providing increased spatial and temporal granularity (e.g. hourly, and at specific locations). Hazard data, defined as physical events or trends that can have harmful impacts, may also be considered when modeling climate risk. Considerations for planning under uncertainty and climate data that may be useful within bulk electricity planning are presented.

## Making Planning Tools Climate Informed

In Chapter 3: Representing Climate Risk in Planning Tools, “Load Projections”, “Asset Vulnerability and Hazard Impacts”, and “Risk Screening” modeling stages are presented. Transitional steps taken to integrate climate data and describe impacts to systems represented within planning models are defined. To include impacts of climate conditions within bulk electric system planning, information relating to system and environmental conditions is necessary. For exposed assets, asset vulnerability functions and projected weather data are used to calculate hazard impacts of vulnerabilities such as outages, efficiency losses, capacity derates, operational cut-off limits, shortened life spans, or changes in required maintenance, which can be represented in modeling tools. Weather-sensitive loads must be modeled to convey climate impacts to system demand. Extreme events serve as useful time periods for stress testing resource plans and to more efficiently target system risks in models. Because climate impacts and risks can vary spatially and temporally across systems and future scenarios, it is important to also include these details when planning climate resilient bulk electric systems.

## Climate-Resilient and Integrated Bulk Electric System Planning

In Chapter 4: Climate-Resilient and Integrated Bulk electric system Planning, “Capacity Planning”, “Technology Adoption Pathways”, “Resource Adequacy”, “Production Cost Modeling”, and “Transmission Reliability” modeling stages are described. The application of the Climate Data Pipeline across generation and transmission planning is described. Novel methods and consistent climate data inputs are required to account for changing conditions in planning and reliability models. System planning often employs several different models, each designed to address a specific question across different operational time-horizons. Often, this planning has been done in isolation, with planning functions and assumptions siloed from each other. Differences in model inputs, resolutions, capabilities, as well as organizational practices can make it challenging to ensure the consistent use of climate data necessary to evaluate system climate risk. The integrated modeling framework presented in the Climate READi System Adaptation and Investment Prioritization Workstream (‘Workstream 3’), with inputs from the Physical Climate Data and Guidance and Energy System and Asset Vulnerability Assessment Workstreams (‘Workstream1 and 2’ respectively), provides a methodology for addressing climate risk in bulk electric system planning models. Climate READi system modeling efforts leverage an integrated modeling framework, and this Climate Data Pipeline describes how climate data and system inputs are linked across modeling stages. Several of the modeling stages also involve potential iterative feedback loops which may be performed to meet certain planning criteria. By consistently including climate data in ways that can represent impacts to assets and demands across these stages, planners can better capture the interconnected risks of climate change across bulk electric systems.

## KEY TAKEAWAYS

- When used consistently across interlinked modeling stages, climate data inputs can support cohesive and climate-informed bulk electric system planning.
- Planners assessing climate risk may find it useful to consistently consider a range of data, including climate, bulk electric system, and broader environmental data, when designing and evaluating scenarios around future uncertainties.
- Climate data has many sources and forms and can include historical and projected climate data in various formats. Downscaling methods, such as those which provide hourly temporal granularity at specific weather locations, can be useful as input when integrating climate impacts into planning models.
- Characterizing the weather sensitivity of supply and demand can facilitate the integration of climate risk assessment directly within bulk electric system models.
- Categories of climate-informed data inputs for modeling the bulk electric system can include asset vulnerability, weather-responsive loads, weather-to-power supply curves, hazard impacts, system performance, and risk screening for extreme events.
- Modeled resource performance impacts are included in planning tools to show altered availability, efficiency losses, capacity derates, physical damage, operational cut-off limits, shortened life spans, or changes in required maintenance.
- Methods that identify periods of potential system risk along with modeling that enumerates potential technology adoption pathways may help facilitate efficient and consistent capacity expansion and reliability modeling.
- Iteration between Capacity Expansion, Risk Screening, and Resource Adequacy models is a process which can be employed to coherently meet planning requirements across linked bulk system models.

# 1 INTRODUCTION

Electricity system planners encounter many uncertainties when developing future generation and transmission infrastructure portfolios that are robust to potential future hazards. Among these, weather and climate are fundamental – impacting all aspects of system operation. While traditional bulk electric system planning practices consider historical weather and climate, changing average and extreme conditions place new risks on assets and challenge existing and future system reliability. To respond to these challenges, planners may first identify how changes to weather-normal conditions and extreme events could impact system operations, and subsequently use these relationships to identify adaptations to maintain reliability and ensure resilience.

To plan bulk electric power system resilience in response to changing conditions planners are working to understand:

- The climate risks for which to prepare
- That periods of risk may evolve as both climate and power systems change
- The importance of resource adaptation and siting decisions for system reliability
- The level of resilience to target in an extreme weather planning scenario

While climate risks are system- and hazard-specific, a common planning framework that incorporates climate impacts and conveys system needs during critical periods can help navigate the uncertainties present.

Through the Climate Resilience and Adaptation initiative (Climate READi),[1] EPRI has developed a climate-informed integrated electric system planning framework to identify cost-effective adaptation and resilience investments. Climate READi is organized into three workstreams, each with a distinct focus on a specific aspect of climate risk. The Climate READi workstreams are used in combination to represent climate risk in bulk electric system planning, with a team dedicated to understanding the physical climate hazard and providing guidance on fit-for-purpose data (Workstream 1), a team dedicated to characterizing asset vulnerabilities and impacts (Workstream 2), and a system modeling team (Workstream 3) that uses these data for load projections, resource planning, and reliability evaluation tasks in order to inform adaptations and prioritize investments to promote resilience.

1 Climate READi: More information can be found at epri.com/READi

## The Climate Data Pipeline

This report guides planners through the Climate Data Pipeline, a description of climate data applications across linked bulk electric system planning stages within Workstream 3 of Climate READi. To explain the processes involved, this report presents climate data inputs and uses across planning models in three parts:

- **Chapter 2:** Scenario Design and Climate Data for Bulk Electric System Planning, which describes the use of scenario planning and climate and weather data relevant to this bulk system planning research;
- **Chapter 3:** Representing Climate Risk in Planning Tools, which introduces ways in which climate information can be represented in electricity system models; and
- **Chapter 4:** Climate Resilient and Integrated Bulk Electric System Planning, which discusses linking the Climate Data Pipeline across multiple planning models for generation and transmission planning.

Figure 2 summarizes the modeling stages and flow of data described further within the chapters of this report.

While the report describes planning stages and mentions some of the tools used in EPRI's application of this research, planners may apply the Climate Data Pipeline approach to their own systems with commercial or custom tools that are capable of accurately capturing climate considerations. In addition, while distribution system planning and operations are critical parts of an integrated planning framework, they are not discussed in this report and will be addressed through other Climate READi deliverables; this work focuses on representing climate data and on linking models within long-term bulk electric system planning and simulation tools.

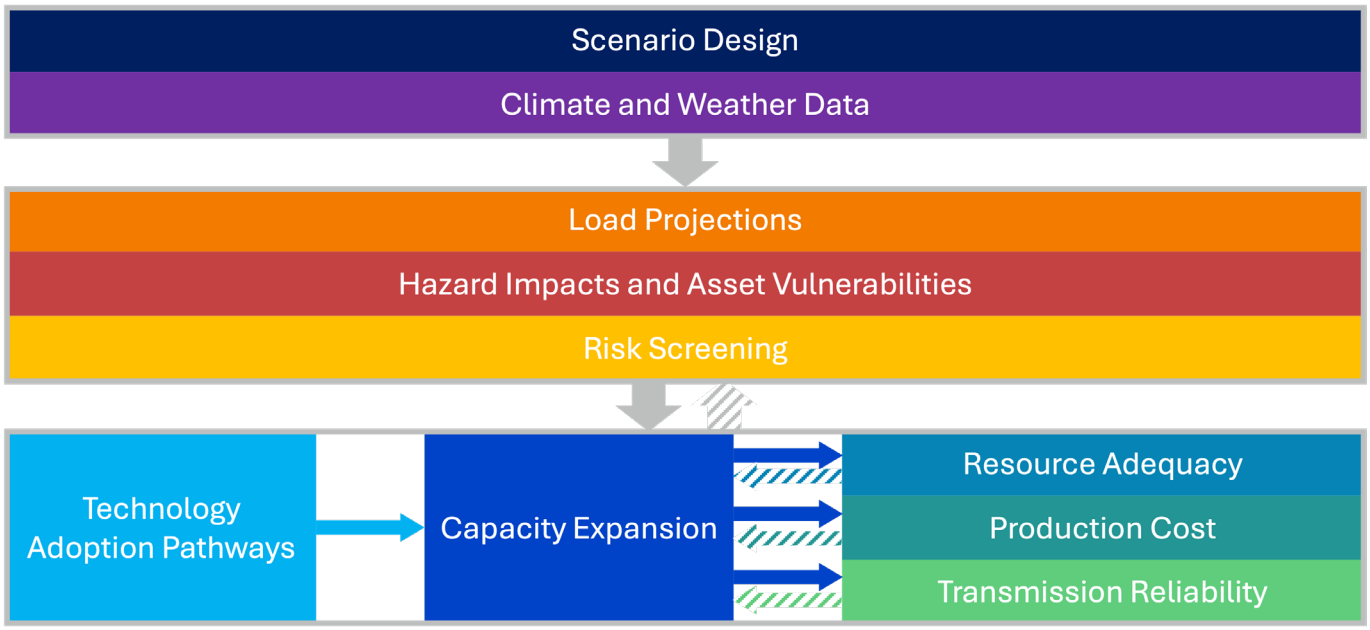


***Figure 2.*** *A high-level summary of the Climate READi Framework shows that the modeling itself depends on the proper consideration of climate risk and the many ways it might impact system operations. Solid arrows between major planning stages and individual modeling tools depict the flow of information within the framework, while dashed arrows designate data flows which may occur given feedback between models.*

## EXAMPLE APPLICATION: TEXAS CASE STUDY

The first demonstration of the Climate READi framework used a synthetic model of the Texas electricity system,[2] selected due to its publicly accessible system data and its representation of a large electric power system with a defined geographic footprint. This system contains 6,717 electric busses (Figure 3) and was developed using a methodology to create structurally realistic characteristics of the Texas power grid, without relating to the actual geographic location of assets. Following descriptions of the Climate Data Pipeline methodology and tools, this report shows how the Climate Data Pipeline has been applied to the Texas Case Study, including lessons learned and insights for each stage in the planning framework.

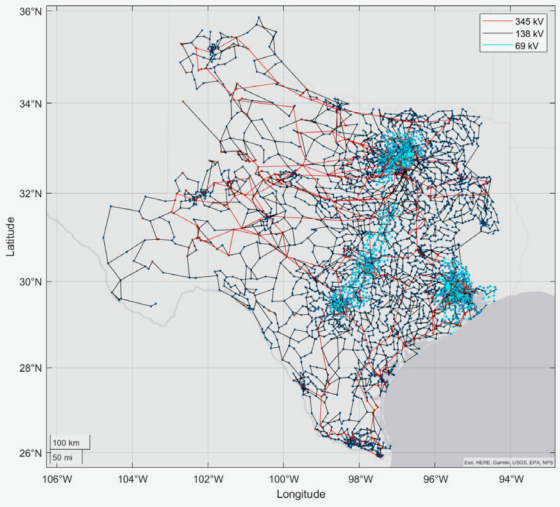


***Figure 3.*** *A map of the Synthetic Texas Grid Test Case, showing the locations of transmission lines and buses*

2 H. Li et al., "Building Highly Detailed Synthetic Electric Grid Data Sets for Combined Transmission and Distribution Systems," in *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 478–488, 2020, doi: 10.1109/OAJPE.2020.3029278.

# 2 SCENARIO DESIGN AND CLIMATE DATA

Incorporating climate risks into power system modeling requires first understanding what climate data are available and identifying which are useful, given the hazards and assets present within a region. Key components of representing climate information at this stage include using best-available data to characterize the historical baseline as a reference case, represent future climate conditions, and capture the statistics of extreme weather events. It is also important to treat weather variability distinctly from climatic change.[3] In Climate READi, the resources and knowledge needed to select and process climate and weather data comes from Workstream 1, and these data choices can inform design choices about linkages and downstream bulk electric system planning models.

Alongside this climate data, defining planning assumptions about potentially interrelated factors that may impact future bulk electric systems, such as policy design or load growth, can support a more holistic approach to climate resilient planning. To that end, this chapter first discusses scenario design, then introduces climate and weather data considerations, including climate hazards relevant to bulk electric system planning. In this Climate Data Pipeline, Scenario Design and Climate and Weather Data are the starting point.

3 *Climate Data Users Guide.* EPRI, Palo Alto, CA: 2024. https://apps.epri.com/climate-data-user-guide/en/.

## Scenario Design

### Scenario Design Takeaways for Planning and Modeling

- Scenarios are a common way to manage uncertainty in long term planning, however climate projections or global warming levels have historically not been the basis of scenario design.
- Weather, demand, policy, fuel supply, supply chain, and technoeconomic uncertainties are often considered in long term electricity system planning, and these are still important to consider in addition to potentially interlinked climate uncertainties.
- Developing scenarios around climate and interrelated assumptions about resulting impacts can facilitate consistency across models and assumptions early on. Climate and weather conditions can be scenarios themselves.

"Scenario design" provides the overarching organiztion for all data inputs and planning tools. Scenario design is a planning technique used to evaluate plausible future states of a given study system, as well as the influential conditions of the broader region where it operates. Given the vast array of possible future techno-socio-economic scenarios, limiting future conditions to specific narratives can provide consistency among models and results. Designing scenarios provides boundary conditions and common assumptions that can be applied throughout, enabling all other planning stages to execute efficiently.

The specifics of a given scenario will vary, driven by the relative importance of different uncertainties across systems and companies. Multiple scenarios are often developed to capture important uncertainties and compare impacts on the system of one future state versus another. Figure 4 displays seven categories of uncertainty that represent important considerations in bulk electric system plans. The subtext describes examples of key uncertainties for an electric power company. Each uncertainty driver determines which modeling constraints and inputs need to be adjusted across scenarios to support consistent analysis on outcomes.

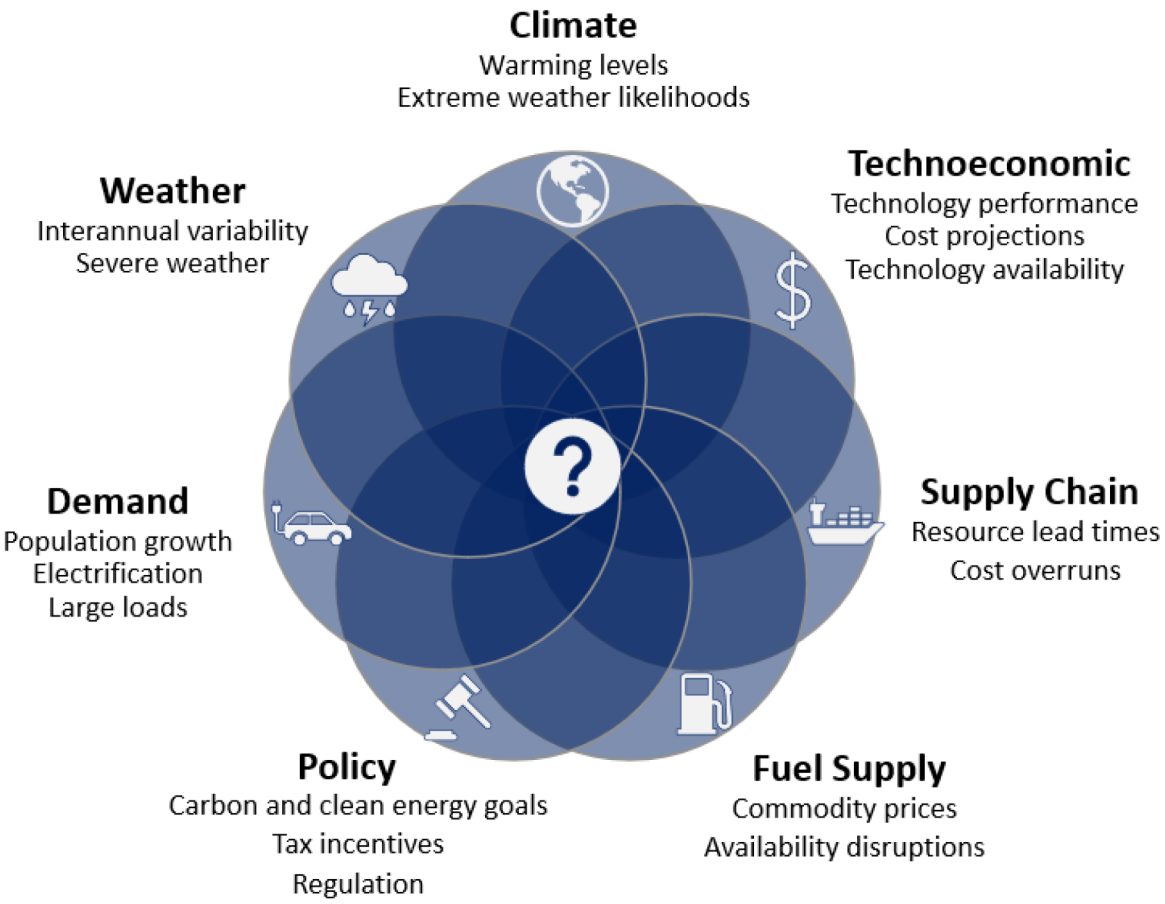


***Figure 4.*** *Categories of future uncertainty often considered in electricity system plans.*

## EXAMPLE APPLICATION: SCENARIO DESIGN

While uncertainty drivers such as supply chain, fuel availability, and advanced technology cost impacts are important, this Climate READi case study focused on two carbon reduction scenarios: "Business as Usual" (BAU) representing current policies (including recent federal Inflation Reduction Act (IRA) provisions and all state RPS/CES targets) and reference technology trends and "Net-zero by 2050" representing faster decarbonization to achieve net zero economy-wide by 2050. To explore uncertainty in the climate dimension, two CMIP6 warming scenarios were selected to represent a higher and lower emissions pathway, and SSP3-7.0 and SSP1-2.6, respectively.[4] Note that each technology/policy scenario was coupled with each climate change scenario for a total of four different assessments: BAU + Higher Emissions, BAU + Lower Emissions, Net-zero + Higher Emissions, and Net-zero + Lower Emissions as shown in Figure 5. These two scenario dimensions were treated independently for the purposes of this analysis and were chosen to demonstrate a limited set of sensitivities while focusing on the process for integration into the broader modeling effort. Others may choose a different set of scenarios for business, scientific, or regulatory reasons.

| SCENARIO | TECHNOLOGY AND POLICY | CLIMATE CHANGE |
|---|---|---|
| 1 | Business as usual | Lower emissions (SSP1-2.6) |
| 2 | Business as usual | Higher emissions (SSP3-7.0) |
| 3 | Net-zero by 2050 | Lower emissions (SSP1-2.6) |
| 4 | Net-zero by 2050 | Higher emissions (SSP3-7.0) |

***Figure 5.*** *Climate READi Texas Case Study scenario sensitivities are described. Scenarios defined focused on projections of technology and policy that pair with higher and lower emission futures, with each scenario dimension considered independent of the other for purposes of this analysis.*

4 O'Neill, Brian C., Claudia Tebaldi, Detlef P. Van Vuuren, Veronika Eyring, Pierre Friedlingstein, George Hurtt, Reto Knutti et al. "The scenario model intercomparison project (ScenarioMIP) for CMIP6." Geoscientific Model Development 9, no. 9 (2016): 3461-3482.

Climate change creates additional uncertainty for planners, which can impact many other categories of uncertainty. There is scientific consensus that human influence has warmed the atmosphere, ocean and land since the start of the Industrial Revolution.[5] The magnitude and local impacts of future warming, however, remain uncertain. For example, global average temperatures were assessed to increase between 2.1°C and 4.6°C by the end of this century for two marker emission scenarios, SSP2-4.5 and SSP3-7.0,[6] but these global estimates depend on future human behavior and global feedback loops that are difficult to model.[7] Global warming levels can also be used for planning considerations, as they can isolate some of the uncertainty present.

5 Intergovernmental Panel on Climate Change (IPCC), ed. "Summary for Policymakers," *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1–2. Cambridge: Cambridge University Press (2023). Accessed at: https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/#A.

6 Intergovernmental Panel on Climate Change (IPCC), ed. "Summary for Policymakers," *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1–2. Cambridge: Cambridge University Press (2023). Accessed at: https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/#table-spm-1.

7 Kopp, Robert E., Rachael L. Shwom, Gernot Wagner, and Jiacan Yuan. "Tipping elements and climate–economic shocks: Pathways toward integrated assessment." *Earth's Future 4*, no. 8 (2016): 346-372.

Additionally, while climate projections are most often presented at the aggregate global level, electricity plans are conducted on individual systems covering a defined geographic region. Understanding future climate conditions at a given location is difficult due to complexities and uncertainties in local weather patterns. Certain regions could experience increased drought, others more floods, and some may experience both.[8]

Scenarios that reflect certain technology, policy, or climate assumptions may have interactive effects. For example, policies that target emissions reductions may alter emissions pathways and therefore impact global climate, or climate outcomes associated with certain emission pathways may impact the adoption and/or performance of certain technologies. It may be important to consider these interconnections when designing studies, selecting data, and developing modeling approaches.

For stakeholders implementing a climate resilient planning framework, it is important to consider the practical limitations of these uncertainties and how best to include them in modeling.[9] Often, it's possible to incorporate climate data by including climate and weather conditions as scenarios themselves (e.g., using multiple weather years as input). When building long-term scenarios for energy system modeling, it also can be important to consider how future climate scenarios are interlinked. Warming scenarios reflect explicit or implicit economic, social, technological, and emissions narratives which can be aligned with other aspects of the study design. Ultimately, this can be a complex space, and it may be important to consider the dominant sensitivities that will drive decisions to simplify the range of scenarios used.

8 "Warming Makes Droughts, Extreme Wet Events More Frequent, Intense - NASA," NASA (March 3, 2023). Accessed at: https://www.nasa.gov/centers-and-facilities/goddard/warming-makes-droughts-extreme-wet-events-more-frequent-intense/.

9 *Climate-Informed Planning and Adaptation for Power Sector Resilience, Section 3: Planning for Bulk System Resilience.* EPRI, Palo Alto, CA: 2023. 3002026317.

## Climate Data

### Climate Data Takeaways for Planning and Modeling

- Many bulk electric system planning efforts today utilize only historical observed data or limited representation of future climate projections.
- There are various types of climate data that can bridge gaps for power system needs, such as data for previously unmeasured locations. Both historical and future projection data are useful for inclusion.
- For some applications, downscaling to relevant spatial and temporal scales may be required to better meet the needs of climate-informed bulk electric system modeling, whereas in other cases or for certain hazards, coarser data may be sufficient.

In Climate READi we define climate data broadly, encompassing a broad array of meteorological and climatological variables at various temporal and spatial scales. Climate datasets are available from many different sources and can have different strengths and limitations. Table 1 provides examples of climate data sources that may be relevant for modeling, and more information about these and other data sources can be found in the Climate Data Inventory. Data choice and preparation should be determined by the application or modeling needs, including the planning time horizon. Climate data can span both historical and future periods. Historical data include direct and indirect observations (e.g., surface station or satellite), reanalysis data products, and historical climate simulations from global climate models (GCMs), while future data include weather forecasts, extrapolated historical trends, and future climate projections derived from GCMs. GCMs are often developed in accordance with the Coupled Modeling Intercomparison Project (CMIP), which is an international initiative meant to coordinate model runs across GCMs to allow for intercomparisons.[10] The most re-

10 *Climate Data Inventory.* EPRI, Palo Alto, CA: 2024. 3002028492.

cent phase of the initiative is CMIP Phase 6 (CMIP6). Climate output from GCMs can be statistically, dynamically, or hybrid downscaled to provide more temporal and spatial granularity at regional or local scales. These and other concepts are described within the Climate Data Users Guide delivered within Workstream 1.[11]

To identify the appropriate resolution for climate data, planners may consider both the limitations or sensitivity of a model as well as how temporal and spatial resolutions can impact the accuracy of results (e.g., averaging wind across larger spatial areas can impact the perceived likelihood of low-wind events and extreme wind gusts at point locations). Presently, the need to consider a range of climate scenario futures is less important for shorter time horizons (e.g., the next decade) as the scenarios do not diverge widely before mid-century. Furthermore, in the near term (1–10 years), inter-annual variability and decadal cycles dominate the longer-term trend in warming. The choice of emissions scenarios is more important for longer-term assessments (i.e. those greater than 10 years in duration).

Increasingly, system planners are interested in accounting for climate trends and variability of extreme weather and climate events when incorporating meteorological variables in planning models. To do so in a way that meaningfully captures system operations, hourly time series spanning complete years are often needed, as they provide sufficient temporal granularity to capture intraday changes in both loads and weather conditions. Climate data can also inform the development of future extreme events utilized as stress tests, and hourly data is often most helpful for this purpose as well. Although GCMs typically output variables at less than hourly detail, there are methods that can produce future hourly time series for system modeling needs.[12, 13]

Terms used to describe historical and future climate datasets:

- **Direct observations:** Recordings and measurements of weather variables at or over points in time.
- **Reanalysis:** Spatially and temporally complete and physically consistent dataset created from the incorporation of a wide range of weather observations (ground station, satellite, etc.) into a weather forecast model which can provide missing information both historically and for current conditions.
- **Global Climate Models (GCMs):** Model representation of the main climate system components (atmosphere, land surface, ocean, sea ice), and how they interact dynamically in accordance with geophysical properties of energy, mass, and momentum.
- **Historical Climate Simulations:** The historical results of climate model simulations, which are useful for characterizing the baseline behavior of a specific GCM and calculating projected changes on a relative basis
- **Extrapolated Historical Trends:** Extrapolation of trends from observed historical records.
- **Future Climate Projections:** Climate model simulations which describe plausible future climate conditions but are not intended as predictions for a specific day or year.
- **Statistical Downscaling:** Method used to increase the temporal or spatial resolution of global climate model output by using statistical relationships within observed historical data. Techniques include delta change, regression, weather generators, and weather classification.
- **Dynamical Downscaling:** Process used to increase the resolution of climate simulations by running regional climate models using global climate model output as boundary conditions. When combined with statistical methods, this can be known as hybrid downscaling.

11 *Climate Data Users Guide.* EPRI, Palo Alto, CA: 2024. 3002028078.

12 *READi Insights: Approaches to Future Hourly Time Series for Climate-Resilient Power System Planning.* EPRI, Palo Alto, CA: 2023. 3002028572.

13 Erik Smith and Delavane Diaz, 2022. *An Approach to Synthetic Future Climate Hourly Profiles for Power System Modeling.* EPRI, Palo Alto, CA. https://esca.epri.com/pdf/EPRI-2022-Synthetic-Future-Climate-Hourly-Profiles-for-Power-System-Modeling.pdf.

***Table 1.*** *Historical and Future Climate Data for Planners to Consider*

| | DATA | SOURCES | SPATIAL COVERAGE | SPATIAL RESOLUTION | TEMPORAL | TEMPORAL RESOLUTION |
|---|---|---|---|---|---|---|
| **Historical** | Direct observations | NASA / NOAA / National Weather Service / Various weather stations | Global | Point location | 1880s – present (satellites since 1980s) | Hourly/Daily |
| | Gridded reanalysis | e.g., MERRA2, ERA5 | Global | 9 km – 54 km grid cell | 1950 – present | Hourly/Daily |
| | Historical climate model simulations (including downscaled products) | CMIP6 | Global | 11 km – 110 km grid cell | 1850 – 2014 | Daily |
| **Future** | Weather forecasts | NOAA/National Weather Service | Global, regional, country level | Point location | Present – ~2 weeks | 15-Minute to Daily |
| | Climate forecasts | e.g., NOAA Climate Forecast System (CFS), ECMWF S5 | Global | 54 km – 110 km grid cell | ~2 weeks – 3 months | Weekly/ Monthly |
| | Future climate model projections | CMIP6 | Global | ~50 km grid cell | 2015 – 2100 | Daily |
| | Downscaled climate projections | e.g., LOCA-CMIP5, LOCA2-CMIP6, NA-CORDEX-CMIP5, NASA NEX GDDP-CMIP6 | Regional, Global | ~6 – 9 km grid cell | 1850 – 2100 | Daily |

Downscaling techniques are methods that can be applied to global climate model simulations to provide greater spatial or temporal granularity. Spatial downscaling involves applying these methods to increase the spatial resolution of climate simulations. Bulk electric system planning models which involve generators or features of a system modeled at a nodal level may benefit from including climate data projections geographically mapped to this spatial granularity. Workstream 3 Bulk System Planning models outlined in this Climate Data Pipeline, such as the Risk Screening tool, do this by matching generators to nodes, and nodes to representative local weather data locations.

Temporal downscaling involves applying methods to increase the temporal resolution of climate simulations (e.g., from daily average to hourly-scale data). By applying statistical methods, such as delta mapping, to increase the temporal availability of climate data, hourly data can be developed for system planning models that are designed to ingest annual timeseries of 8,760 hours or to perform shorter timescale adequacy assessments.

## EXAMPLE APPLICATION: CLIMATE DATA

For the Climate READi Texas Case Study, the underlying hourly time series used ERA5[14] gridded reanalysis data from the European Center for Medium Range Weather Forecasting (ECMWF[15]) as the historical source. ERA5 data is spatially and temporally complete, with a spatial resolution of 31 km x 31 km and covering years from 1950 to present.

The future hourly temperature time series was developed using a monthly quantile anomaly mapping technique.[16] For the future climate data, five CMIP6 climate models and two climate scenarios, SSP1-2.6 and SSP3-7.0, were selected to create a 10-member ensemble (5 models x 2 scenarios) from the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) archive.[17] The GCM projections were evaluated at the 2050 timeframe by centering a 30-year window (2036–2065 projection period) and calculating the monthly, quantile-specific shift from this baseline climatology to apply to the historical temperature records. This method reflects important, real-world characteristics from the historical record that are otherwise missing, such as locationally-specific dynamics which can be missing from coarse climate projections, natural variability which is not always well represented in the climate models, and important joint correlations among physically-linked variables such as wind, solar, and temperature.[18]

To illustrate the general differences among the current and future projected climate conditions, Figure 6 shows the current and shifted probability density plots of hourly temperature for a selected weather station used in the Texas Case Study. While average temperatures and extreme heat events increase, cold events similar to observed historical temperatures have a similar probability in the "2050 climate, low emissions" scenario. In the "2050 climate, high emissions" scenario, tail-end cold temperatures are shown to be warmer and less probable.

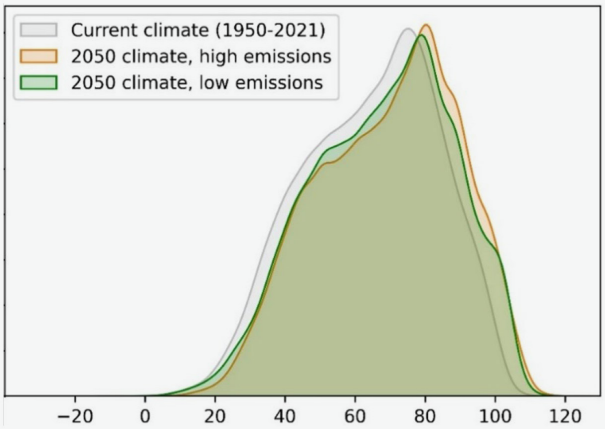


***Figure 6.*** *Example of Hourly Temperature by Climate Scenario for a selected location from the Texas Case Study. Probability density functions of hourly temperature are shown for the:*

- *Current historical climate from ERA5 (1950–2021) in gray*
- *2050 climate (2036-2065 projection period) with hourly temperatures shifted from the historical data based on the high emissions scenario SSP3–7.0 and climate model UKESM1-0-LL in orange*
- *2050 climate (2036-2065 projection period) with hourly temperature shifted from the historical data based on the low emissions scenario SSP1–2.6 and climate model MRI-ESM2-0 in green.*

14 ERA5 refers to the fifth generation of ECMWF ReAnalysis data. ECMWF refers to the European Centre for Medium-Range Weather Forecasts. https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5.

15 https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803.

16 Smith, E. and Diaz, D. (2022). *Synthetic Future Climate Hourly Profiles for Power System Modeling.* EPRI ESCA, Palo Alto, CA. https://esca.epri.com/pdf/EPRI-2022-Synthetic-Future-Climate-Hourly-Profiles-for-Power-System-Modeling.pdf.

17 Stefan Lange, Matthias Mengel, Simon Treu, Matthias Büchner (2023): ISIMIP3a atmospheric climate input data (v1.2). ISIMIP Repository. https://doi.org/10.48364/ISIMIP.982724.2.

18 *Climate Data Users Guide.* EPRI, Palo Alto, CA: 2024. 3002028078.

## Extreme Weather Events

### Extreme Weather Takeaways for Planning and Modeling

- Extreme events can significantly drive resilience concerns and adaptation needs. Planners may currently be incorporating these events through historically observed events, but it can be beneficial to also consider projections of future extreme events, which may look different from historical events
- How extreme events are identified is dependent on the system being planned for and vulnerabilities within. Some ways to define these events are based on threshold criteria such as magnitude, intensity, duration, frequency, or spatial coverage. Specific events can also be directly defined based on occurrence.

Climate data are essential to characterize climate trends and baseline variability, as well as to better understand acute climate hazards, also known as extreme weather events. Extremes can be defined through univariate or multivariate means where meteorological, hydrological, or other event variables surpass specified thresholds for criteria such as magnitude, intensity, duration, frequency, and/or spatial extent. Acute climate hazards such as tornadoes and wildfires can also be identified simply through their occurrences. Examples of weather and climate hazards that can translate into system impacts include heat waves, cold snaps, and extreme wind speeds. More information on weather and climate hazards relevant to the power sector can be found in the EPRI's *Climate Data Users Guide*.[19]

19 *Weather and Climate Hazards to the Energy System. Climate Data Users Guide.* EPRI, Palo Alto, CA: 2024. 3002028078.

### EXAMPLE APPLICATION: EXTREME WEATHER

To illustrate potential climate hazards related to extreme temperature events within climate datasets, a series of historical heat waves is shown below in Figure 7. Using the ERA5 record for Travis County, TX, heat wave events lasting five days that represented the 5-, 10-, 25-, 50-, and 100-year return periods (with annual probabilities of occurrence of 20%, 10%, 4%, 2%, and 1% respectively) were identified. The figure below shows a gridded map of the 5-day average daily maximum temperature values for each heat wave event for the given county in Texas. When planning it is important to consider the associated weather responses of demand and supply to weather events such as these. Further methods described within this Climate Data Pipeline framework show how this weather data can be used alongside modeling tools to assess the impact of climate hazards on the bulk electric system.

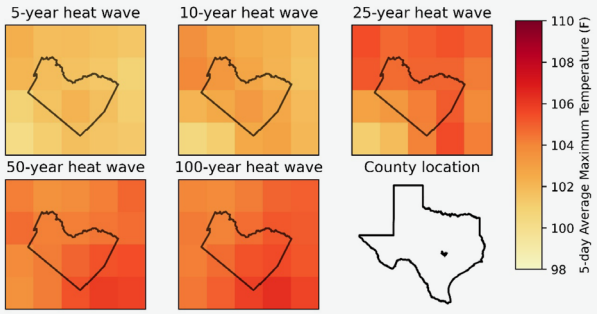


***Figure 7.*** *Historical Heat Wave Events for Travis County, TX. The five subplots display the daily maximum temperature from the gridded ERA5 reanalysis dataset for the 5-day average maximum temperatures of the 5-, 10-, 25-, 50-, and 100-year heat wave events identified empirically from the ERA5 historical record.*

# 3 REPRESENTING CLIMATE IMPACTS IN BULK ELECTRIC SYSTEM PLANNING TOOLS

When it comes to considering climate within modeling tools, climate data itself is often not used directly as model input, but instead is first translated into the type of inputs, constraints, and parameters usable in such models. This can come in the form of adjustments to loads, generator availabilities, generator capacities, or asset performance limits, to name a few examples. Planners can then incorporate these weather-driven load and asset performance impacts as data inputs for planning models. This is a critical step in climate-resilient bulk electric system planning, because it is how climate impacts are represented in system planning and operational models.

It is also important to consider that climate and weather conditions can vary across time and physical location when representing climate data impacts. Weather can impact supply and demand at different times on both short and long-term scales, so understanding the temporal dynamics of a particular model's formulation (e.g., static/snapshot versus chronological simulation) is an important detail. Temporal representations are often vital to detail climate impacts on supply and demand at different times. Climate hazards also have a regional footprint, so sufficient spatial resolution to assess differentiated exposure throughout the system (or even across neighboring systems) can also be valuable. Distinguishing between location- and time-specific impacts can provide downstream models the detail needed to represent bulk system operation in a changing climate.

Following scenario design and the selection of climate data, a process for developing climate data and modeling linkages is summarized below. These steps lead to a temporal and spatial representation of weather, supply, and demand projected for a system, and this information can then be used to identify periods of interest, to focus the planning scope within what might be a very large data space. There may be several different ways to develop the linkages needed for these processes, and depending on model frameworks these steps may be done within a preprocessing step prior to modeling, or within each modeling stage itself.

**System and Weather Data Mapping**

1. The locations of climate and weather data are identified for smaller geographic areas known as *nodes* in the system. System assets and infrastructure located within or associated with each node are accounted for.

**Asset Vulnerability Functions and Hazard Impacts**

2. Asset vulnerabilities for new and existing infrastructure are characterized to identify the possible ways bulk system infrastructure are exposed to climate impacts.
3. Hazard impacts to infrastructure are calculated based on asset vulnerabilities and weather conditions at each weather location over the time. This includes for generation resources and transmission lines.

**Load Projections**

4. To represent how demand may change with environmental conditions, weather sensitive and insensitive loads are defined. These loads may also be summarized at the system level and downscaled, or estimated consistent with the spatial and temporal detail of each node.

**Extreme Events and Risk Screening**

5. The combination of load, asset performance, and weather conditions over all climate data series are screened to identify periods where the system may be at risk. These estimates of weather informed load and supply are used in system planning models as the new operating characteristics of the asset. The risk periods identified are used as additional planning periods for modeling. Depending on the scope of each modeling tool the extent of this data used may vary.

## Asset Vulnerability Functions and Hazard Impacts

### Asset Vulnerability Takeaways for Planning and Modeling

- Oftentimes, the response of individual generator and transmission assets and loads to weather has not been specifically detailed when modeling bulk electric systems.
- There are many possible vulnerabilities and hazard impacts that system assets may be susceptible to. Modeling the different ways assets respond to weather hazards is essential to communicating the impacts of climate on bulk electric systems and understanding the drivers of system stress.
- Asset vulnerabilities can be realized through outages, capacity derates, efficiency losses, shortened life spans, and increased maintenance requirements, among others.
- When determining the modeling detail needed for resilience planning, planners can evaluate how climate risks present across time and space for the system under consideration. Spatial detail (such as the physical location of assets) and temporal detail (such as operations over time) are important, as climate risks depend on geographic and meteorological factors that are not typically considered in power flow models.

As described above, modelers can integrate climate data into bulk electricity planning models by translating weather hazards into system impacts, and then passing these inputs to planning models. Within modeling tools, climate and weather data have influence through modeled impacts on the system and its components. These system impacts can impact the aggregate bulk electric system, or specific parts of a system such as specific generating resources, components, loads, and other infrastructure.

Each type of asset may be vulnerable to different weather hazards in different ways. While individual asset risk assessments may be appropriate for some types of investment or operational decisions, bulk system planning often benefits from grouping assets together with similar risk or vulnerability profiles (e.g., generic asset type or asset-class level vulnerability assumptions that can be applied to theoretical future assets that don't exist yet). In addition to new and existing assets, asset vulnerability information is also required to evaluate potential adaptations – new and retrofit. Again, while actual vulnerabilities may vary by specific asset, a more consistent representation of expected vulnerability (and therefore performance) is useful to assess if and how an asset can contribute to future system reliability and resilience. Even with the need for generic assumptions, they can often be easily adjusted based on region, design standards, or expert judgement. For company specific applications, this data can be modified to reflect detailed knowledge of asset configurations or historical performance data.

Among other factors, asset characteristics like age or technology type can influence vulnerability, and these can be taken into account for both asset-level and system-level vulnerability considerations.[20] Specific asset vulnerabilities to hazardous conditions may include forced outage, efficiency losses, capacity derates, operational cut-off limits, shortened life spans, or changes in required maintenance. These responses are described as impacts applied to expected performance of an asset.

20 *Asset Vulnerability Assessments: Considerations and Resources.* EPRI, Palo Alto, CA: 2024. 3002029124.

Terms used to describe potential vulnerabilities for assets include:

- **Outage:** An asset becomes unavailable for a period of time.
- **Capacity derates:** Peak capacity of an asset is lost for a period of time.
- **Efficiency losses:** An asset is forced to operate at a lower efficiency.
- **Operational limits:** The inability of an asset to operate outside design limits.
- **Shortened life spans:** Wear and tear on assets can cause premature retirement.
- **Maintenance:** Assets may need increased maintenance due to hazard exposure.

When asset vulnerabilities are realized, they can be observed as hazard-induced impacts on asset performance. The result of this altered performance at different times and under different conditions is what dictates the parameters of an asset within planning models. The aggregation of hazard impacts represents the effects that impacted performance and damaging conditions may have on the system. Within the Climate Data Pipeline, hazard impacts are based on asset vulnerability functions and calculated given weather conditions. Among other considerations, climate informed planning models may consider these impacts when solving for resources and operations that minimize cost or meet planning thresholds for unserved load.

Secondary considerations for asset vulnerabilities may include the following impacts, some of which require knowledge beyond the asset itself to capture in a model:

- **Damage and Recovery:** The potential for widespread damages can be tracked and constrained in the model to limit resource plans that admit the possibility of a protracted recovery.
- **Increased Costs:** Exposure to extreme weather can increase maintenance and repair costs, accelerate aging, and decrease average operating efficiencies. In bulk electric system models, these costs can be accounted for and incorporated into the asset cost and performance parameters.
- **Other Harms:** In some cases, it may be important to capture the contribution of the asset itself to increased risk or harms, as asset operation can sometimes contribute to hazardous impacts. For example, this could include wildfire ignition or hazardous material spill. The potential for widespread harm can be tracked and constrained in the model, subject to assumptions in place, to avoid candidate expansion plans that allow for unacceptable risks of harmful consequences.

Defining hazard impacts involves developing assumptions about capabilities of future investments, as well as in assessing the feasibility and capability of retrofits, and screening for feasible expansion sites and quantifying each site's exposure to the hazards under study. For purposes of modeling, it may be possible to assign hazard impacts among vulnerabilities into more general categories. For example, the vulnerabilities related to winter storms, such as cooling water intake ice and internal pipe freezing could be aggregated into a single impact category for modeling purposes, subject to supporting data for the assumptions being made.

## EXAMPLE APPLICATION: ASSET VULNERABILITY FUNCTIONS AND HAZARD IMPACTS

An excerpt of an asset vulnerability matrix used for risk screening in the Texas case study is shown in Table 2. Potential system impacts are based on weather variable thresholds associated with specific technology types, leading to derates.

***Table 2.*** *Illustrative examples of generalized Asset Vulnerabilities describing derates (here, meaning unavailable capacity for any number of reasons) by technology and weather condition. This can be applied as a series of if-then statements, i.e., if "Weather Condition 1" is met and (if applicable) "Weather Condition 2" is met, then the asset capacity will be derated by the value shown for "Maximum Capacity Derate." In reality, these relationships are more complex and depend on age, condition, model, asset location, and coincident or preceding conditions.*

| TECHNOLOGY | WEATHER CONDITION 1 | | WEATHER CONDITION 2 | | MAXIMUM CAPACITY DERATE | VULNERABILITY |
|---|---|---|---|---|---|---|
| **Wind (onshore)** | Wind speed at 100 m | > 23 m/s | | | 100% | High speed cutout |
| **Solar PV** | Temperature | > 95°F | Temperature | ≤ 122°F | 22% | High temperature derate |
| **Combined Cycle** | Temperature | > 87°F | Temperature | ≤ 105°F | 11% | High temperature derate |
| **Gas Turbine** | Wind speed at 10 m | ≥ 26 m/s | Precipitation | > 0.2 in. | 10% | Tropical storm risk |
| **Gas Turbine** | Temperature | ≥ 0°F | Temperature | < 10°F | 33% | Low temperature derate |
| **Gas Turbine** | Temperature | ≥ -20°F | Temperature | < 0°F | 43% | Low temperature derate |
| **Gas Turbine** | Temperature | < -20°F | | | 100% | Low temperature limit |

Hazard impacts are used across several models that were applied to the Texas Case study. Below is an example of vulnerabilities modeled, including the hazard type, assets impacted, weather vulnerabilities that define the hazard, assets at risk, the type of impact that occurs to that asset class, and the magnitude of derate. Decisions regarding which hazards and vulnerabilities to include may vary by system, region, or data limitations.

***Table 3.*** *Selected examples of hazards and impacts characterized for modeling, demonstrating how vulnerability information can be used to build up asset impact relationships, often requiring some simplifying assumptions.*

| HAZARD | VULNERABILITY | ASSET AT RISK | HAZARD IMPACT | MAGNITUDE |
|---|---|---|---|---|
| **High temperature** | Heat-induced derate or cooling system constraint | Thermal generators | Reduced capacity | 0–30% |
| **Low temperature** | Cold-induced fuel disruption | Natural gas plants without backup fuel | Generation unavailable | 100% |
| **Low temperature, humidity, and precipitation** | Ice accretion | Wind turbines | Reduced capacity | 40–80% |
| **Snow** | Snow buildup | Solar panels | Generation unavailable | 100% |

## Load Projections

### Load Projection Takeaways for Planners

- Load projections have typically been produced considering historical or weather-normal conditions. Representing weather sensitivity in loads, combined with assessments of changing end-use technologies, and estimating their response to future climate conditions is important for understanding system needs.
- End use projection models can be useful for understanding sensitivities in demand associated with differing assumptions about future load drivers.

Within system planning models, load projections are a key input; supply is built in response to projected demand. In planning for a resilient energy system adapted to current and future climates, coordinating load projections with weather data is especially important. To ensure that climate impacts are represented, load projections should consider future climate conditions and weather sensitivity. Across location and time, assumptions about future loads can vary greatly based on the scenario design and climate projections defined in previous stages of the Climate Data Pipeline. These differences in location, timing, and magnitude of demands given consideration for weather can vary and necessitate differing system buildouts.

While there are many techniques for estimating future loads, an end-use focused, or "bottom-up" load projection methodology is used in the Workstream 3 Framework to model longer term changes in end use characteristics, while also enabling weather-sensitive loads to be accounted separately from other loads. End use models aggregate assumptions about the number, type, and usage of individual end uses in an area to determine a total projection of load. This is done across all characterized sectors and end uses to estimate total demand. The flexibility to simulate varying technology types and impacts based on scenario and climate assumptions makes end use forecasting a particularly useful tool to represent loads across the Climate Data Pipeline.

Many end uses are sensitive to changing weather conditions, and this can be a significant driver of demand when representing climate change impacts on the electricity system. Varying climate and weather assumptions could potentially have a significant impact on the timing and magnitude of demand on an energy system. Climate conditions particularly impact demand from space conditioning, water heating, and electric vehicles.[21, 22] The response of space conditioning demand to temperature varies greatly based on the individual technology involved and a building's thermal characteristics. End use capacity and coefficient of performance curves vary depending on the type of equipment being considered. For example, air-source heat pumps operate at decreased capacities and lower coefficients of performance as temperatures decline, sometimes leading to the need for auxiliary heating systems.

Additionally, because climate impacts, grid resilience, and adaptation needs can vary across different areas, granular system modeling requires geographically specific weather-sensitive projections of load. While spatial granularity depends on the available data products, gridded meteorological data may be better suited to this application than weather station data due to the relative ease of mapping uniform grid cells to irregular geographic boundaries for a large area (e.g., state, county, utility service area, etc.). Workstream 1 developed mapped gridded climate projection data and weather assumptions for the Climate Data component of this Pipeline, which underlies the link between climate and bulk electric system impacts. By using consistent climate data, it's possible to estimate end use load projections given future climate projections, and these

21 *Climate Vulnerability Considerations for the Power Sector: End Use Assets and Distributed Energy Resources.* EPRI, Palo Alto, CA: 2024. 3002030444.

22 *Climate-Informed Planning and Adaptation for Power Sector Resilience.* EPRI, Palo Alto, CA: 2023. 3002026317.

climate-informed load projections are necessary as input into all modeling stages within the integrated planning framework, as load is essential for modeling grid operations.

For creating load projections as data inputs within bulk electric system modeling tools, load projections are calculated for each respective year based on "base load" and "weather sensitive" loads. Base loads are those based on future projections of end use adoption and performance, which are not weather dependent. Weather sensitive loads, on the contrary, are end uses which have different demand characteristics based on weather conditions. When applied to system planning tools in this application of the Climate Data Pipeline, loads are calculated based on hourly weather projections, with the weather data mapped to representative locations across the region of study. The sum of base loads and weather sensitive loads given temperature for each weather station is calculated and can be referenced within tools that input load data directly.

## **EXAMPLE APPLICATION:** LOAD PROJECTIONS

To develop load projections for the Texas Case Study, EPRI leveraged a bottom-up end-use model designed to evaluate changes in future energy consumption based on differences in market growth, energy efficiency, building attrition, fuel prices, and technology adoption. This framework combines various public data sources to estimate consumption by end-use for different geographies, including data from the U.S. Census Bureau, U.S. Energy Information Administration (EIA), U.S. Environmental Protection Agency (EPA), the National Renewable Energy Laboratory (NREL), and other organizations. Where available, it's possible to also apply supplementary, utility-specific data sources to improve the limited geographic granularity of national surveys or to account for new loads expected to arise.

In this model, technology adoption is driven by a discrete choice modeling (logistic) approach in which the relative economic utility of each technology option (both electric and non-electric) is compared, with more economically-beneficial options gaining market share over time. This approach is similar to, for example, the U.S. EIA scenarios published in the *Annual Energy Outlook*.[23]

While climate change will have an impact on future loads, changing end-use technology mixes are likely to drive the bulk of any shift in total demand, as shown in Figure 8. Still, it is important to model the weather-sensitivity of any future loads to understand both the seasonality and magnitude of potential future peaks.

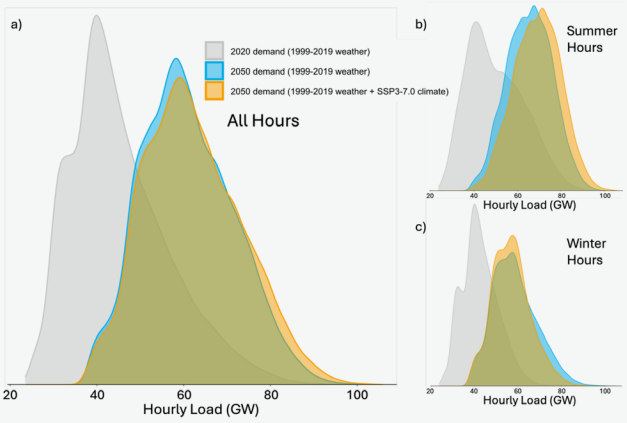


***Figure 8.*** *Density plots of modeled long-run hourly electricity demand for Texas, comparing demand simulated for the end-use technology mix of 2020 under twenty years of historical meteorology (1999-2019) to that of the end-use technology mix of 2050, with and without climate change considered. The shifts illustrate that expected changes in end-use technologies due to electrification, efficiency, and socioeconomic trends are the primary driver of future load patterns, with a secondary impact from shifting temperature distributions when climate signals are included, here using SSP3-7.0 projections. Note that the 2050 distributions are more similar when looking at (a) all hours across the 20-year period, which balances out the climate-related directional changes seen in (b) summer shifts and (c) winter shifts.*

23 https://www.eia.gov/outlooks/aeo/

## Data Selection and Risk Screening

### Data Selection and Risk Screening Takeaways for Planners

- Computational limitations have restricted the amount and complexity of climate data that can be modeled at a time in many bulk system models. Introducing techniques to distill the extent of data down to important periods of high risk can help.
- Risk screening involves identifying situations during which the combination of climate informed asset impacts and load projections show risk of supply shortfall.
- Once identified, these high-risk weather conditions and time periods can be passed on to downstream models to focus the overall analysis.

When evaluating climate impacts to the bulk electric system, a planner may need to understand which conditions are indicative of high-stress periods. Additionally, it may not be feasible to model detailed climate impacts across every projected time period in bulk electric system modeling tools due to the vast amount of data required to capture both sufficient inter-annual variability and long-term warming trends.

High stress periods can bring an increased risk of the system failing to meet demand. While often thought of as extreme events, these high-stress time periods depend not only on weather extremes, but also on system operating conditions, the makeup of the power system itself, asset vulnerabilities, and system demand. For these reasons, the time periods likely to cause severe system stress may not be obvious from a weather-only perspective, and it is therefore important to consider the aggregation of asset vulnerabilities that may be realized, both in space and in time. When these time periods are identified, the corresponding conditions leading to elevated risk can then be used as stress tests for system planning.

Given the importance of these critical time periods, it can be useful for planners to have a process to identify periods of risk when planning resources and testing the effectiveness of those plans. This can be done through a process defined here as “Risk Screening”, which evaluates asset vulnerabilities and hazard impacts calculated from projected weather data alongside geographically tied system demand from load projections. With this information in hand, event-periods are developed for each projected climate year, where overlapping supply and demand impacts are evaluated. From all analyzed events, the top periods at risk are compiled and clustered into risk event types. Outputs of the risk screening process enumerate periods of risk and identify both individual risk events as well as clusters of related risk events. Figure 9 shows an illustrative example for the purposes of visualizing how this may work in practice. From a very large weather dataset, the risk screening tool narrows down the periods of potential high system stress, and these periods can then be used to aid downstream modeling processes.

Within the Climate Data Pipeline, the Risk Screening stage can be run iteratively with subsequent modeling stages, until no new, high-stress conditions are identified. More detail on this iterative process is described within the following chapters describing bulk electric system modeling tools. Screened system risks are investigated, and critical periods are identified for capacity planning models to consider. Identifying times of system risk early in the process can facilitate a more efficient modeling framework by focusing the large climate data space of potentially hazardous conditions down to a set of representative events. In the Climate Data Pipeline, events identified by risk screening are run in addition to the other samples of input data considered in planning models.

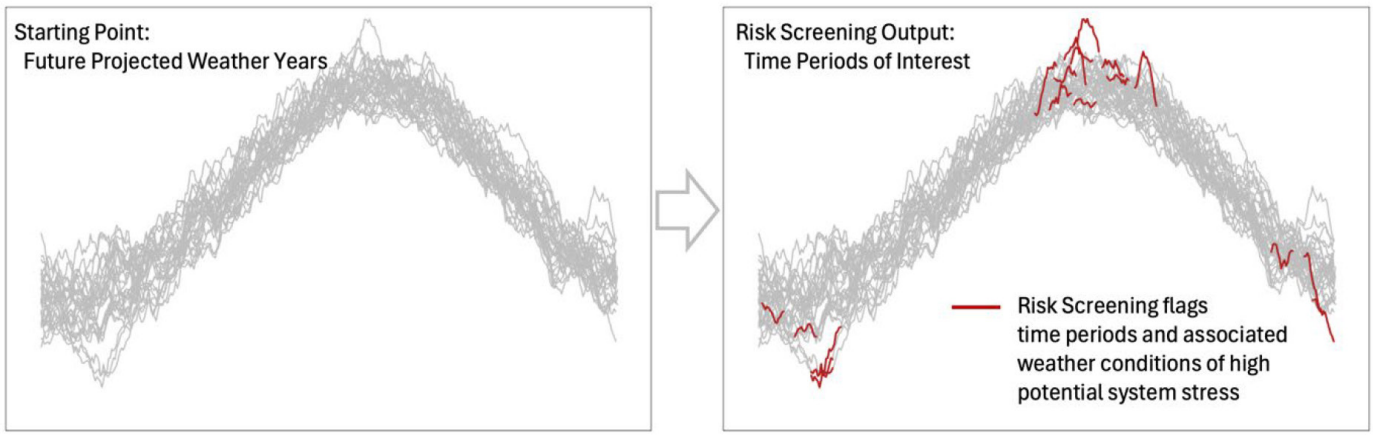


***Figure 9.*** *A simplified illustration of how risk screening uses a vast amount of weather data across multiple years to screen for potential periods of high system stress. In this example showing fictional temperature curves across a year, one can visualize how the tool may identify time periods that are not always the most extreme for a single variable but instead for which the combination of weather conditions and generation unavailability combine for high risk.*

## **EXAMPLE APPLICATION:** RISK SCREENING

EPRI developed the Climate Risk Screening Tool (RiSc) to screen a large set of climate data for potential periods of system stress. In the Workstream 3 Texas Case Study, RiSc screened candidate expansion plans for the synthetic Texas grid that were generated during the capacity planning step and then identified periods of risk considering hazard impacts, load projections, and climate data. Asset vulnerability data from Workstream 2 and GEM-derived temperature response curves for loads were used alongside system buildouts. Modelers identified and investigated system risks, and fed critical periods back into capacity planning models as study periods that should be considered for resilient system planning. Figure 10 shows an example of Risk Screening used to compare system risk across events as both the power system and climate evolve.

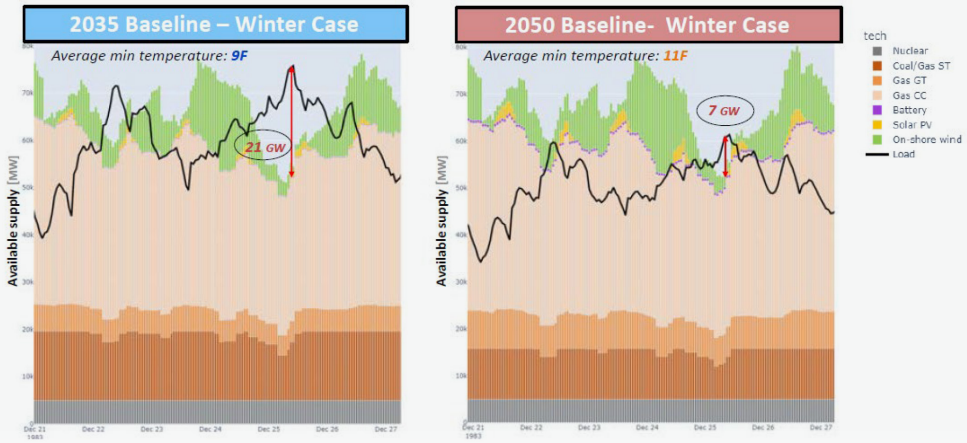


***Figure 10.*** *An example of risk events identified by the RiSc tool. The relative capacity shortfall of weather sensitive supply and demand is shown for the Texas Case Study system with 2035 and 2050 projected climates, demonstrating how changes in both system buildout and climate hazards dictate the calculated risk of supply shortfall.*

The screening tool assesses potential system risks for each climate projection over a span of many future weather years and reports the top 5% of all multi-day events. These top events are then clustered using k-means clustering. Clusters may, for example, correspond to event types such as periods of low wind and solar in combination with high load, or periods of low wind, low thermal generation due to high-temperature derates, and high demand. An illustrative example is provided in Figure 11.

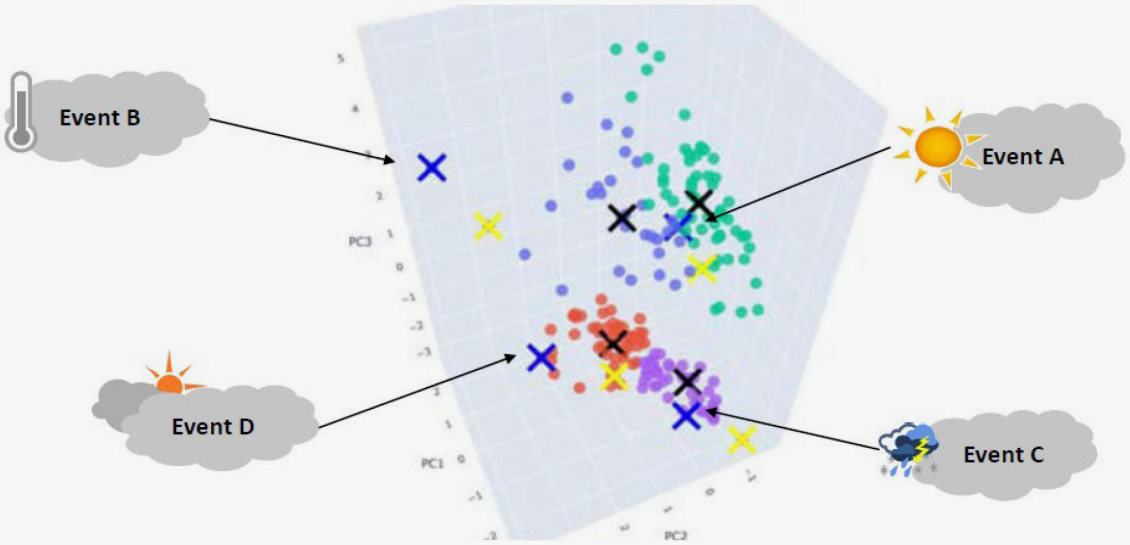


***Figure 11.*** *The EPRI RiSc tool uses unsupervised machine learning to identify clusters of related risk events, allowing the user to narrow the evaluation space while maintaining diversity in event classes.*

## 4 CLIMATE-RESILIENT AND INTEGRATED BULK ELECTRIC SYSTEM PLANNING

The integrated modeling framework presented here relies on the use of climate data inputs and resulting asset performance impacts across each model. By consistently including climate-specific impacts across modeling stages, planners can more holistically capture the interconnected risks of climate change across bulk electric systems. Particularly when planning for changes in climate and new weather extremes, this approach requires novel methods to accurately reflect climate data and hazards. Ensuring the consistent use of climate data and assumptions across models with varying specializations can be challenging given the differences in model inputs, resolutions, and capabilities, as well as an organization's current business practices. Still, there is value in setting this as a target for full model and team integration. The information provided in Chapter 3 can serve as guidance for each step in a modeling process.

## What Is Integrated Bulk Electric System Planning and Why Is It Important?

To capture the benefits of planning holistically in a changing environment, utility planning processes are becoming increasingly interconnected. An integrated approach to planning links multiple modeling stages with common assumptions, and outputs in one stage may be the inputs of another. Each stage gives insights about interrelated but different questions about system performance and risks, reliability, and resilience. There may also be iterations of this process needed to converge on an acceptable result across all models.

Despite the challenges, the benefits of climate-informed integrated system planning can be significant. Coordinated information between interdependent and weather-sensitive planning stages can avoid the sort of planning oversights that occur when performed in isolation. Critically, an integrated plan can identify system investments and climate adaptation options to efficiently support future reliability and resilience.

## A Framework for Climate-Resilient Bulk Electric System Planning

In practice, advanced solutions for climate-resilient electricity system planning involve deploying a suite of modeling tools spanning scenario planning, capacity expansion, resource adequacy, operational simulations, and transmission reliability. These tools enable planners to analyze tradeoffs among resource investment and system adaptation options across different sub-systems of the power system (e.g., generation, transmission, distribution, and/or end-use) alongside reliability impacts when considering climate change.

The subset of the Climate READi Framework shown in Figure 12 takes this approach, building off the framework developed through EPRI's Integrated Strategic System Planning initiative (ISSP).[24] Climate READi proposes an integrated planning framework that extends the ISSP approach by incorporating Climate Data Pipeline linkages: information about future projected climate conditions, climate data, asset impacts from climate change and extreme weather, and other approaches necessary for planning that reflect the changing climate, capture weather uncertainties, and focus on resilience. Workstream 3 system models have insight into future hourly modeled weather inputs that span typical and stressful weather conditions, and different models use different portions of these inputs. In turn, asset impacts are represented in each model by coupling data relating asset vulnerabilities to climate and weather variables across space and time. [25, 26, 27, 28] In combination, climate data, asset vulnerability, and system modeling come together to support climate-resilient planning.

Under this modeling framework, climate data are consistently represented across new and existing assets within interlinked tools to capture climate risk. Practically, no single tool can address all aspects of climate risk that could be considered, nor can all tools handle the full spectrum of climate data that may be relevant. Instead, integration between tools, each with their own insights and capabilities, is required. The following sections detail each of these planning models, how they consider climate data, and how they interconnect.

24 *Integrated Strategic System Planning Initiative: Modeling Framework, Demonstration Study Results, and Key Insights.* EPRI, Palo Alto, CA: 2023. 3002028640.

25 *Climate Vulnerability Considerations for the Power Sector: Nuclear Generation Assets.* EPRI, Palo Alto, CA: 2023. 3002026313.

26 *Climate Vulnerability Considerations for the Power Sector: Non-Nuclear Generation Assets.* EPRI, Palo Alto, CA: 2023. 3002026314.

27 *Climate Vulnerability Considerations for the Power Sector: Health and Safety, Environmental Justice, and Ecological Patterns.* EPRI, Palo Alto, CA: 2023. 3002026316.

28 *Climate Vulnerability Considerations for the Power Sector: Transmission and Distribution Infrastructure.* EPRI, Palo Alto, CA: 2023. 3002026315.




***Figure 12.*** *EPRI's Workstream 3 integrated framework for climate-resilient planning. Each box represents a planning model with distinct roles in bulk system planning and reliability analysis. Data movement between models is depicted within arrows to show the flow of information, with dashed arrows indicating possible points of feedback given desired planning criteria.*

## Capacity Expansion

### Capacity Expansion Takeaways for Planning and Modeling

- Capacity expansion models have typically considered resource additions or retirements as a means of meeting planning requirements for future loads without directly considering resilience.
- In response to climate hazards, capacity expansion models address resilience more directly by additionally considering where resources are located, how hazards impact assets across space and time, coordinated generation and transmission decisions, adaptation, and hardening options – all while considering both nominal operations and selected extreme events.

Capacity Expansion is a central hub of climate-resilient planning, where much of the Integrated Bulk electric system plans originate and where many tool linkages are required. The aim of the Capacity Planning stage is to help develop a long-term generation and transmission expansion plan that minimizes the total system cost while ensuring reliable operations. Metrics for reliable operations have generally made exceptions for extreme weather, but climate change threatens to make normal weather more extreme than the system was originally designed for. Recognizing a growing need for resilience, it can be advantageous to include these extreme weather events in bulk electric system planning, thus aiming for both reliability and resilience within this initial modeling stage.

Because resilience planning needs to coordinate with other system planning stages and is a computationally difficult problem, EPRI developed a flexible methodology to represent hazard and adaptations within a capacity expansion model to conduct this research. In addition to what is considered by traditional capacity planning models, this capacity planning model also considers:

- **Spatial Disaggregation:** Hazards have a regional footprint, so the capacity model needs enough spatial resolution to assess the exposure of assets throughout the system. Estimating the exposure of candidate assets requires more detail on the siting of those candidate assets than is typical in capacity planning models.
- **Coordinated Generation and Transmission Decisions:** Both generation and transmission assets are vulnerable to hazards, so modeling the system's vulnerability requires accounting for both together. Moreover, the best adaptation strategies will use a mix of generation and transmission investments. Optimal adaptation strategies require a coordinated planning approach.
- **Resilience Criteria:** The aim of resilience planning is to limit the adverse consequences of extreme events. There are many possible metrics and thresholds that can define what is considered to be a resilient system. The capacity expansion plan is a least-cost model, minimizing the net present value cost of investments

and operations. The main resilience criterion used is the proportion of unmet load in any of the selected extreme event scenarios. To be resilient, the system must meet a specified percentage of demand in all extreme events. Another resilience criterion prevents excessive damage, to the extent that the system cannot recover sufficiently quickly, from any one event.

In addition to resource siting, build, and retirement decisions, hardening and adaptation investments are also considered. The addition of adaptation options enables the capacity expansion model to build a system in response to climate risks by considering:

- **Hardening Decisions:** The term hardening is used to refer to an investment that makes an asset more resistant to the impacts of a hazard. Assets can be protected from hazard impacts through hardening. A good way to improve the resilience of the system is often by hardening key assets. Strategies may also balance standard capacity with hardened capacity. Hardening additions are modeled as optional investments that are applied to generation and transmission assets. For example, investments in winterizing a thermal plant or in burying a transmission line are decision variables in the capacity planning model. Assets might have many hardening options available. Each hardening option has a cost which will be particular to the asset and its siting. The practicality of each hardening option, or combination of hardening options, will also depend on the details of the site and the asset to be hardened.
- **Adaptations:** Adaptations refer to any changes in the investment plan, relative to a baseline plan, that make the system more resilient. Adaptive investments include hardening, but adaptive investments can be much broader, encompassing ways to make normal planning decisions more resilient. The location, timing, sizing, and technology mix of new investments can all contribute to resilience, so there are potentially many ways to make a baseline plan more resilient with minimal added costs. A range of options can be directly considered within a model if cost and performance metrics can be quantified.

In practice, this planning process can be summarized into two parts: data preparation and optimization. The data preparation occurs before the optimization step, and this is where climate and weather data conditions are translated into system impacts in the ways described in Chapter 3. Asset vulnerability functions and viable hardening options are assigned to existing and new resources. The potential impacts for each hazard, for each asset, for each hardening option, and for each planning period are then calculated and passed to the model. The optimization step is where the model is solved. For purposes of optimization, hazard impacts can be considered as 'potential' impacts which are pre-calculated and given to the optimization model, which chooses the combination of resources, adaptations, and hardening options to meet cost and resilience planning criteria. When selecting the hazard events to consider in capacity expansion, the risk screening tool can aid in reducing a very large data space to a small set of key events. An illustrative example of how this may work is shown in Figure 13.

The capacity expansion model returns investment and retirement decisions for generation, transmission, and hardening options; this includes the nodal siting of new capacity and the timing (investment window) of these decisions. From this modeling, the performance of an asset under exposure to hazardous climate conditions is based on its location, age, technology, fuel source, and water source, and this all contributes to its ability to improve system resilience.

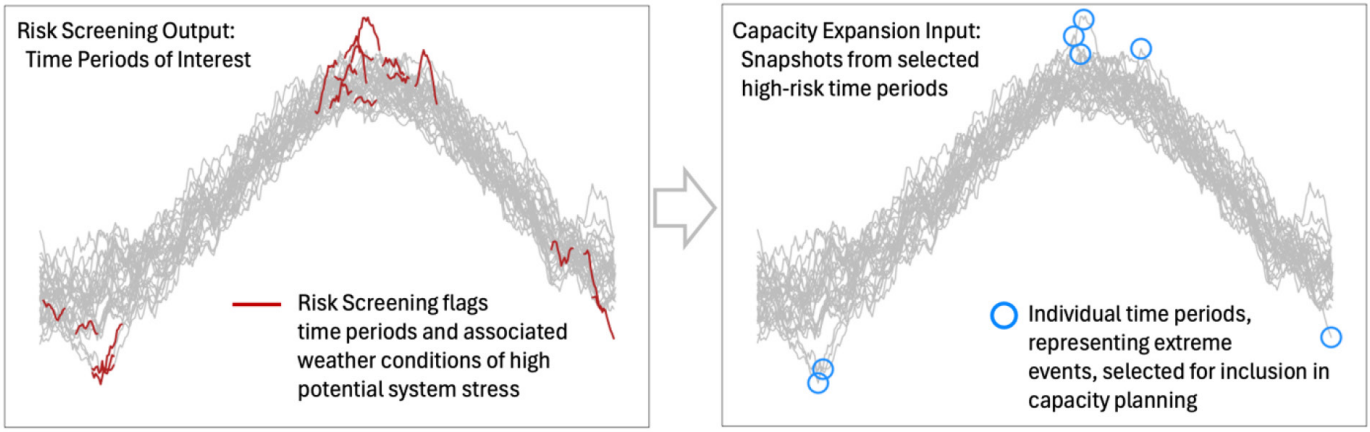


***Figure 13.*** *An illustrative example showing how the risk screening tool can be used to inform the selection of climate hazards (in the form of identified time periods and associated weather/load conditions) to plan for in a capacity expansion model. Here, individual time periods are illustrated, and capacity expansion inputs may include varying chronology to represent high-risk time periods with longer durations from Risk Screening output.*

## **EXAMPLE APPLICATION:** CAPACITY EXPANSION

For the Texas case study, EPRI leveraged the Adaptive Coordinated Expansion Planning (ACEP) tool.[29] ACEP coordinates the expansion of generation, transmission, and storage with flexible spatial and temporal resolution using a multi-stage investment planning optimization, which finds the lowest cost plan through the simulation of investment and retirement, operations, power flow, and policy impacts. Using event snapshots to plan for high impact, low probability events, it models resilience decisions through the representation of hazards and hardening options.

Examples of the capacity expansion data considerations are highlighted below. Temperatures from a high heat extreme event are shown within the Texas Case Study system in Figure 14.

Asset vulnerability functions, along with these weather conditions are used to determine the heat related hazard impacts on expected performance in the form of capacity derates. Hardening options and adaptations are also calculated as potential choices for the capacity expansion when optimizing resource selection.

While only shown above for a selected example of a heat event and natural gas turbine resources, this process is performed across all resources, representative times sampled, and risk-screened extreme events within the capacity expansion study. As a result of this optimization, least cost plans are identified, which can vary given planning tolerances for lost load. Figure 17 shows an illustration of more resilient plans with less tolerance for lost load, which may increase investment and operations costs relative to baseline plans.

29 *Adaptive Coordinated Expansion Planning Too.* EPRI, Palo Alto, CA: 2023. 3002024594.

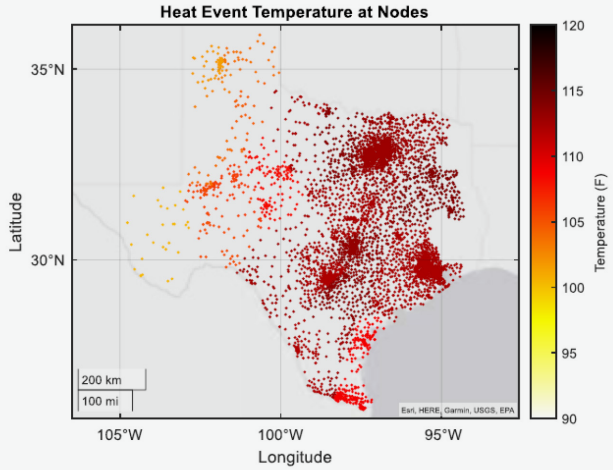


***Figure 14.*** *Map of Texas, showing the projected temperature at each node in the synthetic system for an extreme heat event used in capacity planning.*

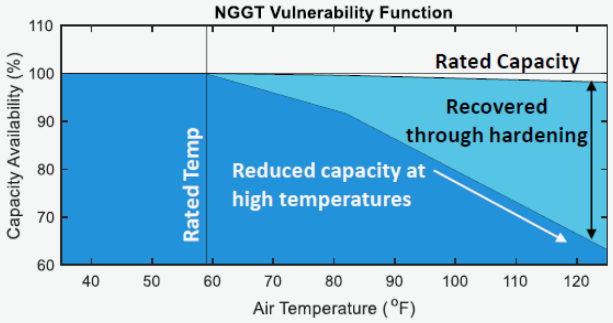


***Figure 15.*** *Natural gas turbine asset vulnerabilities to air temperature are shown in the form of reduced generating capacity (dark blue), also showing the benefits (i.e., in the form of recovered capacity) that may be gained through hardening investments – here showing expected performance with an inlet air chiller installed at the generating unit (light blue).*

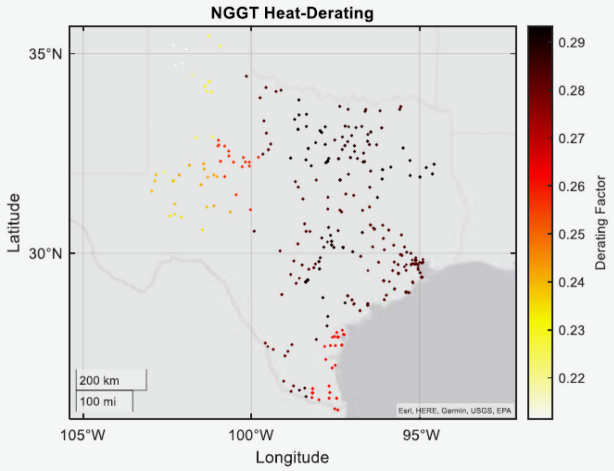


***Figure 16.*** *Based on asset vulnerability and weather conditions, the impacts of the high-temperature hazard during this event were calculated for natural gas turbine resource across the system, shown for units without hardening adaptations applied.*

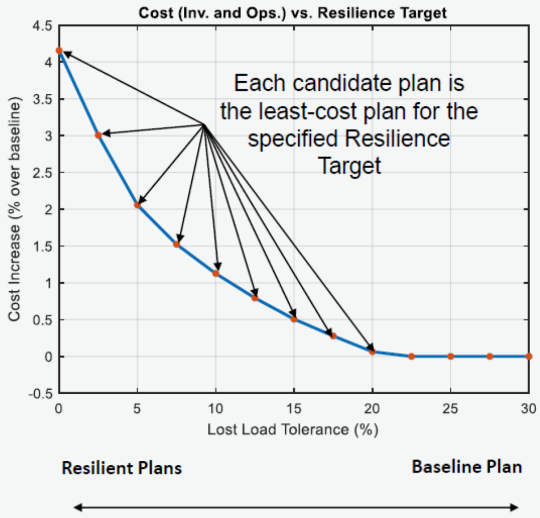


***Figure 17.*** *Candidate plans that result from the capacity expansion optimization of resources can be described across a frontier of investment (Inv.) and operating (Ops.) cost and resilience. Each plan identified is least-cost for the resilience objective targeted, but the cost associated with each differs given lost load tolerance, i.e., the constraint that controls allowable load lost during extreme event planning scenarios.*

## Capacity Planning Linkages

### Capacity Expansion Linkage Takeaways for Planning and Modeling

- Interlinking capacity expansion models with other bulk electric system models can help to focus modeling inputs and provide a more robust evaluation of proposed system buildouts. To do so, it is important to maintain consistency across modeling stages.
- System models that provide broader aggregations of the energy system and describe the amount and type of generating technologies viable in a given scenario can help to reduce the options needed in more detailed capacity expansion.
- Capacity expansion models can be linked with resource adequacy models and run iteratively so that portfolios which meet system planning criteria are identified.
- Including a step to screen periods of risk for inclusion into the capacity expansion model, and iteration with resource adequacy models, can help to distill what data to consider when modeling by focusing on key periods or event types.

The Capacity Expansion stage orchestrates climate informed planning linkages while optimizing system expansion to meet projected future electricity demands, and the proposed system buildout plans are then evaluated for reliability and resilience using other methods. There is likely to be some iteration between capacity expansion and these evaluation steps to ensure that performance targets are met. As such, it serves as a hub for referencing linkages across bulk electric system planning models. The climate informed capacity planning models described in Workstream 3's integrated framework are linked in the following ways:

### Technology Adoption Pathways to Guide Capacity Expansion

A technology adoption pathways model links with the capacity expansion model to screen for economically viable technologies across a larger economy and policy landscape, and it provides their performance characteristics and costs over time. Filtering the technology options is critical because the localized capacity expansion planning model is computationally demanding, and it can be helpful to simplify assumptions and provide a discrete, limited choice set to keep the model tractable. In addition to filtering variables, the technology pathway is loosely imposed on the capacity planning model via constraints that force the capacity solution to adhere to the technology pathways solution and ensure consistency in scenario representation.[30]

### Resilience, Cost, and Reliability Criteria

Reliability criteria evaluated through Resource Adequacy modeling, as defined in further sections of this report, might find that the expansion solution does not meet normal adequacy criteria in non-extreme events. Likewise, production cost modeling might find that the capacity expansion solution does not meet other planning targets such as emissions reductions, which could be resolved by tightening emissions constraints, or that the actual cost to operate is much higher than the capacity planning model anticipated. All of these situations may result in iterations where new information is passed to capacity expansion to better meet performance targets in other model evaluations.

### Extreme Events and Risk Screening

The risk screening tool and the capacity planning model form an iterative loop. The risk screening step evaluates planned systems to identify times of high risk. A diverse subset of these risk events is incorporated into the capacity planning

30 *Linking Capacity Expansion, Resource Adequacy, and Production Cost Modeling Tools for Integrated Strategic System Planning.* EPRI, Palo Alto, CA: 2024. 3002028534.

model, which aims to adequately mitigate the represented risks. The solution to the capacity model is then given back to the risk screening tool to screen for new risks that are pertinent with the new capacity plan. New events can be added to the capacity plan with each iteration until a robust event subset is constructed that sufficiently covers the risks in the full set of risk screening data. The risk screening tool identifies time periods associated with high risk of lost load because of weather-driven generator unavailability and high loads. These time periods can then be passed to the capacity expansion model. In addition to other representative time periods, the capacity planning model translates weather data for all time periods into relevant asset impacts.

### Coordinated Generation and Transmission Decisions

Both generation and transmission assets are vulnerable to hazards, so modeling the system's vulnerability requires accounting for both together. Moreover, using a mix of generation and transmission investments can be an optimal adaptation strategy. However, a capacity planning model is not a comprehensive transmission planning tool; detailed transmission studies are still needed to more precisely evaluate reliability, and these can be run based on candidate expansion plans while also considering the realities of hazard impacts across several scenarios of high system risk.

## Technology Adoption Pathways

### Technology Adoption Takeaways for Planning and Modeling

- Large scale energy-economy models can be used to inform more localized considerations for individual systems.
- Understanding the makeup of broad technology and policy futures can provide boundary conditions, useful for constraining the decisions that more granular capacity expansion models can consider.

In the context of EPRI's Climate READI initiative, a "technology adoption pathways" model is a large-scale energy-economy model that simulates an extensive geographical scope (e.g., nationwide or continental) of an energy system to analyze how changes in technology or policy constraints can impact the economic and energy-related dynamics of such systems.

Examples of such models used in the U.S. are EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy Model (US-REGEN),[31] NREL's Regional Energy Deployment System (ReEDS) model,[32] EPA's Integrated Planning Model (IPM),[33] and EIA's National Energy Modeling System (NEMS).[34] While these models may differ in their scope and methodology, they are essentially numerical abstractions of the complex economic and energy systems they represent. They are typically applied for scenario analysis, allowing users to change underlying economic and policy assumptions to investigate how these changes impact the results. Because of their extensive geographical scope and longer time horizon, these models typically have coarser spatial and temporal resolutions to maintain computational tractability. Individual generator units in each of the model's regions (which can be a combination of multiple states) are usually aggregated and represented as capacity blocks according to their types. Models also use only a subset of time-slices in the year to approximate intra-annual variability. Given these limitations on model resolution, these models typically do not support detailed climate resilient planning on their own.

31 "US-REGEN Documentation," EPRI, Palo Alto, CA (n.d.). Accessed Jan. 12, 2024, at: https://us-regen-docs.epri.com/.

32 Ho, J. et al., "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020," National Renewable Energy Laboratory, Golden, CO, NREL/TP-6A20-78195 (2021). Accessed at: https://www.nrel.gov/docs/fy21osti/78195.pdf.

33 "Documentation for EPA's Power Sector Modeling Platform v6 – Summer 2021 Reference Case," U.S. Environmental Protection Agency (n.d.). Accessed at: https://www.epa.gov/power-sector-modeling/documentation-epas-power-sector-modeling-platform-v6-summer-2021-reference.

34 "The National Energy Modeling System: An Overview," U.S. Energy Information Administration (2023). Accessed at: https://www.eia.gov/analysis/pdfpages/0581index.php.

Such models can have an important role in defining scenario-specific boundary conditions for more detailed and region-specific downstream planning and operation models. Boundary conditions can inform downstream models by limiting their decision space to become tractable in a way that is consistent with aspects of the defined scenario. Additionally, other scenario pathways, such as policy outcomes or technology changes, can be well represented in the long timeframes these models simulate.

Similar to the more detailed scope of Capacity Expansion modeling described above, a Technology Adoption Pathways model can also use climate data in the form of future adjusted hourly weather to define generator responses to climate impacts. Additionally, emissions scenarios, associated policy assumptions, and weather-sensitive load projections are also utilized by the model when determining pathways. For consistency across models, it can be beneficial to use the same climate data and load projections developed in previous steps. If consistent inputs cannot be used however, for example, due to differences in tool functionality, planners may benefit from comparing input data to assess if similar assumptions and trends are present to ensure modeling assumptions are sensible

Outputs from this stage link to downstream capacity expansion modeling, which define technology pathways, provide boundary conditions, which help to define the expected number, cost, and types of generator technologies to be considered within the capacity expansion model. This process contributes to the representation of climate impacts across modeling tools by representing the pathways and outcomes which may associate with broad economic scenarios modeled. Understanding the resulting bulk electric system boundary conditions provides consistent data and guidance regarding climate data choices that downstream modeling stages then build on.

## **EXAMPLE APPLICATION:** TECHNOLOGY ADOPTION PATHWAYS

For the Climate READi Texas case study, EPRI used the U.S. Regional Economy, Greenhouse Gas, and Energy Model (US-REGEN)[35] as its "technology adoption pathways model." As with other tools in this Climate Resilient Planning Framework, using US-REGEN requires the input of weather data adjusted to potential future climate conditions (dependent on the scenario's assumptions). This weather data is used to simulate the availability of wind and solar resources, to set capacity deratings of thermal generators and inter-regional transmission lines, and to directly drive projections of end-use electricity demand.

Figure 18 shows the modeled installed capacity of Texas' generator fleet in 2050 for two different scenarios. The results show the transition to a high renewable system, though changes in climate and associated policy assumptions can result in different resource builds. By 2050, the Texas capacity mix could be as much as 57% wind and solar, up from 25% in 2020, driven by decreasing capital costs of renewables, Inflation Reduction Act incentives, and other policy incentives, high-quality wind and solar resources, and strong growth in battery storage. This renewable uptake increases a further ten percentage points when accounting for climate change, as the winter peak drops by 5-10 GW.

35 EPRI, "US-REGEN Documentation." Accessed: Jan. 12, 2024. [Online]. Available: https://us-regen-docs.epri.com/.

Outputs of US-REGEN results in this Texas Case Study were then explicitly passed to the downstream, more spatially-detailed Capacity Expansion model to ensure internal consistency and reduce its solution space for climate-resilient investments. These US-REGEN outputs defined boundary conditions about the assumed performance characteristics and costs of economically viable technologies in the capacity expansion model.

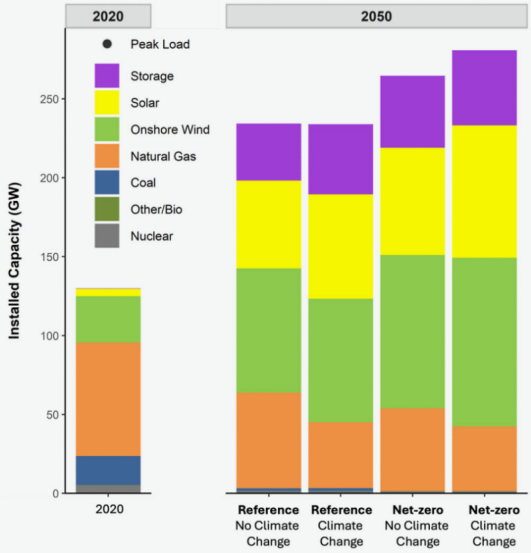


***Figure 18.*** *Results from US-REGEN showing different technology buildouts to installed capacity in 2050 related to four scenarios: Reference Decarbonization Policy/No Climate Change Impacts; Reference Decarbonization Policy/With Climate Change Impacts; Net-zero Decarbonization Policy/No Climate Change Impacts; and Net-zero Decarbonization Policy/With Climate Change Impacts. These big-picture results of viable technologies can serve as useful starting points for more detailed assessments of resource planning, while also providing insight into sensitivities within policy assumptions.*

## Resource Adequacy

### Resource Adequacy Takeaways for Planning and Modeling

- Resource adequacy assessments have typically been run using historical weather conditions. To understand system reliability under a changing climate, additional weather conditions from climate projections can be integrated along with asset impacts modeled from asset vulnerability data.
- Events during which reliability criteria are violated can be identified and passed back to the capacity expansion model, to be incorporated explicitly for both capacity and adaptation considerations.

Resource adequacy assessments are used in integrated planning to investigate the system reliability of an expansion plan under many potential operational scenarios. Metrics defined for these assessments help assess levels of system reliability. If an assessment of a candidate expansion plan does not lead to adequate performance, the capacity expansion model can be updated accordingly, such as through the inclusion of additional extreme events or an updated planning reserve margin.

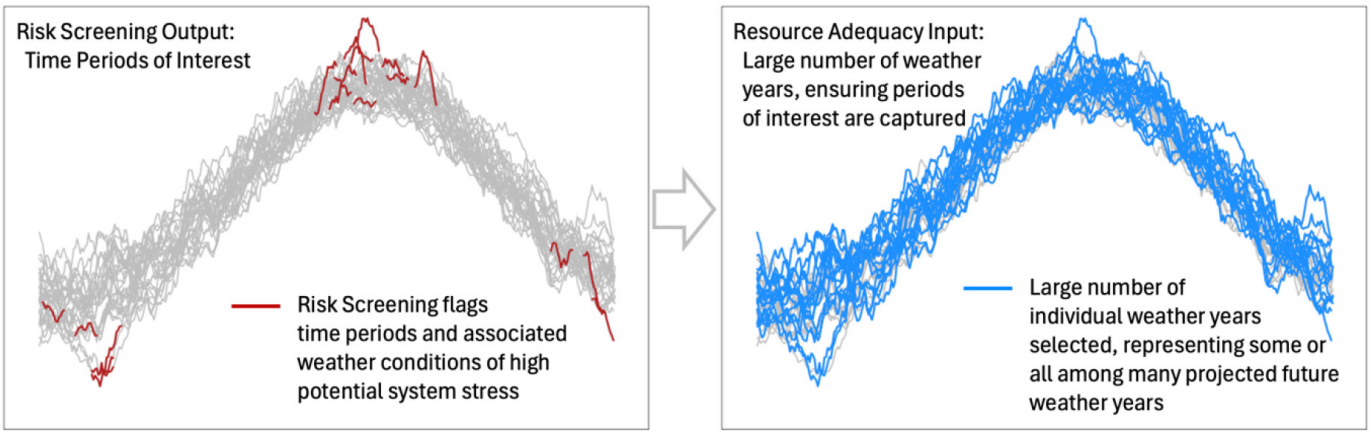


***Figure 19.*** *An illustrative example showing how the risk screening tool can be used to inform the selection of climate data (in the form of weather years with a mix of high- and low-risk) to evaluate using resource adequacy.*

After running the capacity expansion model, the resulting system can be tested through a reliability assessment on the adequacy of a proposed resource mix. The data pipeline includes both climate data and load inputs, along with detailed representation of system generation and transmission assets. By explicitly including climate data input, the adequacy assessment can be designed to study system adequacy and reliability under a wide range of weather possibilities. The resource adequacy assessment investigates operational reliability, generally run on an hourly basis for multiple weather years to provide insight on system performance over a wide range of operating conditions. This assessment is necessary as, practically, capacity planning models may only be able to handle a limited amount of chronological timesteps, due to the high computational burden. Therefore, resource adequacy assessments serve to provide insight about operational performance over a large set of operating scenarios. Operating scenarios are often created via the inclusion of different weather years and the use of Monte-Carlo simulation to analyze reliability over multiple time-sequential simulations that include additional operational details such as outage state-transitions of generators. Figure 19 shows an illustrative example of how resource adequacy can make use of a large dataset of weather years, using information from risk screening to capture a diverse set of years for evaluation.

Typically, resource adequacy assessments rely on historical weather observations, but for climate-related resilience assessments, resource adequacy should instead be assessed using projections of future conditions, ideally using a large number of weather years to capture inter-annual variability. Selection considerations can leverage insight from the Risk Screening tool, to include risk prone time periods, in addition to time periods which are representative of the range of future conditions. When selecting weather years to represent climate extremes however, it should be noted that assessments based on extreme events may over or underestimate risks as compared to other scenarios. For example, years with more heat related extremes may underestimate risk related to cold related extremes. Selecting weather years which test system adequacy in a variety of conditions can result in a richer set of results.

Climate data moves through this stage of the pipeline, as multiple climate-projected weather years are included in the resource adequacy model to represent the widest possible range of operating conditions. Climate-projected weather data is used to create generation profiles for vari-

able renewable energy resources and informs the availability of thermal generation depending on weather conditions. Outage probabilities of thermal generators are calculated based on temperature using historically observed outage data from the North American Reliability Corporation's (NERC) Generating Availability Data System (GADS) database. If adaptation options are realized for thermal generators, this temperature dependency of outages is adjusted to reflect the new performance parameters. Further, temperature dependent availability can be imposed as timeseries values to, for example, represent high temperature derates.

As described in the Risk Screening and Capacity Planning stages, an iterative process also occurs between Capacity Planning and Resource Adequacy modeling to determine bulk electric system adequacy and reliability. When violations of system reliability and resilience metric targets are identified in these more granular reliability models, these identified events may be passed back to the capacity expansion model. The capacity expansion model would then be updated by taking in additional events as snapshots or representative periods to plan for, and re-run to produce a new resource mix that addresses the violations.

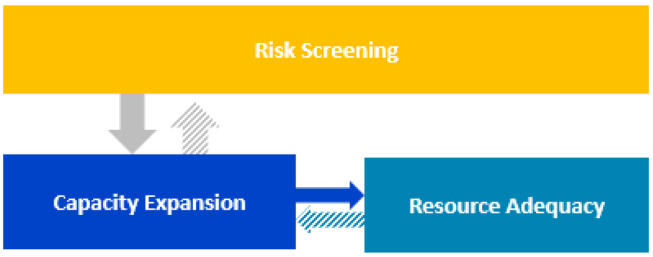


***Figure 20.*** *The iterative process between Risk Screening, Capacity Expansion, and Resource Adequacy can be repeated until the system meets targeted resource adequacy standards.*

The evaluation of Resource Adequacy assessments is based on reliability metrics, for example, the probabilistic Loss-Of-Load-Expectation (LOLE) and Expected-Unserved-Energy (EUE). Further, risk-based metrics such as the 95th percentile of LOLE or the conditional value at risk specifically reflect performance at or over, respectively, the worst 5% of cases and can therefore provide additional insight on tail event risks. These reliability metrics provide information on system reliability and inform the necessity of updates to the planning reserve margin or the need for additional weather year time periods of stress to further investigate.

## EXAMPLE APPLICATION: TEXAS CASE STUDY

For the Texas synthetic case study, Energy Exemplar's PLEXOS Energy Modeling Software was used to perform the resource adequacy assessment. A time-sequential Monte-Carlo optimization-based approach allowed for a detailed analysis of the system's operational constraints. The resource adequacy assessment was performed for multiple weather years in cross-combination with multiple outage draws. The weather years represented 71 years of historical hourly data that were then shifted to represent the climate of the year 2050, resulting in 71 climate-projected weather years for analysis.

To reduce the computational burden of the resource adequacy analysis in the Texas Case Study, nodes were aggregated to the 8 weather zones defined for the Electric Reliability Council of Texas (ERCOT) system. Transmission capacities were aggregated and represented by inter-zonal interfaces. GEM-provided load response functions were available on a county level. Temperature dependent, county level response curves were mapped to corresponding weather stations, and hourly load profiles for each of the 71 climate projected weather years were created. Base and temperature dependent load profiles were then aggregated to corresponding zonal levels.

Transmission limits were also represented by zonal aggregation representing inter-regional transfer through single transmission lines, using transport-based network representation. Installed generators and characteristics were input from the proposed capacity expansion buildout and, if unavailable there, from US-REGEN.

Key metrics presented in Table 4 highlight the drastic difference in reliability across different future systems, here differentiated by lost load tolerance. Only the LLT – 0% case (i.e., a system built with a capacity planning target of 0% lost load during all extreme events considered) falls within a standard LOLE=0.1 planning criterion. Similarly Expected-Unserved-Energy (EUE) and Loss-of-Load-Hours (LOLH) exhibit these differences, with, for example, an expected 38 times more days of lost load in the baseline case versus the LLT-0% case. These results provide an example of the type of climate-informed model output that can be used to justify investments in a more resilience system, as the benefits of reduced load loss can be compared to the investment and operational costs of each proposed system buildout.

***Table 4.*** *Reliability results from resource adequacy modeling across 71 climate-projected weather years mapped to the year 2050, showing the variation in results across levels of lost load tolerance*

| SCENARIO | LOSS OF LOAD EXPECTATION (DAYS/YEAR) | EXPECTED UNSERVED ENERGY (MWH/YEAR) | LOSS OF LOAD HOURS (HOURS/YEAR) |
|---|---|---|---|
| **Lost Load Tolerance: 0%** | 0.08 | 7.77 | 0.09 |
| **Lost Load Tolerance: 10%** | 0.46 | 1,837.62 | 1.16 |
| **Baseline** | 3.06 | 19,994.21 | 8.67 |

The Texas case study shows again the importance of looking at multiple metrics and across a manifold of weather years, as illustrated in Figure 21 and Figure 22 respectively. Figure 21. Monthly distribution of Loss-of-Load-Expectations (LOLE) and Expected-Unserved-Energy (EUE) for the Baseline case and Lost-Load-Tolerance (LLT) Cases 0% and 10%. The highlighted months of July and July for the baseline case demonstrate the insight gained from different metrics – the LOLE is much higher for July compared to June, but the EUE values are similar, meaning that June has fewer but more severe loss of load events.

As can be seen from Figure 21, high-risk periods predominantly appear during the summer months. Moving from the Baseline case to the LLT-10% case, these risks are alleviated to some extent. Looking at the Baseline case, it becomes clear that while July experiences a higher LOLE (i.e., frequency-based metric) and therefore more events, June experiences less frequent but more severe events (i.e., lower frequency (LOLE), but similar expected unserved energy (EUE)). As illustrated in Figure 22, events are also not equally distributed across weather years, but can vary significantly across weather years. Here, for example the year 2011 seems particularly pronounced because of heatwave events.

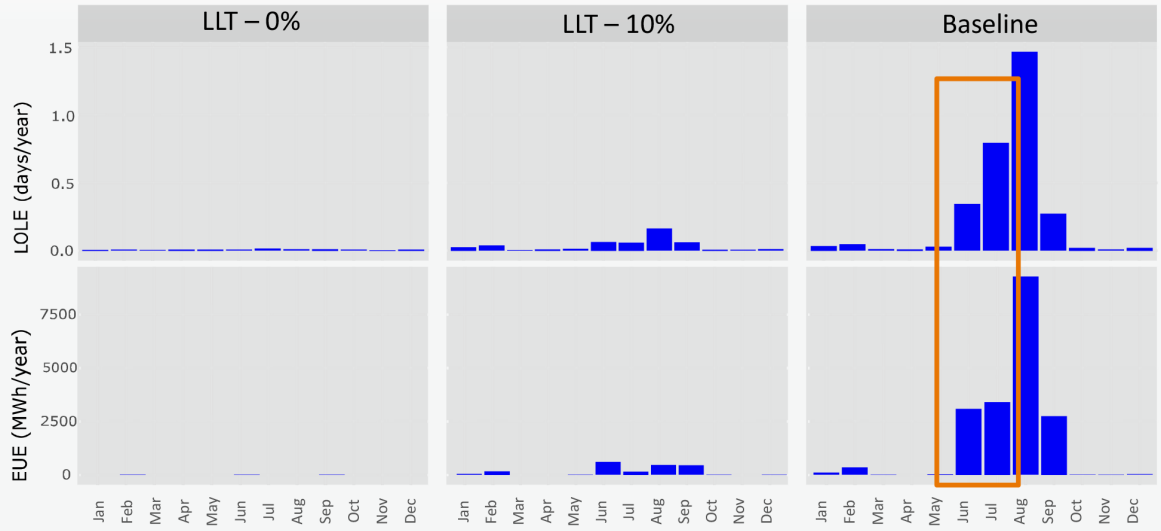


***Figure 21.*** *Monthly distribution of Loss-of-Load-Expectations (LOLE) and Expected-Unserved-Energy (EUE) for the Baseline case and Lost-Load-Tolerance (LLT) Cases 0% and 10%. The highlighted months of July and July for the baseline case demonstrate the insight gained from different metrics – the LOLE is much higher for July compared to June, but the EUE values are similar, meaning that June has fewer but more severe loss of load events.*

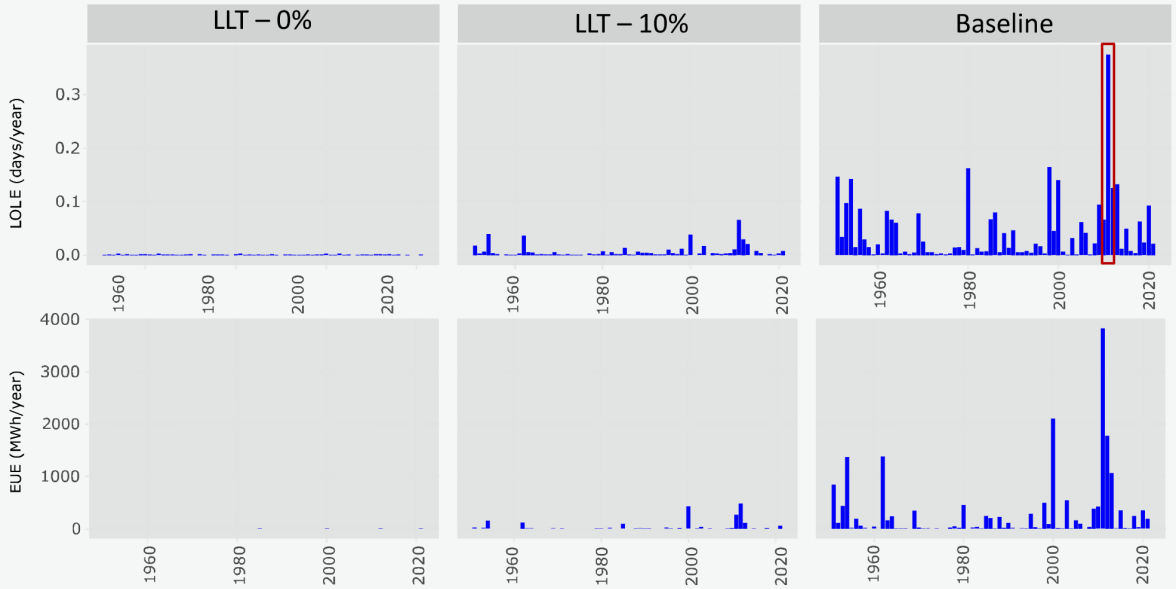


***Figure 22.*** *Loss-of-Load-Expectations (LOLE) and Expected-Unserved-Energy (EUE) for the Baseline case and Lost-Load-Tolerance (LLT) Cases 0% and 10% across climate-projected historical weather years, with each year mapped to represent the climate of 2050. I.e., the x-axis labels represent the weather variability from historical years, but each year is mapped to the climate of 2050. There is large variation across years, with the highlighted year showing the severity of what a bad year may look like, along with how much might be lost if evaluating only a small selection of weather years.*

## Production Cost Modeling

### Production Cost Takeaways for Planning and Modeling

- Production cost models typically simulate representative system conditions. Including screened high-risk events in addition to representative ones can provide important insight into system operations and impacts during extreme events.
- Representing climate impacts to assets in production cost models, along with adaptation or hardening options under consideration or identified in the capacity expansion stage, can help quantify the benefits of adaptations to assets or operations.

Production cost models allow the study of various aspects of power system operation and the efficiency of its associated markets through a detailed representation of a system. These models are usually characterized by a detailed temporal (hourly or sub-hourly time intervals) and geographic (nodes in the network) representation. This type of analysis can provide valuable information for short- and medium-term planning for a variety of purposes, including system and unit operating costs, system operational resilience and flexibility, and market efficiencies and incentives.

Simulations are typically run using a two-stage model. Resources are first selected for use (i.e., committed to the market) and then dispatched to a specific power output level. This is done to approximate a system operator's operational processes given uncertain day-ahead information and the realizations of actual conditions. Detailed temporal representation of the system has become even more important to adequately analyze operational flexibility as variable generation and energy-limited resources become more widespread. These can introduce higher levels of variability and may require modeling of constraints between time steps.

Production cost models can be run for multiple weather years to further investigate the cost and operation of a system during a wider variety of weather conditions. Weather years selected may include specific climate projected years which represent normal or extreme climate conditions. Contrary to Resource Adequacy assessments, which may simulate as many weather years as possible to uncover situations where a system could experience loss of load events, production cost model simulations may focus on simulating fewer weather years, but at a greater level of detail to understand realistic operations. Understanding these realistic operations can help planners evaluate the system resilience and operational reliability of the same expansion plan, including operational characteristics. Figure 23 shows an illustrative example of how data selection for production cost modeling may be informed by risk screening to capture a diverse set of years for evaluation.

Climate adaptation strategies can improve the performance of the system in the face of climate hazards. Aside from investment-based strategies, such as hardening or adaptation options described in the Capacity Expansion stage, operational strategies explored in production cost models may use different operating practices to improve the performance of existing assets. Examples of these operating practices can include dynamic reserves, transmission rerouting, and gas-electric coordination.

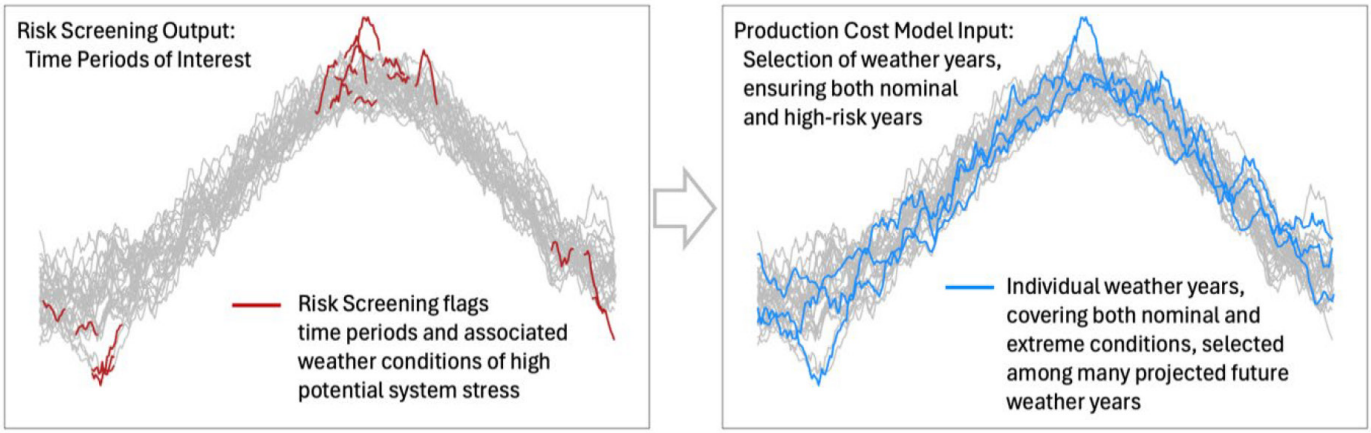


***Figure 23.*** *An illustrative example showing how the risk screening tool can be used to inform the selection of climate data (in the form of weather years with a mix of high- and low-risk) to evaluate using production cost modeling.*

The representation of climate hazards in production cost models is done in a similar way as within other bulk electric system planning tools and as summarized in Chapter 3. Projected climate data from Workstream 1 is mapped to representative weather stations to obtain hourly future climate weather year projections. Nodes and generators mapped to each node are also matched with the closest weather station. Resources identified from Capacity Expansion results can be input into production cost models, including new and existing resources with hardening options and adaptations. The operational time series for these generators is calculated including hazard impacts to generators, given the asset vulnerability functions and impacts input from Workstream 2. Demand time series are also climate-informed, as described in previous sections. With these consistent climate and impact data inputs, production cost simulation output can be analyzed to identify operational strategies that complement those used to devise investment plans and improve overall resilience planning.

## EXAMPLE APPLICATION: PRODUCTION COST MODELING

For the Texas Case Study, PLEXOS was used to perform a multi-cycle production cost simulation. Based on the results of the Capacity Expansion Model, generation portfolios were selected to build the study scenarios. Projected climate data for the year 2050 was simulated with weather patterns from some historical years to produce forecasts for solar and wind generation and demand profiles. The temporal and spatial coverage of the different cycles in the PCM aligned with the RA model.

A Climate Adaptation Investment Strategy consisting of hardening thermal generation units to prevent capacity reductions due to high temperature was considered through production cost modeling. The impact of an ambient temperature increase on the technical parameters of the thermal generators was preserved to analyze a Climate Adaptation investment Strategy: hardening resources for temperature impacts using an inlet air chiller as the target adaptation investment.

Simulations carried out analyzed the impact that an increase in ambient temperature may have on: 1) the operational resilience of the system, characterized by the changes in unserved energy and reserves shortages, 2) market efficiency, which is characterized by changes in the total cost of the system and hourly price variations, and 3) the incentives that generation owners in energy-only markets may have to develop climate adaptation strategies.

The model was used to study the impact of heat waves on system reliability and energy market efficiency with and without an adaptation strategy. Incentives that can be generated in the energy market so that the generation units decide to invest in these hardening options were also studied.

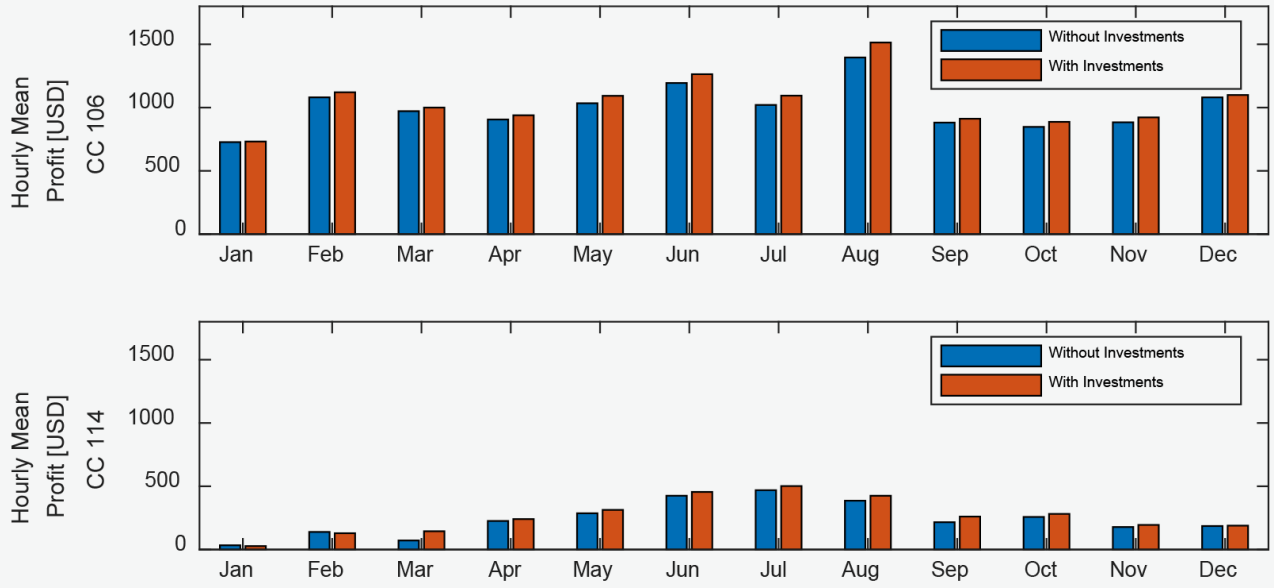


***Figure 24.*** *Hourly mean profit is shown for two selected natural gas combined cycle units for cases run with and without the additional investment in an inlet air chiller, which is an adaptation that can increase available capacity during high-temperature events. Results show that with additional adaptation investments, units may be able to maintain rated capacity and increase profit.*

As can be seen in the figure, the installation of adaptations to prevent the generation units from falling below their rated capacity during heat waves leads to an increase in the profitability of the units due to the increase in their electricity generation in the short term. However, it is necessary to analyze the market price implications of a massive deployment of this type of mitigation strategy in the medium term to ensure that these investments are adequately incentivized.

## Transmission Reliability

### Transmission Reliability Takeaways for Planning and Modeling

- Climate projections to represent periods of extreme weather can be incorporated within transmission reliability models. Including periods of screened risk which have also been evaluated across other systems models allows for consistency in evaluating the climate risk of certain events.
- The selection of snapshot events for more detailed study may require bigger picture thinking, considering spatial and temporal asset and load impacts, to better represent the variability among high-stress system conditions.

After producing a climate resilient capacity plan, a transmission network reliability assessment is performed as one of the bulk electric system reliability and deliverability tests. Transmission reliability planning identifies a bulk transmission system that can deliver the generation to loads with a satisfactory level of reliability. While long-term expansion planning and resource adequacy analysis can inform transmission needs, they lack detailed modeling of the transmission system and require additional analysis specific to transmission reliability. Additionally, transmission reliability assessments are conducted on static, snapshot representations of system conditions.

Transmission reliability planning utilizes models that represent the physics of electrical quantities in the grid in much higher detail; however, representation across all identified time periods of stress is infeasible due to the computational demands of creating and running each assessment. As such, analysis is required to reduce the dimensionality of possible system conditions worth studying. Workstream 3 developed approaches to evaluate the statistical nature of periods of climate stress that may occur for hours to many days, as identified in the Risk Screening and Resource Adequacy modeling stages. This allows the transmission reliability assessment to focus on the most critical operating conditions that can functionally serve as boundary conditions for transmission planning analyses. Additionally, they can uncover operational issues in the transmission system that need mitigation measures. A more detailed overview of the Transmission Reliability stage is shown below (Figure 25).

Hourly datasets representing system operating conditions are estimated from the translation of weather to bulk electric system impacts, and risk screening can then be used to guide the selection of representative hour snapshot events for transmission models to use for further analysis. Figure 26 shows an illustrative example of how the risk screening tool can aid in reducing a very large dataset to a small number of key events that may be most critical for detailed study using transmission reliability models.

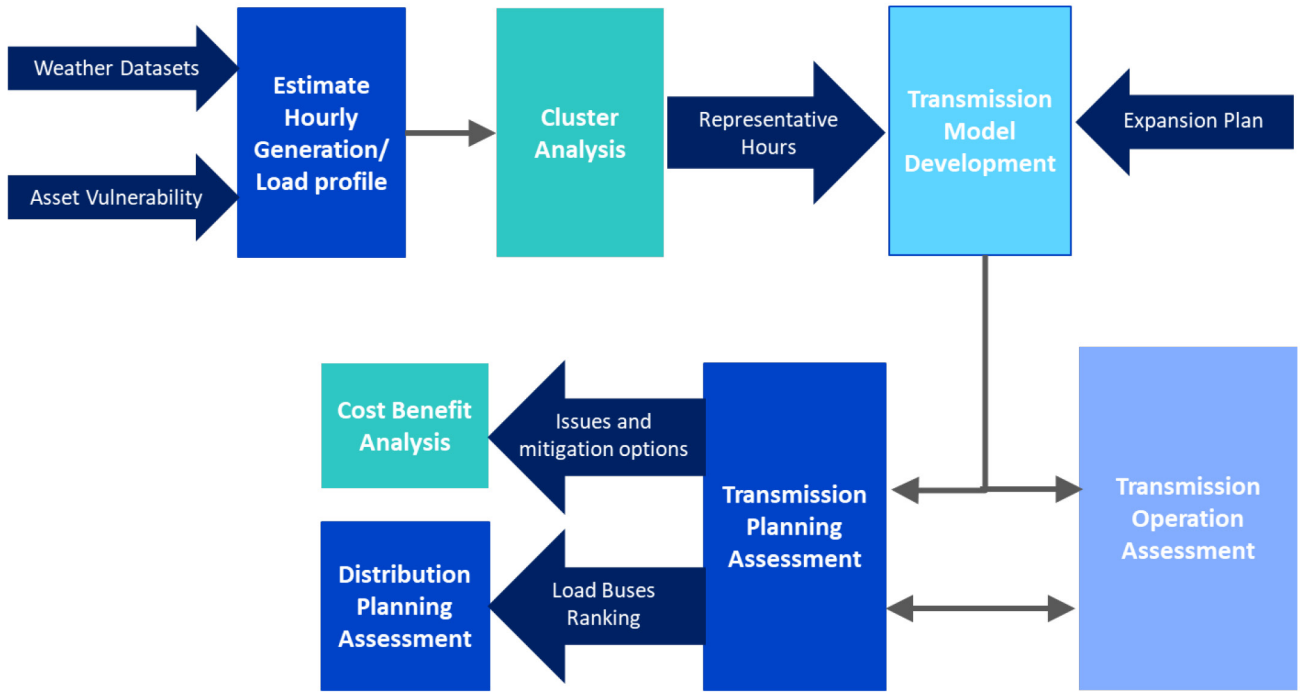


***Figure 25.*** *Climate-informed transmission reliability planning framework*

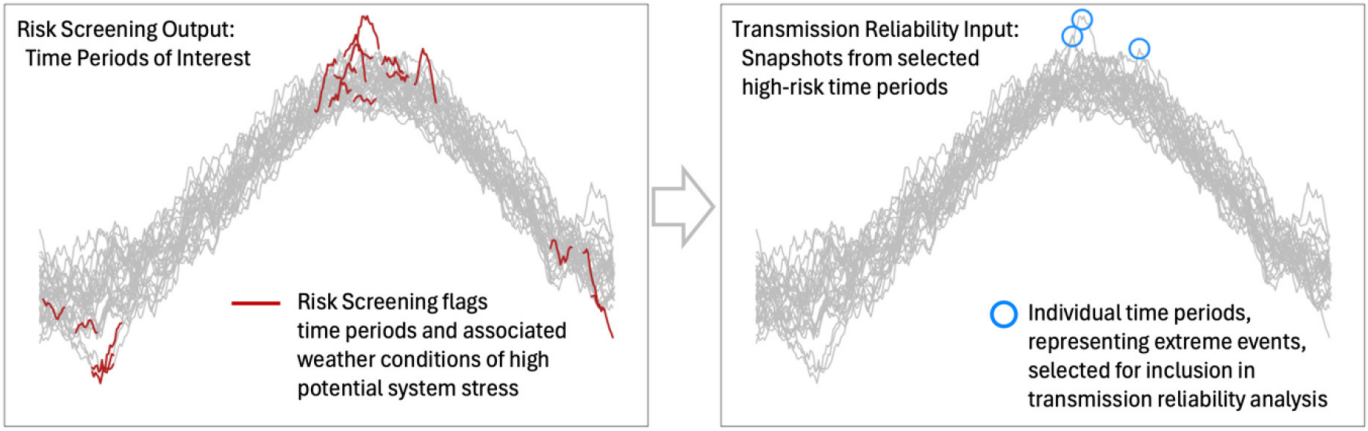


***Figure 26.*** *An illustrative example showing how the risk screening tool can be used to inform the selection of event snapshots (in the form of identified time periods and associated weather/load conditions) to study with transmission reliability models.*

While a time series analysis that creates transmission models for each hour of the entire input dataset would be ideal for providing a picture of the full operating spectrum, this may not be computationally tractable. One strategy to address this constraint is to focus on specific critical operating conditions. An approach that analyzes all operating hours to identify clusters of similar operating conditions can be useful. By prioritizing high-risk future conditions

and identifying representative study hours, it is possible to select suitable operating conditions to develop power flow cases for reliability/resiliency assessments. This approach can help transmission planners sample a manageable number of operating hours from the clusters for analysis with high confidence that they have not missed critical operating scenarios.

After selecting an appropriate number of representative hours, planners can build transmission reliability models for those snapshots, with these models accounting for nodal demand, resource outputs, and best available transmission facility ratings for those selected hours. Expansion plans that come from long-term planning/resource adequacy assessments need to be incorporated during the model builds as well.

The system response, as represented by these models, is reflected by applying a contingency event to the initial operating conditions. The existing practice is to apply contingencies representing one or more associated facility failures, as defined by the NERC planning standard.**36** In addition to standard contingency lists, additional contingencies representing extreme weather scenarios such as hurricanes or wildfires, which can cause the failure of multiple generation or transmission assets, can be applied to the transmission models to analyze the bulk electric system's response. Finally, identified issues and potential adaptation options for such issues can be evaluated for their potential reliability value.

36 "TPL-001-5 "Transmission System Planning Performance Requirements," NERC (nd). Accessed at; https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-5.pdf

## EXAMPLE APPLICATION: TRANSMISSION RELIABILITY

For the Texas case study, high-risk periods screened by the RiSc tool were utilized for cluster analysis. RiSc estimates available capacity of generators utilizing weather data and asset vulnerability information highlighted in previous Data Pipeline stages and Climate READi workstreams. The inclusion of these inputs enables the direct consideration of climate impacts into transmission planning. Another EPRI tool for dimensionality reduction, the High-Level Screening (HiLS) tool, was used for cluster analysis during transmission planning. HiLS identified key features and common system state clusters using principal component analysis concepts. Representative hours were sampled from the identified clusters. Per the recommendation of the capacity planning assessment, the system operating condition from these selected hours, base topology, and expansion plan (new generation and lines) was used to create the power flow cases.

As a reference case for comparison purposes, a set of power flow models (winter peak and summer peak) were also developed using the reference expansion plans, which did not consider any climate dataset. Following the power-flow model building, a N-1 contingency assessment was performed for the set of reference cases as well as climate-informed cases. Results were compared to assess the performances between the two scenarios. This process is illustrated below in Figure 27 and Figure 28. Results found that additional reinforcements were needed and that planning transmission without considering weather may be inadequate during stressed weather conditions.

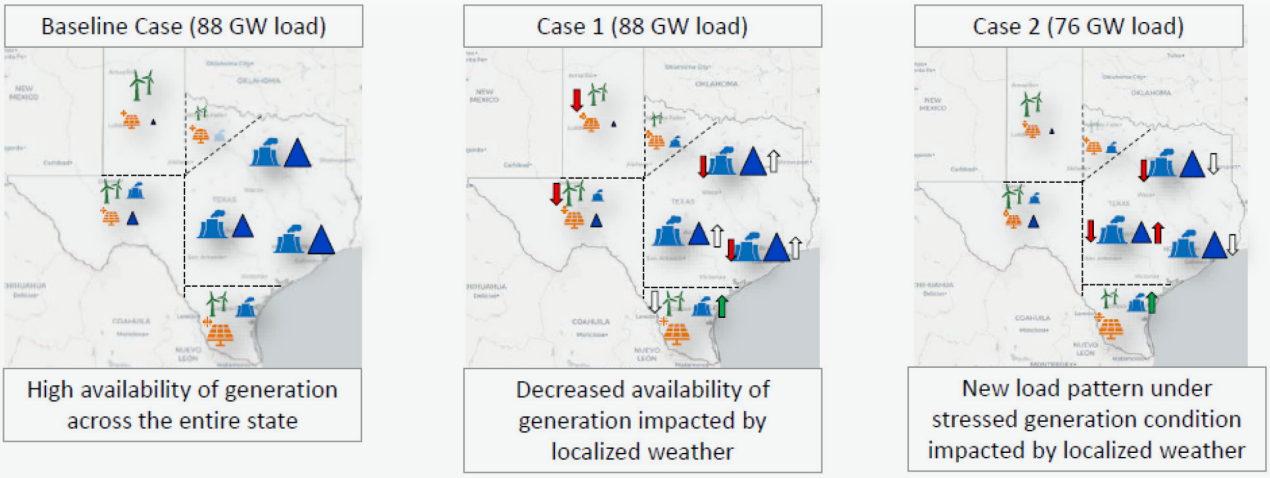


***Figure 27.*** *These maps illustrate a variety of medium- and high-load system conditions that result in different power flow patterns as a result of weather conditions. Reliability of these new conditions was compared against a "traditional" worst case condition, which was not informed by weather. Results show a changing risk landscape, requiring different sets of solutions, when climate is considered in evaluating transmission reliability.*

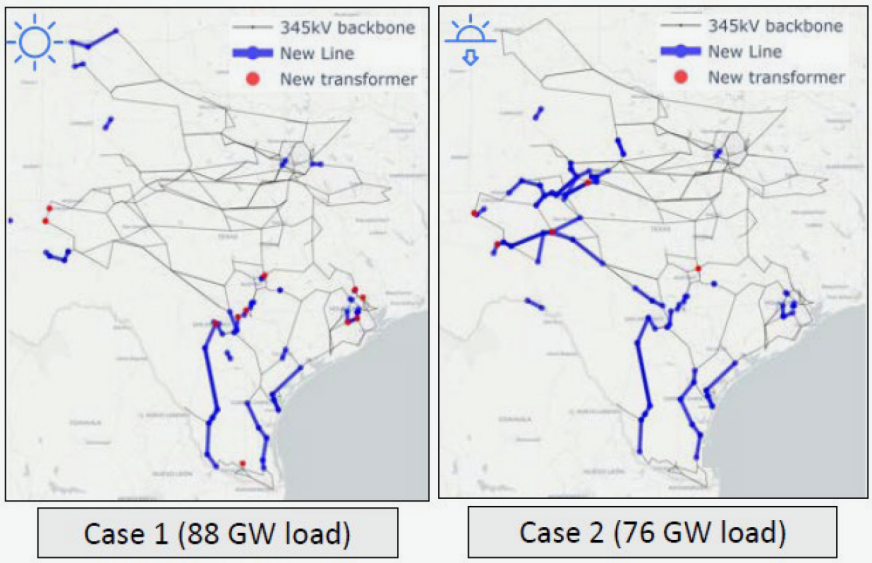


***Figure 28.*** *Additional reinforcements, required on top of the baseline plan were needed because of the weather informed cases. Planning transmission without considering weather may be inadequate during stressed power system conditions.*

# 5 CONCLUSIONS FOR PLANNERS IMPLEMENTING THE CLIMATE DATA PIPELINE

## Determining the Benefits of Resilience Investments

Planning for the impact of climate hazards on the bulk electric system is necessary to ensure that a future system can meet the needs of customers under changing climate conditions. However, added resilience usually comes at a cost which needs to be weighed against the benefits of improved resilience. The integrated modeling methodology highlighted in this report enables these comparisons, and it is important to understand how costs and benefits can be assessed to support decision making, all while consistently representing climate hazards, impacts, and uncertainties across the modeling pipeline.

After consistently integrating climate data into integrated bulk electric system planning stages, a natural question is how to use the results to support planning decisions and changes to operating procedures. Each step of the integrated modeling framework discussed here can provide insight into the value of planning a system with climate considered in a meaningful way, and this value can be assessed using measures such as load served, reduction in damaged assets, operational costs, capital costs, and emissions reductions, among others. The results that come out of these models can be used to determine the differing impacts to cost and performance for systems planned with and without climate considerations, using the 'without climate change' results as the reference case from which to then calculate the differences in climate-informed planning. Whether through detailed cost-benefit analysis, where each benefit is monetized, or by comparing proposed options based on several selected criteria, the combined set of model results can inform the calculation of both costs and benefits, given that sufficient climate variability is captured in the input data. This can inform cost justification for new assets, hardening decisions, and other adaptations to improve asset or system resilience. By using consistent assumptions about scenarios, climate hazards, and asset vulnerabilities, results more clearly articulate the relationship between assumptions and outcomes, which ultimately aids in the determination of benefits that are expected to come from planning with resilience in mind. In contrast, inconsistent modeling assumptions and underlying data can produce irreconcilable conclusions and confuse the interpretation of results.

## Key Takeaways

Navigating the interconnections of bulk electric system planning for resilience within changing climate norms and extremes is new for the electric power industry. The Climate Data Pipeline lays out a set of considerations and approaches for transforming climate and weather data inputs into information that can inform planning models consistently across modeling stages.

To perform climate informed bulk electric system planning, planners need to consider how to incorporate relevant climate data across an integrated modeling framework. Parameterizing the relationships between aspects of the bulk electric system and weather provides a way to reflect climate related impacts within modeling stages. This is done by using temporally and spatially relevant climate data, defined asset vulnerability functions, and weather-sensitive load projections to model location- and time-dependent asset operations that will inform system needs. Linkages between modeling stages, where these bulk electric system climate inputs are utilized, allows for planning results that are consistently informed by climate risk and targeted to meet a shared objective for resilience. Following this integrated planning approach, the opportunity for evaluation of resilience benefits and adaptation prioritization can be conducted.



Key takeaways for integrating climate impacts into bulk system planning include:

- When used consistently across interlinked modeling stages, climate data inputs can support cohesive and climate-informed bulk electric system planning.
- Planners assessing climate risk may find it useful to consistently consider a range of data, including climate, bulk electric system, and broader environmental data, when designing and evaluating scenarios around future uncertainties.
- Climate data has many sources and forms and can include historical and projected climate data in various formats. Downscaling methods, such as those which provide hourly temporal granularity at specific weather locations, can be useful to produce more relevant input when integrating climate impacts into planning models.
- Characterizing the weather sensitivity of supply and demand can facilitate the integration of climate risk assessment directly within bulk electric system models.
- Categories of climate-informed data inputs for modeling the bulk electric system can include asset vulnerability, weather-responsive loads, weather-to-power supply curves, hazard impacts, system performance, and risk screening for extreme events.
- Modeled resource performance impacts are included in planning tools to show altered availability, efficiency losses, capacity derates, physical damage, operational cut-off limits, shortened life spans, or changes in required maintenance.
- Methods that identify periods of potential system risk along with modeling that enumerates potential technology adoption pathways may help facilitate efficient and consistent capacity expansion and reliability modeling.
- Iteration between Capacity Expansion, Risk Screening, and Resource Adequacy models is a process which can be employed to coherently meet planning requirements across linked bulk system models.

## About EPRI

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## About Climate Readi

Climate READi (**RE**silience and **AD**aptation initiative) is seeking to address the challenges of assessing the impacts of physical climate risks on the power system, convening global thought leaders, members of the scientific community, and other stakeholders necessary to build a consistent, industry-accepted framework to identify optimal adaptation and resilience investments. For more information, visit www.epri.com/readi or contact ClimateREADI@epri.com.


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