Climate READi: Power

Planning for Climate Resilience in the Power Sector

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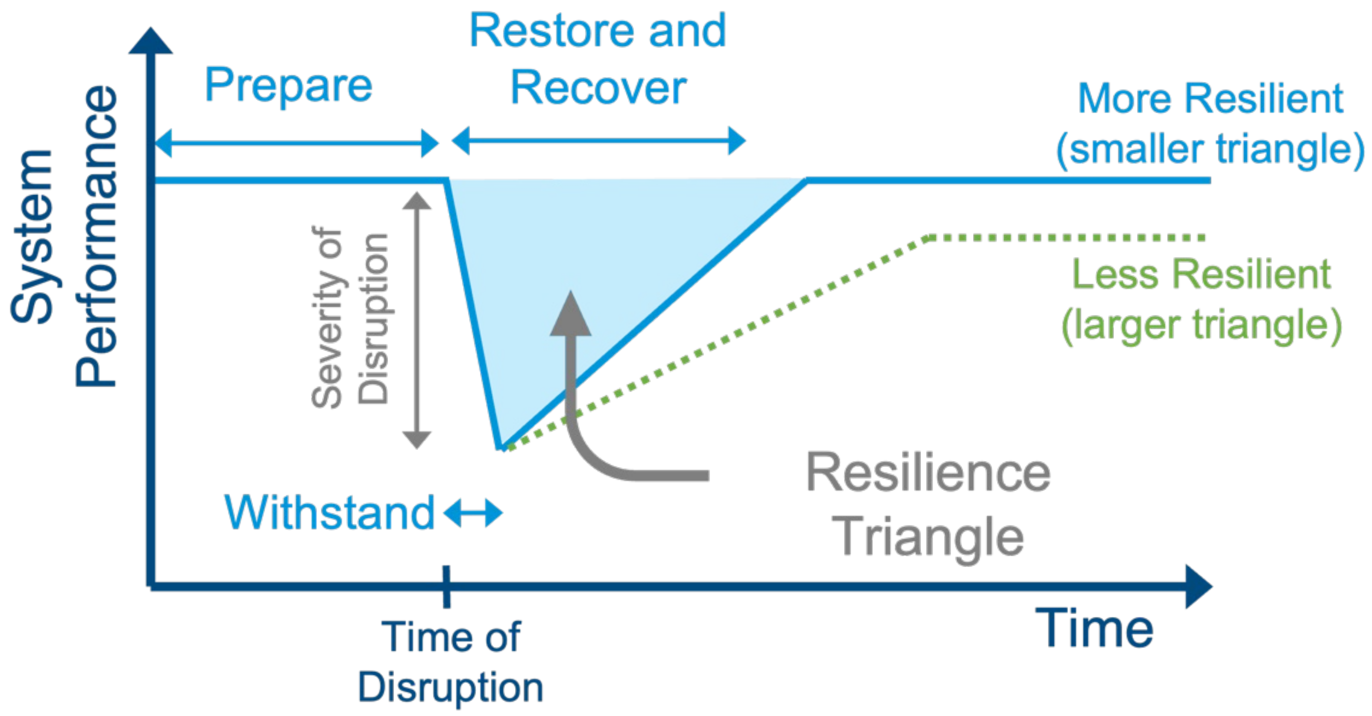
Andrea Staid, PhD
Energy Systems and Climate Analysis

What is Climate Resilience?

Resilience: the ability to anticipate, prepare for, respond to, and recover from potentially disruptive events, ideally while maintaining an adequate level of system function and with minimum damage or adverse impact



- Climate hazards can result in disruptions to infrastructure assets and services
- Being resilient to those hazards means ensuring that our society does not experience outsized loss or suffering because of these disruptions

What does climate resilience look like for the power system? What can go wrong?

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Generation

- Reduced efficiency in high temperatures
- Fuel supply disruptions in extreme low temperatures
- Wind and solar droughts
- Severe storms damaging assets
- Drought limiting hydropower availability

Transmission & Distribution

- Reduced capacity in high temperatures
- Wildfire damage
- Severe storms damaging assets
- Trees falling on lines
- Decreased asset life

Electricity Demand

- Potential for severe increases in demand as temperatures rise
- Climate-driven technology adoption will change load shapes
- Potential for demand-side resources to contribute to resilience
- Electrification increasing criticality of service for many customers

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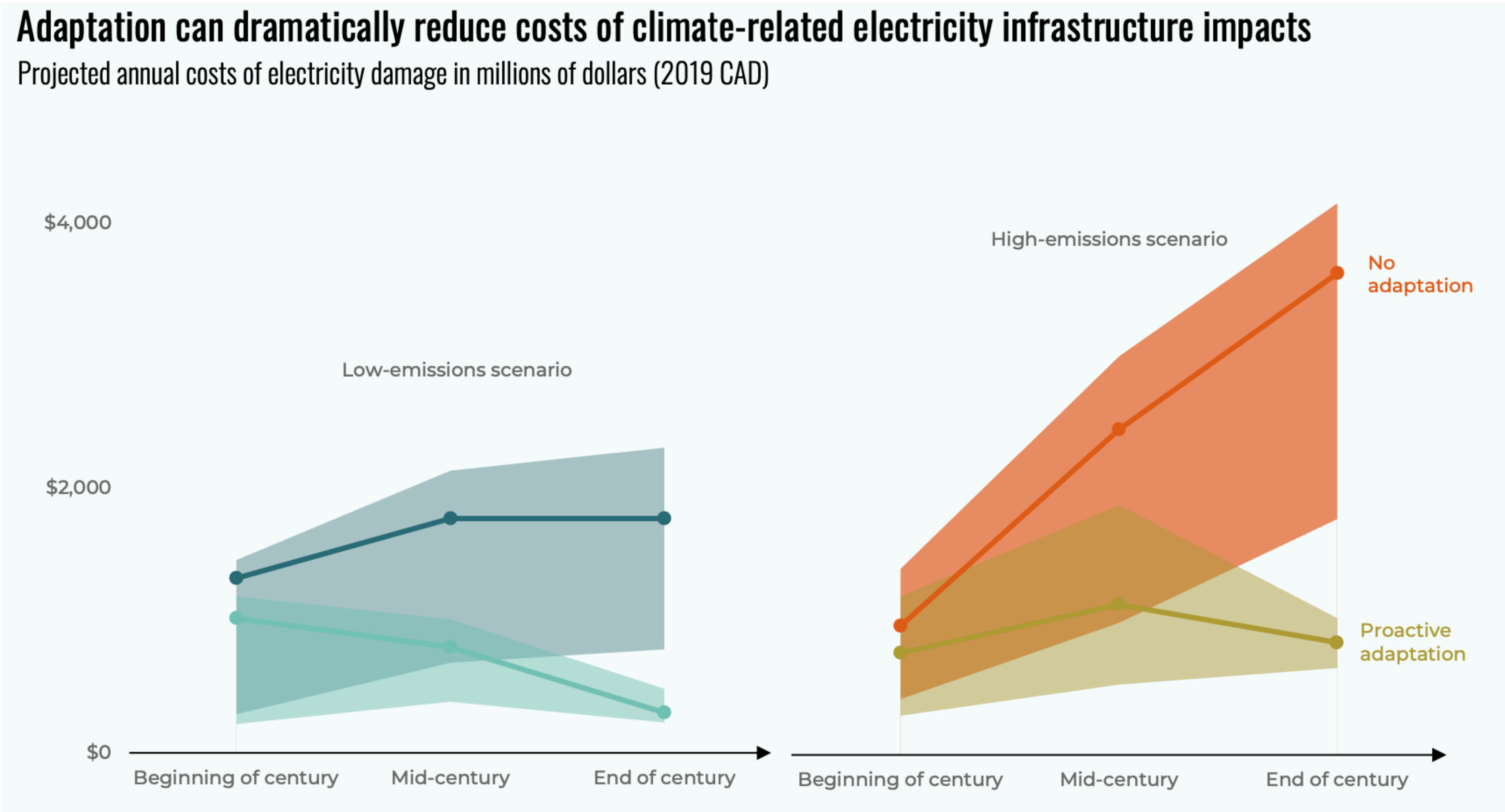
Can we anticipate and plan for these risks?

- Yes! …but the uncertainty space is large
  - What will the grid look like in 10, 20, 30 years?
  - How confident are we of changes in temperature, wind speeds, ice storms?
  - How will current assets respond to changes in climate conditions?
  - How will new technologies respond to changes in climate conditions?
  - How will changes in climate impact demand for electricity?
  - How much will it cost to repair climate damages?
  - How much will the impacts of climate damages cost customers?

Ultimately, we need a standardized approach to determine the best set of adaptation investments to improve resilience

A forward-looking lens will likely go a long way



"Replacing transmission and distribution infrastructure components at the end of their life with more resilient materials and components—in many cases a marginal expense—can **eliminate 83 to 77 per cent of damage costs** that would have occurred without adaptation by the end of the century for the low- and high-emissions scenarios, respectively."

Canadian Climate Institute, "Under Water: The Costs of Climate Change for Canada's Infrastructure," Canadian Climate Institute, 2021. https://climateinstitute.ca/reports/under-water/

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EPRI Climate Resilience and Adaptation Initiative (READi)

- **COMPREHENSIVE:** Develop a *Common Framework* addressing the entirety of the power system, planning through operations
- **CONSISTENT:** Provide an informed approach to climate risk assessment and strategic resilience planning that can be replicated
- **COLLABORATIVE:** Drive stakeholder alignment on adaptation strategies for efficient and effective investment

Workstream 1	Workstream 2	Workstream 3
Physical Climate Data & Guidance	**Energy Asset Exposure & Vulnerability**	**System Planning & Investment Prioritization**
• Identify climate hazards and data required for different applications • Evaluate data availability, suitability, and methods for downscaling & localizing climate information • Address data gaps	• Evaluate vulnerability at the component, system, and market levels from planning to operations • Identify mitigation options from system to customer level • Enhance criteria for planning and operations to account for event probability and uncertainty	• Assess power system and societal impacts: resilience metrics and value measures • Create guidance for optimal investment priorities • Develop cost-benefit analysis, risk mitigation, and adaptation strategies

Deliverables: Common Framework

- Climate data assessment and application guidance
- Vulnerability assessment
- Risk mitigation investment
- Recovery planning
- Hardening technologies
- Adaptation strategies
- Research priorities

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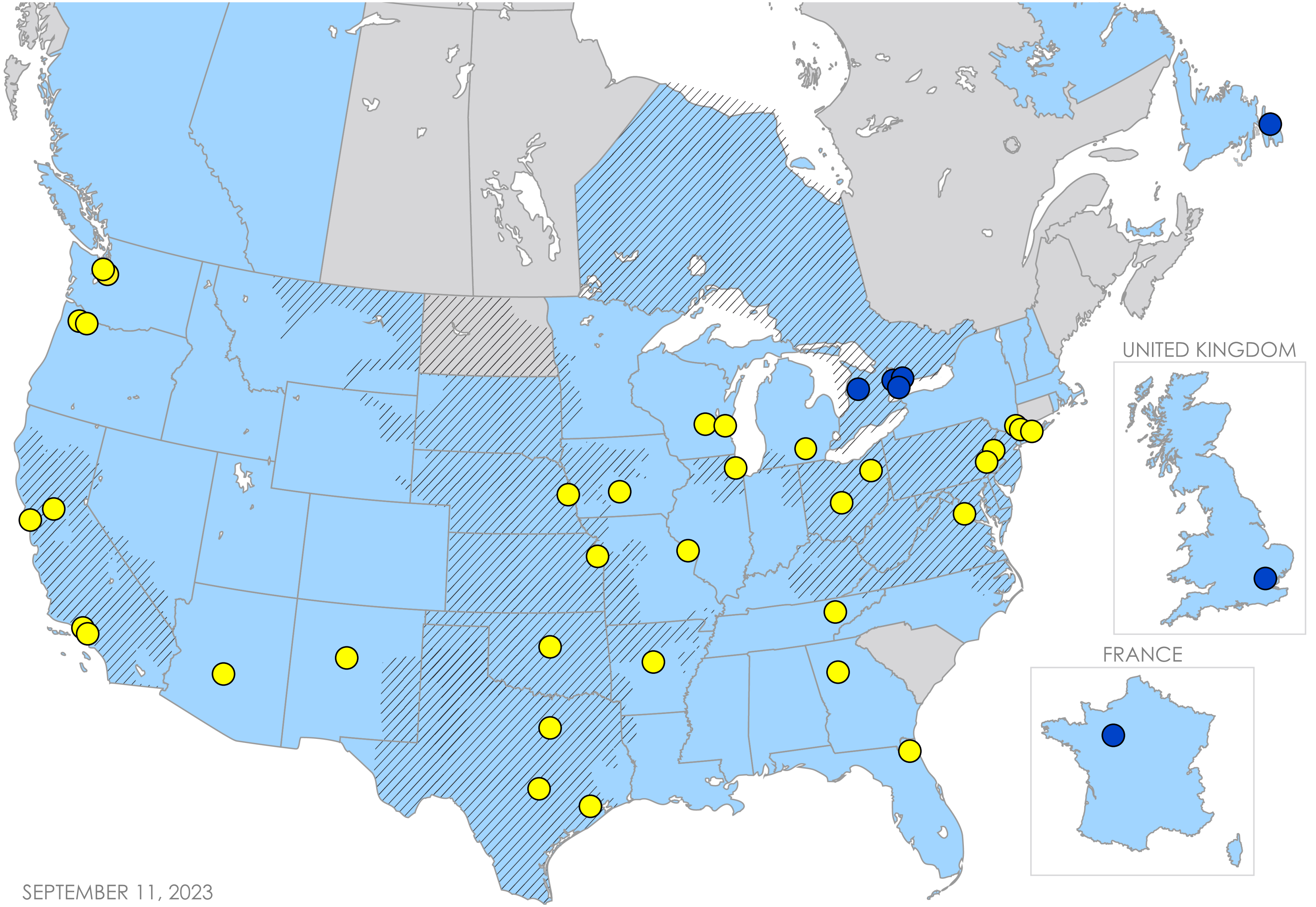
Climate READi Member Companies

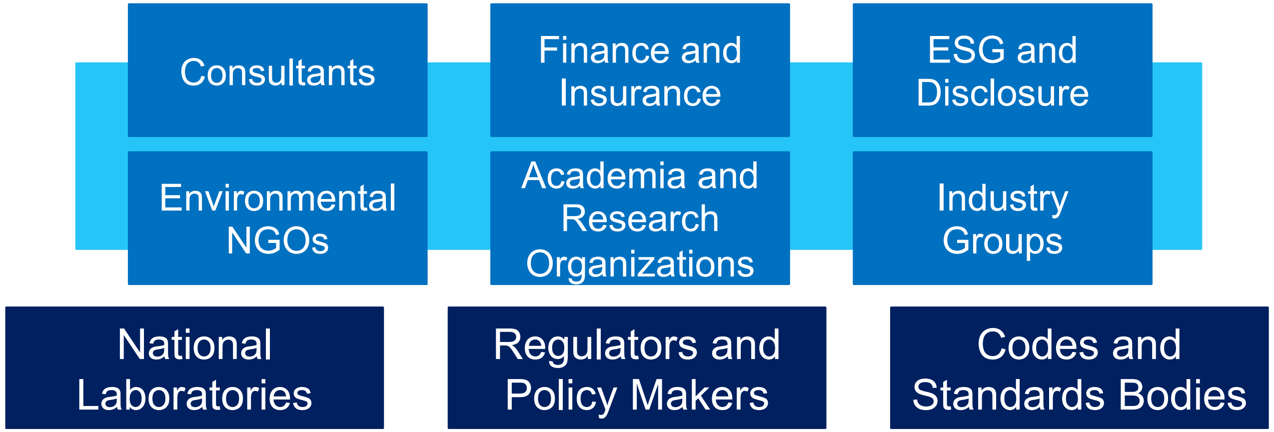


◯ Member Headquarters ▢ Member Operating States/Provinces ▨ ISO Service Territories *(only HQ location shown for IPPs)*

- AES Indiana
- AES Ohio
- Alliant Energy
- Ameren
- American Electric Power – Boundless Energy
- Berkshire Hathaway Energy
- Bonneville Power Administration
- Bruce Power
- California ISO
- CenterPoint Energy
- Consumers Energy
- conEdison
- ercot – Your Power. Our Promise.
- evergy
- exelon
- FirstEnergy
- FORTIS INC.
- hydro one
- ieso – Connecting Today. Powering Tomorrow.
- JEA
- LA DWP – Los Angeles Department of Water & Power
- LIPA – Long Island Power Authority
- nationalgrid
- New York State of Opportunity – NY Power Authority
- OG&E
- OPPD – your energy partner – Omaha Public Power District
- Ontario Power Generation
- PGE
- PG&E
- pjm
- PNM
- ppl
- PSE – Puget Sound Energy
- Rte
- SRP
- Seattle City Light
- Southern California Edison
- Southern Company
- SPP – Southwest Power Pool
- TVA – Tennessee Valley Authority
- VISTRA
- WEC Energy Group

Climate READi Affinity Group

The Climate READi Affinity Group (CRAG) is comprised of individuals from academia, consulting, finance and insurance institutions, non-governmental organizations, national labs, regulators and government— among others—bringing their expertise to address the critical challenge around resilience and adaptation to the energy sector.



- Accenture
- ADEX
- Alison Silverstein (Consultant)
- Andrew Dessler (Consultant)
- Applied Weather Associates
- Argonne National Laboratory
- Baringa
- Battelle
- Black & Veatch
- Brookhaven National Laboratory
- CAMPUT
- Canadian Climate Institute
- CANDU Owners Group
- CarbonPlan
- CDP North America
- Center for Climate & Energy Solutions
- Chemonics
- Clark Miller (Consultant)
- Clean Air Task Force
- Climate Risk Institute
- Columbia University
- Copperleaf Technologies
- CSA Group
- Department of Energy
- Desert Research Institute
- Disaster Tech
- Eagle Rock Analytics
- Eaton
- Electricity Canada
- Energy Networks Association
- Energy Systems Integration Group
- Enline Transmission
- Exponent
- Grid Lab
- Grid2.0
- Guidehouse
- Houston Advanced Research Center
- ICF
- IEEE
- Imperial College London
- Institute of Nuclear Power Operations
- International Hydropower Association
- Jacobs Engineering
- Khalifa University
- King Abdullah Petroleum Studies and Research Center
- King's College London
- Korea Atomic Energy Research Institute
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- McCormick Taylor
- Midwest Climate Collaborative
- Model World Consulting
- National Association of Regulatory Utility Commissioners
- National Association of State Energy Officials
- National Center for Atmospheric Research
- National Oceanic and Atmospheric Administration
- National Renewable Energy Laboratory
- North American Electric Reliability Corporation
- North American Transmission Forum
- Nuclear Energy Institute
- Nuclear Electric Insurance Limited
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Oregon State University
- Pacific Northwest National Laboratory
- Pacific Northwest Utilities Conference Committee
- Pike Engineering
- Power Systems Engineering Research Center
- Quanta Services
- RAND Corporation
- Resources for the Future
- Rhizome
- RS Poles
- RUNWITHIT Synthetics
- Sharply Focused
- SLR Consulting
- StormImpact
- Sunairio
- Union of Concerned Scientists
- Universidad Pontificia
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- University of Saskatchewan
- Verdantas

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WORKSTREAM 1

Physical Climate Data & Guidance

WS1: Physical Climate Data and Guidance

The power system is a physical system that is exposed to multiple climate hazards (e.g., extreme heat, wildfire, hurricanes).

+

The power system is transitioning to greater reliance on weather-dependent resources (e.g., wind and solar).

↓ ↓

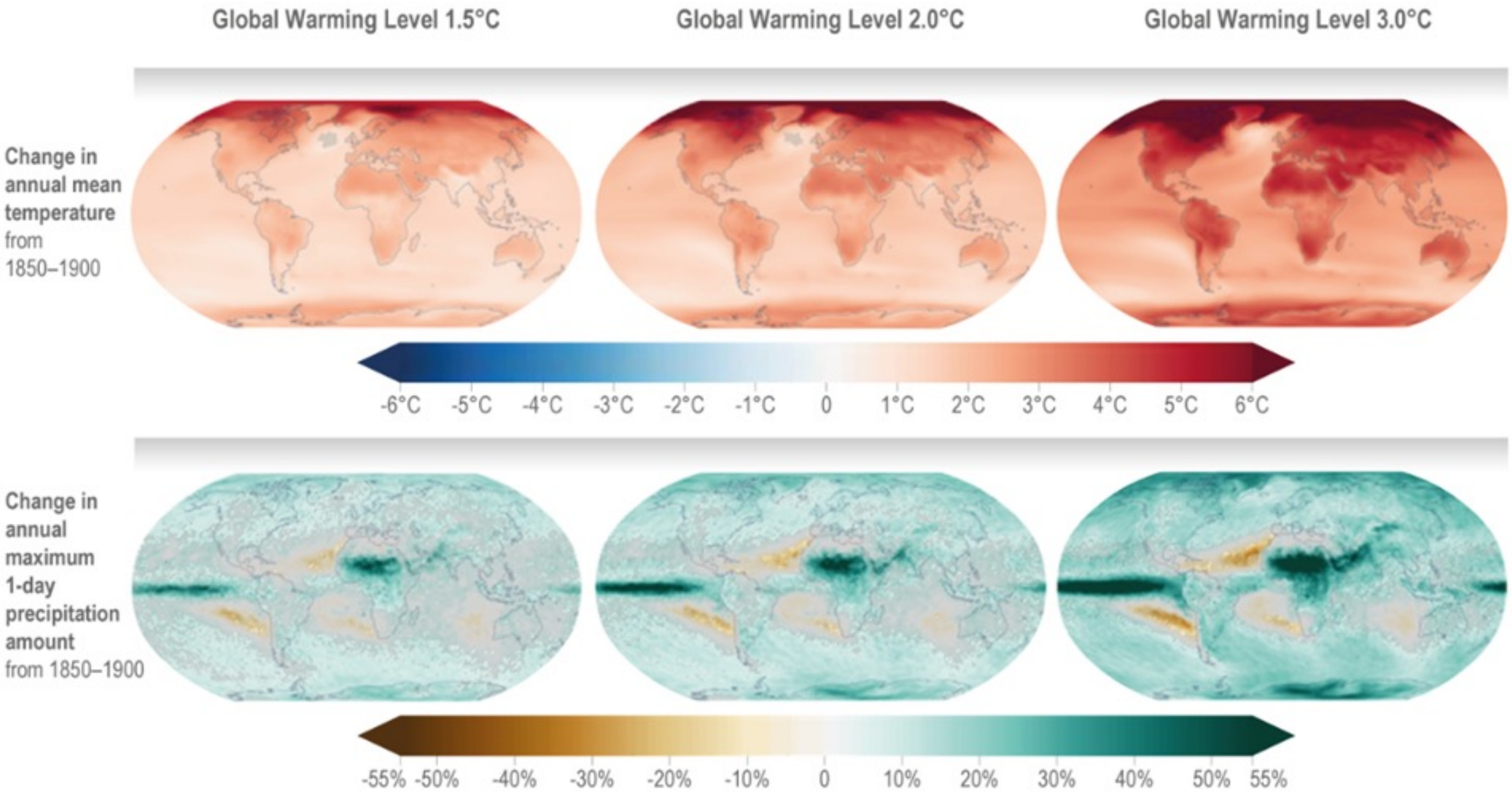
Multiple types of climate data are needed to assess the potential impacts of climate and climate change on the operation and planning of the electric power system.

WS1's goal is to understand how and where climate data are used in different applications for the electric power system. WS1 seeks to assess the availability and suitability of climate data for different analysis contexts and provide guidance on selecting, interpreting, and applying climate data for various applications.

What does this look like in practice?

Educating and level-setting

- Findings from one study cannot be blindly applied elsewhere
- Bridging the gap between what climate models provide and what power system models need
- Power system needs may not be perfectly met with existing climate modeling efforts

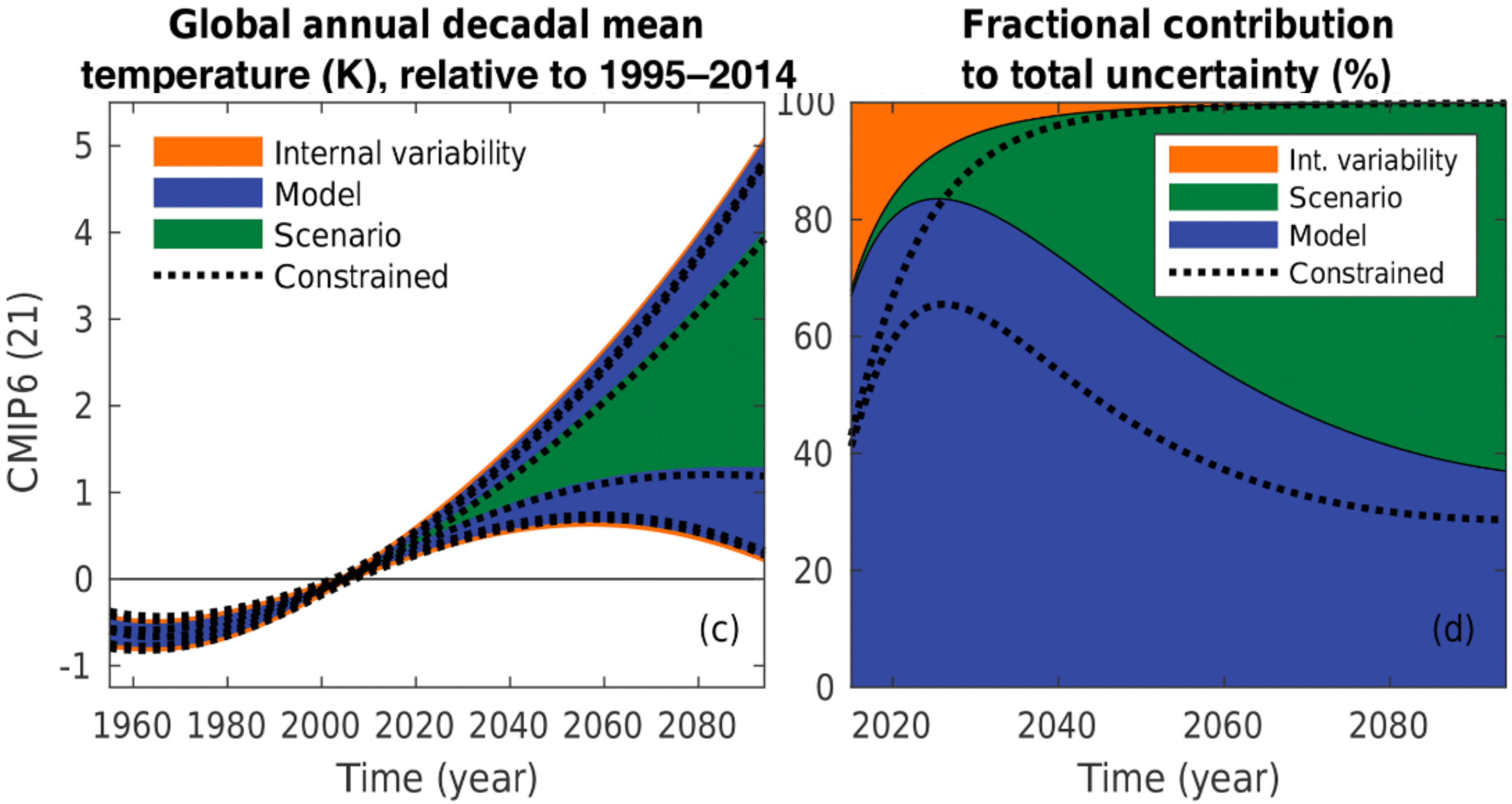


Regional projected selected climate change and impact variables by global warming level. Source: Schipper et al. 2022

What does this look like in practice?

Matching data to applications

- Which data will best address the questions posed?
- What are the pros and cons of choosing one data source over another?
- How and when can you combine data to better represent climate hazards?

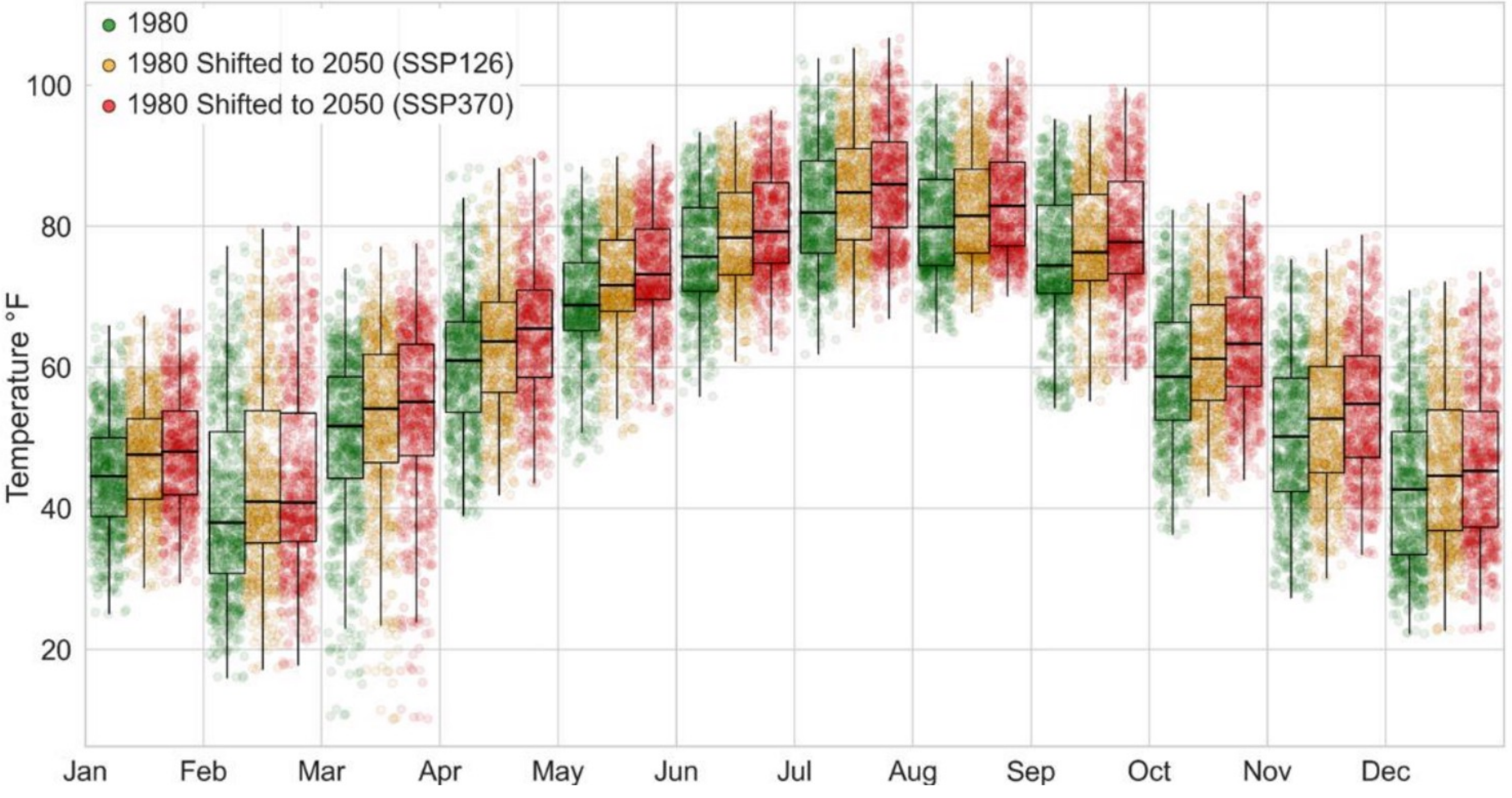


(c) Sources of uncertainty in the multimodel multi-scenario mean projection of global annual decadal mean temperature in CMIP6. (d) Fractional contribution of individual sources to total uncertainty. Observationally constrained projections are given by the dotted lines. Source: Lehner at al., 2020.

What does this look like in practice?

Providing fit-for-purpose data for modeling efforts

- How can a specific system understand the range of conditions they should be planning for?
- Bridging the gap between what climate models provide and what power system models need
- Ensuring realistic relationships for variables critical to power system operations

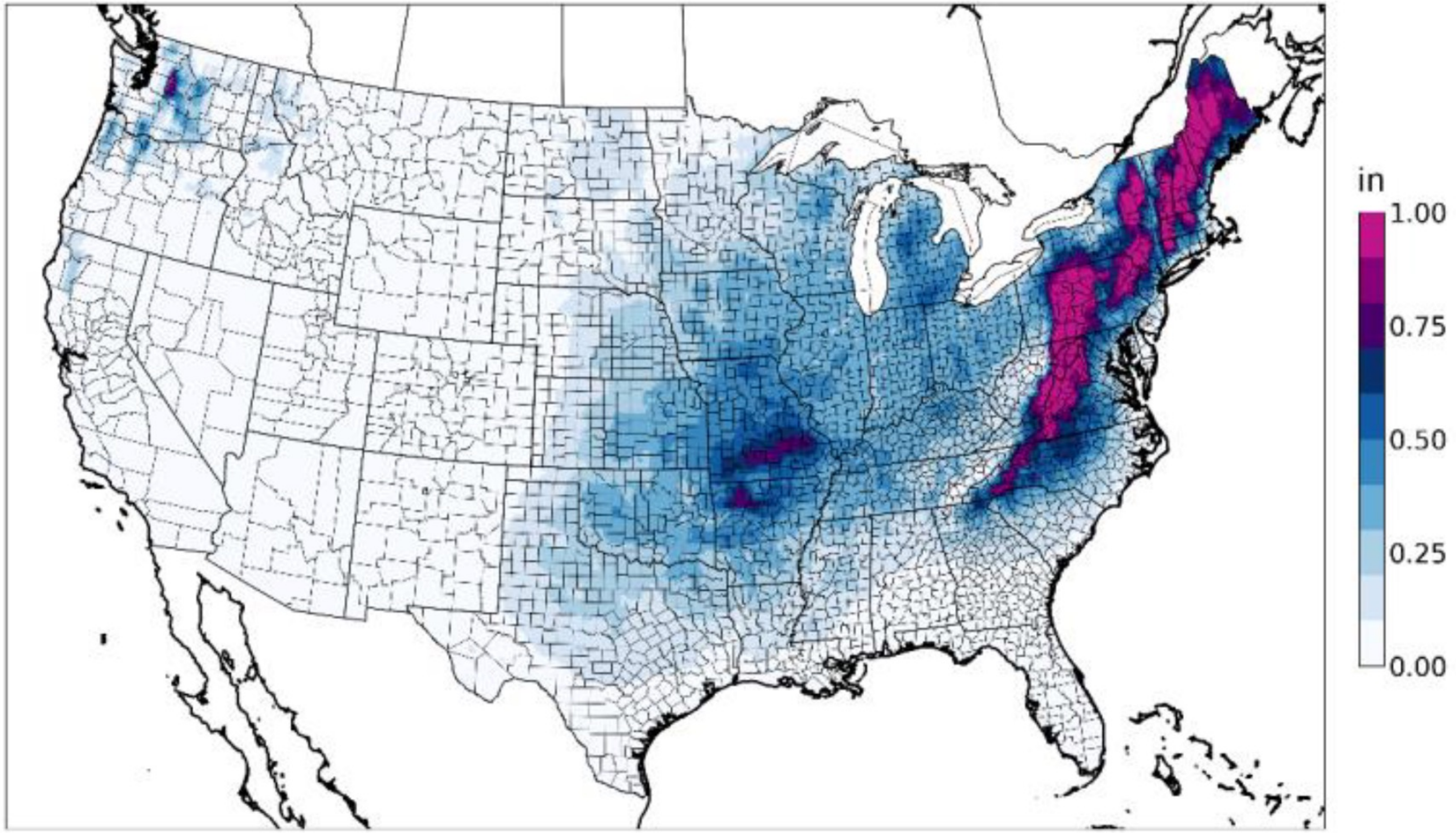


Comparison of 1980 shifted to 2050 for a single model (MRI model) and two different climate scenarios (SSP126 and SSP370) for Atlanta, GA. Source: Smith and Diaz 2022

What does this look like in practice?

Identifying and filling gaps

- What can we do about variables that climate models cannot resolve?
- How do we ensure decisions are still grounded in science when faced with data limitations?
- How can we combine models to better understand hurricanes, wildfires, ice storms, or tornadoes?



Average annual total freezing rain from historical data. Source ERA5 reanalysis and EPRI processing.

WORKSTREAM 2

Energy Asset Exposure & Vulnerability

Climate Risk Assessment – Big Picture

Climate Change

Hazard

Are local physical conditions changing?

Exposure

What is or will be in harm's way?

Vulnerability and Response

Will assets be impacted and if so, how?

Risk Management

Is the risk large? Can we adapt to reduce risk?

Climate Risk Assessment – Big Picture

Climate Change

Hazard

Are local physical conditions changing?

Exposure

What is or will be in harm's way?

The realm of WS2

Vulnerability and Response

Will assets be impacted and if so, how?

Risk Management

Is the risk large? Can we adapt to reduce risk?

<u>For all assets in the power system…</u>

- Thermal Generation (Coal, Gas, CC, Nuclear)
- Renewable Generation (Wind, Solar, Hydropower)
- Transmission & Distribution
- DER and End Use Products
- Cross Cutting Topics
  - Worker Health & Safety
  - Energy Equity
  - Ecological Patterns

<u>How will they respond to, perform in, and withstand changing conditions?</u>

Air Density
Air Humidity
Air Quality
Air Temperature
Barometric Pressure
Cloud Cover
Concurrent Effects
Drought
Hydrology: Discharge
Hydrology: Flooding
Hydrology: Water Quality
Hydrology: Water Temperature
Hydrology: Waterbody Elevation
Lightning
Precipitation
Sea Level Rise
Severe Storms: Hurricanes/Tropical Storms/Typhoons
Severe Storms: Tornadoes & Derechos
Soil Characteristics
Solar Irradiance
Wildfires
Wind

Asset Working Groups – Diving even deeper

- Confirm detailed impacts, variable and threshold for impact, and consequence
  - Quantify as much as possible
    - Threshold e.g., Asset 1 experiences 90% derate at 90°C
    - Exposure-Response e.g., Asset 2 experiences a derate of 1% per degree above 85°C
- Identify adaptation strategies
  - Relative cost (e.g., \$-\$\$\$\$) and relative benefit
- Prioritize critical impacts and components per asset
  - Where might it make sense to invest for resilience?

Transmission & Distribution Infrastructure	Nuclear Generation
Non-nuclear Thermal Generation	Solar
Wind	Hydropower
Cross-Cutting (Health & Safety, Energy Equity)	End Use Assets

Over 130 Individuals from 42 organizations

Asset-Climate Metrics Matrices

Thermal Generation (focused on nuclear, coal, gas, and combined cycle)					Impact	
Impact ID	Application	Climate Variable Category	System/Facility Type	Sub-System	Impact	Specific impact measure (e.g., threshold, exposure-response function)
6.1	Operations	Air Temperature	Coal, CCGT, and Nuclear	Cooling Tower	Cold air temperatures can lead to low water temperature which can damage hardware or cause **freezing in cooling tower**, restricting flow	Derate depends on the loss of cooling capacity; structural damage can force out unit <32F
6.2	Operations	Water Temperature	Coal, CCGT, and Nuclear	Cooling Tower	Cold air temperatures can lead to low water temperature which can damage hardware or cause **freezing in cooling tower**, restricting flow	Derate depends on the loss of cooling capacity; structural damage can force out unit <32F

- Inform asset adaptation options
- Inform WS3 system modeling

Providing key input for asset owners and downstream modeling efforts

For companies and industry:

- Which components are the most vulnerable or the most critical?
- Do codes & standards need to be modified? If so, can we provide guidance on where and how, based on WS1 climate data analysis?

For Climate READi modeling and guidance:

- Ensuring realistic performance and failure behaviors in system models
- What adaptations are reasonable to consider in system planning?

For both:

- What are the relative costs and benefits of various adaptation strategies?

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WORKSTREAM 3

System Planning and Investment Prioritization

Workstream 3 Objective

Investment prioritization for resilience that accounts for climate risks, asset vulnerability, and impacts on society and communities

To identify and prioritize investments, we need to:

- **Account for what the system might look like in response to climate and technology development**
- **Understand how existing assets and infrastructure will be vulnerable to climate hazards**
- **Identify potential adaptations and associated benefits under consideration for resilience investments**
- **Evaluate how grid performance during climate hazards impacts society to guide adaptation prioritization**

Enable feedback through integrated modeling efforts

The basic idea of climate-informed planning

1. Consider the range of climate uncertainties of most concern for a region and/or power system
   - Rising temperatures, natural variability, severe weather, etc.

2. Plan for those conditions, subject to the computational capabilities of the planning model(s)
   - This requires choosing a *selection* of time periods, events, climate scenarios, etc. as well as adaptations to consider

3. Test that proposed system plan against additional data to cover a wider range of conditions
   - If the proposed system fails to meet reliability and resilience targets, go back to the planning stage – use new data, new planning parameters, etc.
   - If the proposed system meets reliability and resilience targets, we're done!

How to represent climate hazards in planning models?

What planning models are often designed to take as input:

Typical Meteorological Year	Extreme Event Scenario	Hourly Snapshot
Resource planning, production cost modeling, etc.	Production cost modeling, distribution outage analysis, etc.	Transmission planning, stability analysis, etc.

How to represent climate hazards in planning models?

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What we want to represent:

Future Climate Conditions

Natural variability

Climate change

Uncertainty

Typical Meteorological Year

Extreme Event Scenario

Hourly Snapshot

We need to ensure the 'right' data is passed from climate projections to planning models and then to evaluation processes – without leaving potentially critical periods out!

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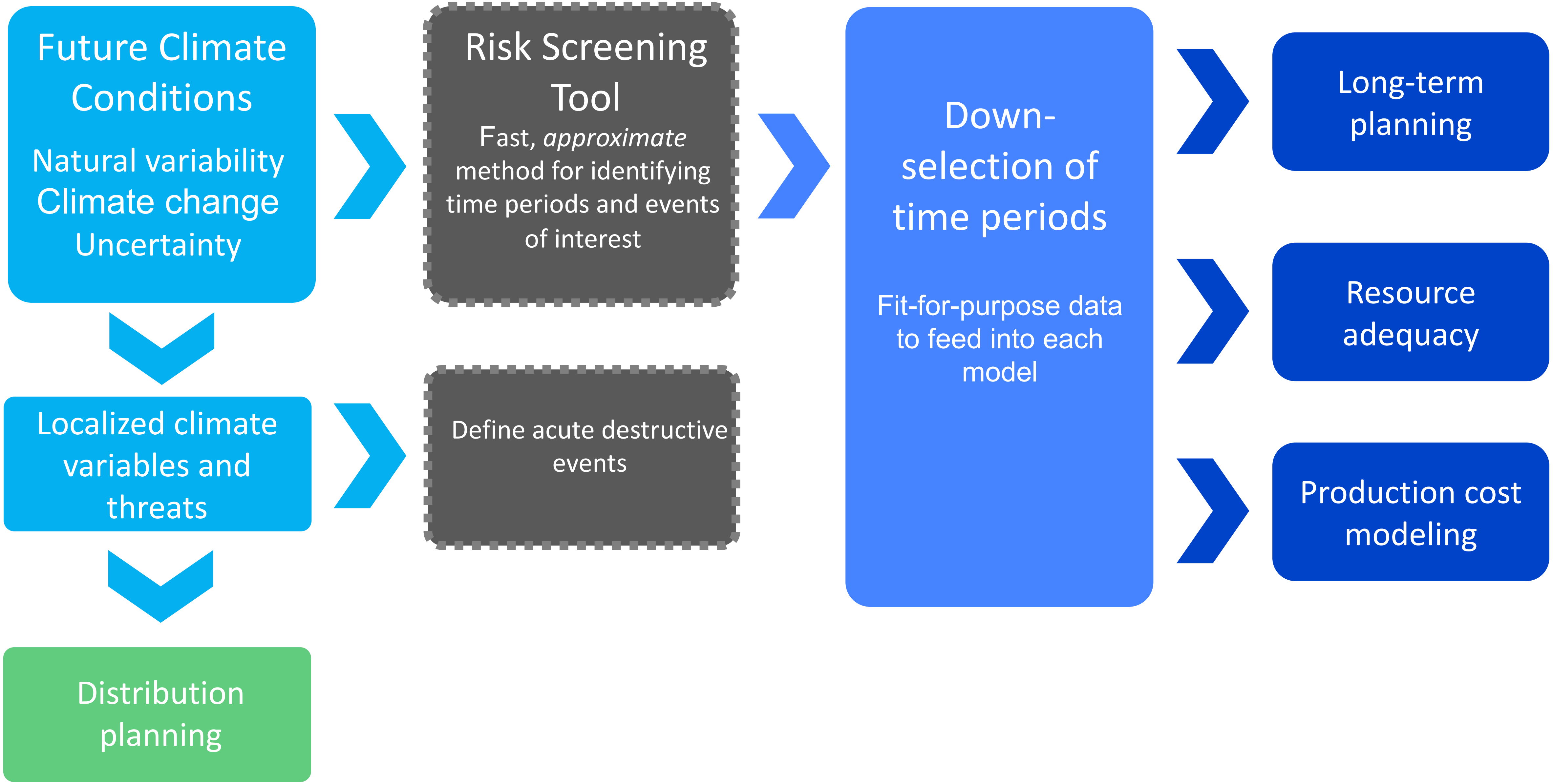
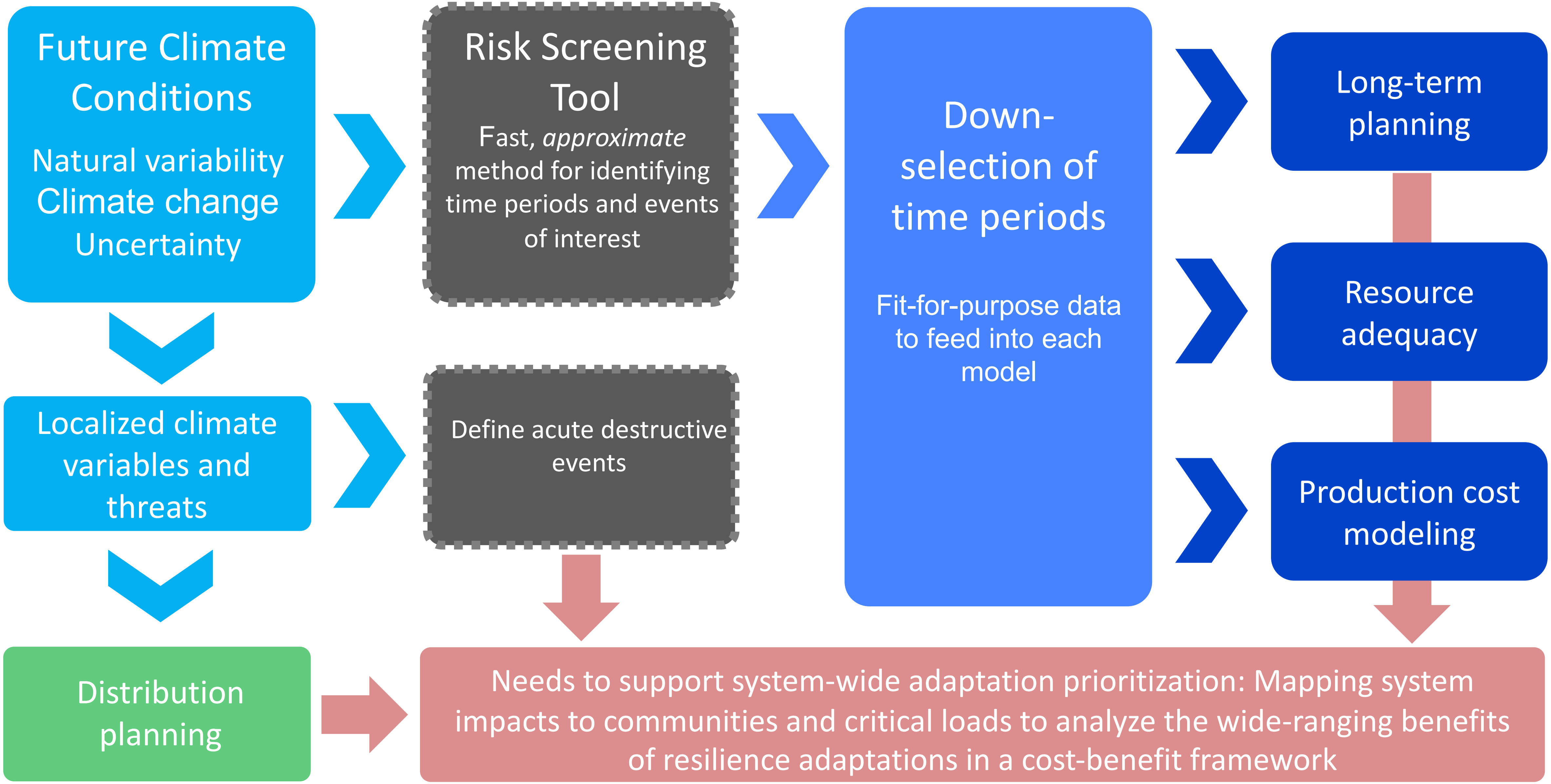
Our climate data pipeline



Our climate data pipeline



Risk Screening Tool in Practice

Risk Screening: Weather dependent asset vulnerabilities

- Define asset vulnerability matrix and derating factors that include supply and demand risks as a function of weather variables (e.g., temperature, irradiance, windspeed)

Technology	Weather variable 1	Operator 1	Threshold 1	Weather variable 2	Operator 2	Threshold 2	Derating	Asset vulnerability label
PV	temperature	<=	32F	Snow	>=	1inch	90%	Snow storm
PV	Irradiance	<	200 W/m2	Irradiance	>=	80 W/m2		Low sun
PV	Irradiance	>	200W/m2	Irradiance	<=	600 W/m2		Mid sun
CCGT	Temperature	<	10F				50%	Cold exposure
Wind On/offshore	Wind speed	>=	60m/s				100%	Hurricane/Tornado
Wind On/offshore	Wind speed	<	3m/s				100%	No wind
Wind Onshore	Wind speed	>	25m/s				100%	Cut-off wind speed
Wind Offshore	Wind speed	>	30m/s				100%	Cut-off wind speed
….	…	…	….	…	…	…	…	…

Note: The values in this table might vary significantly depending on the study region.

Risk Screening: Map Risks to Weather Conditions

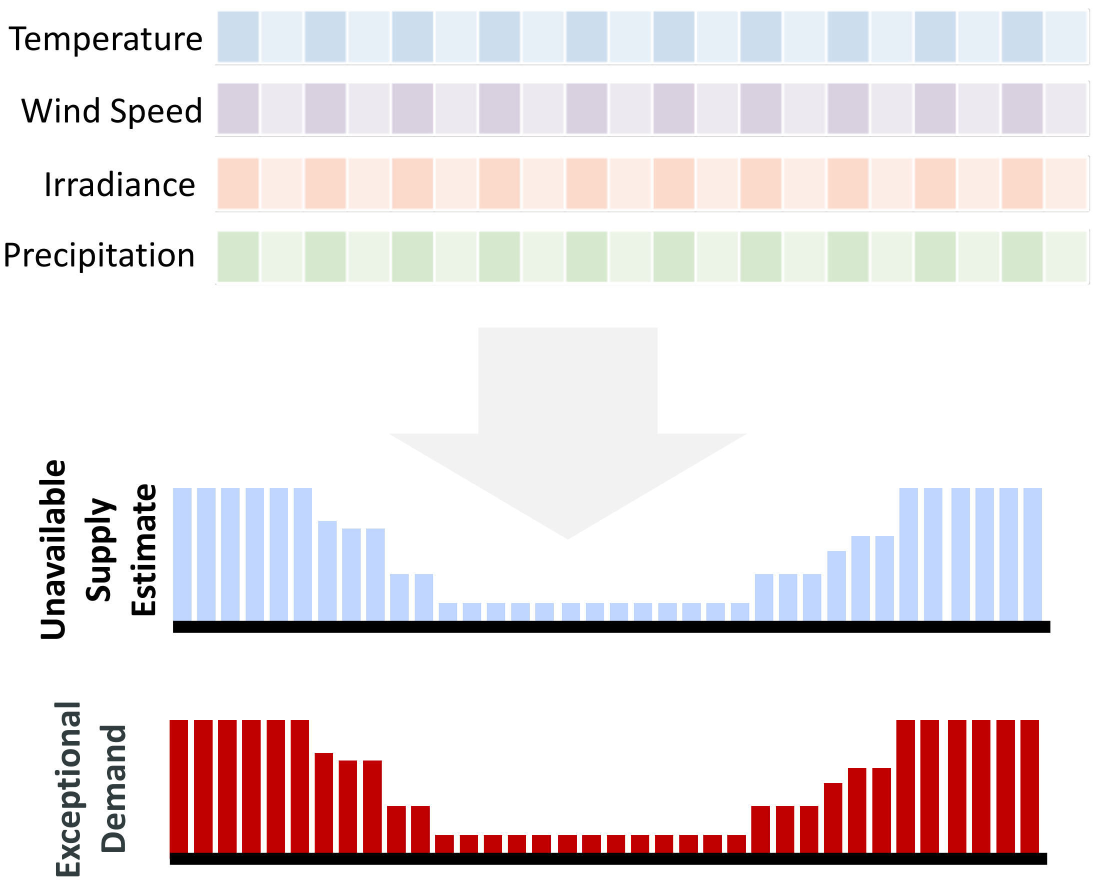
Plant Risk Models

Offshore Plant 1

Wind output
Low Wind: 0-4 m/s: 100 %
Med Wind: 4-10 m/s: 50 %
High Speed Shutdown: 25+ m/s: 100 %

Offshore Plant 1
Type: Wind (Off)
Weather point: XX
Capacity : 800 MW

Weather Year: 2005, Model 4, SSP3

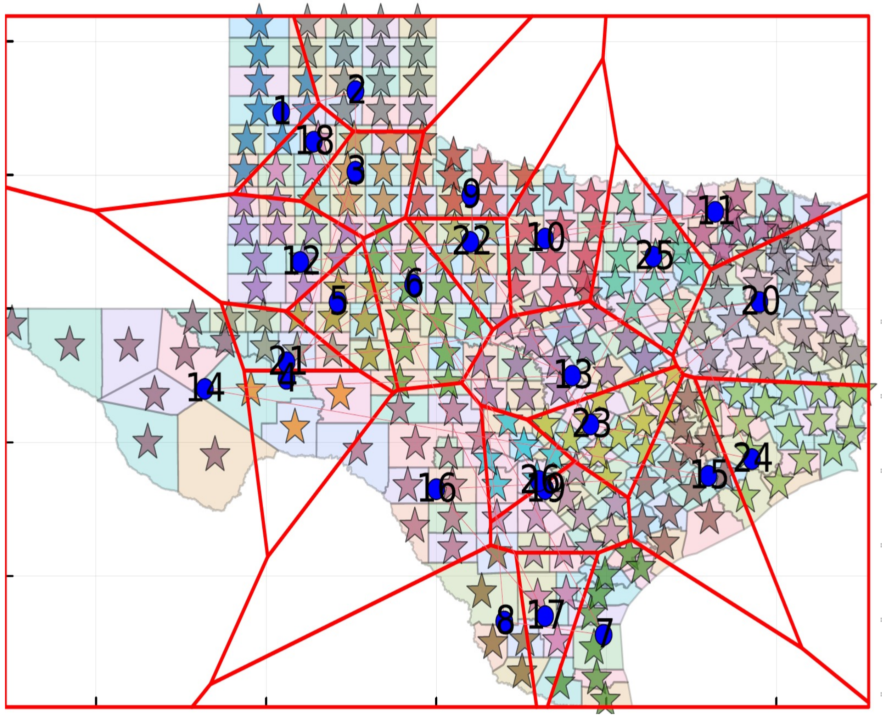


- Each plant risk model is evaluated at each interval in the weather data provided and the unavailable capacity is estimated
- Unavailable capacity is aggregated across all resource types in each interval

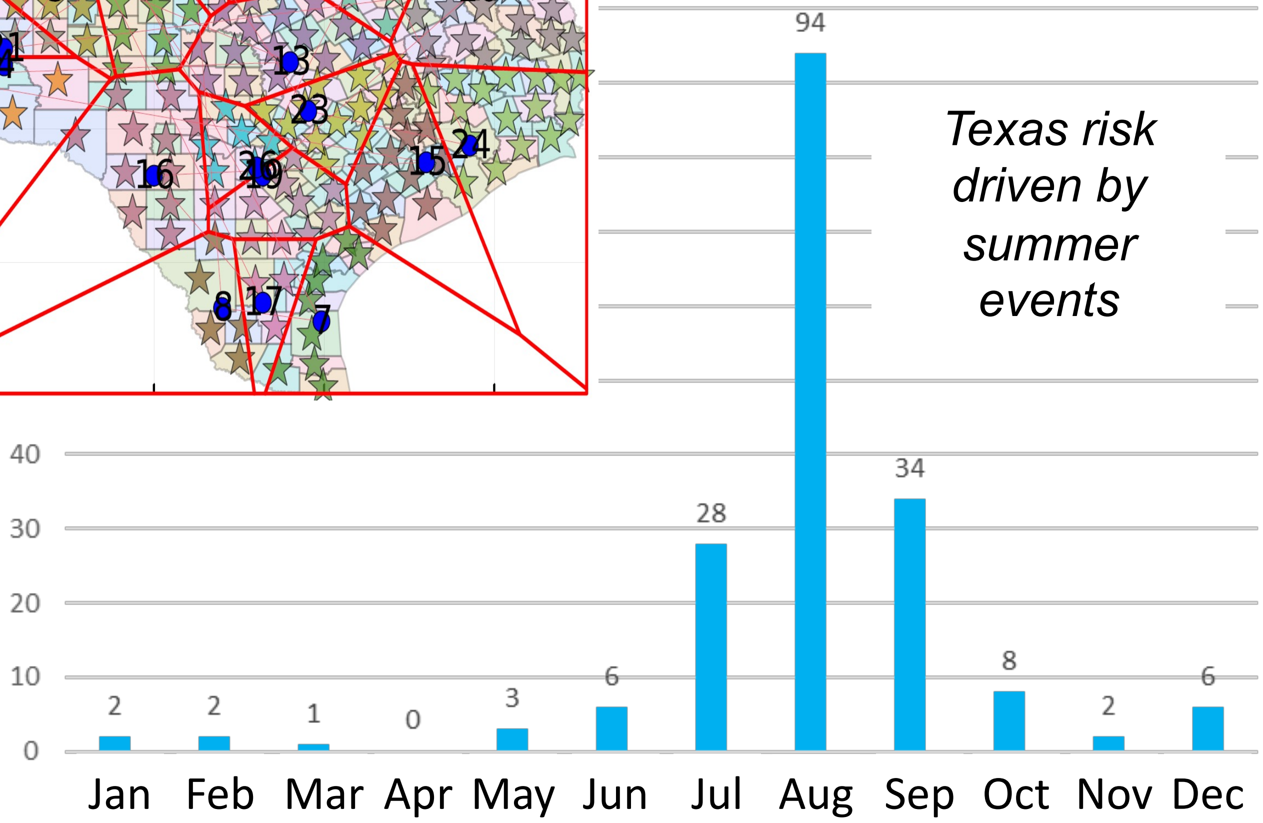
- Exceptional demand represents demand above a fixed threshold
- Example: demand above 23 GW

Risk Screening for Synthetic Texas System

- Weather data mapped to 2050 from GFDL model, SSP126 for 71 historical weather years and 26 weather stations
- Load profile derived from technology adoption projections with temperature response curve applied to weather data
- Power system based on preliminary capacity expansion output to reflect 2050 buildout



Weather stations (blue dots)



S1: Summer high temperature and low wind

Event Description

Event Raw Ranking: 2

Date: Aug 26 – Sept 16

Max 3-day risk date: Sept 4-Sept 6

Weather year: 1996

Cluster: S1 (85% of events)

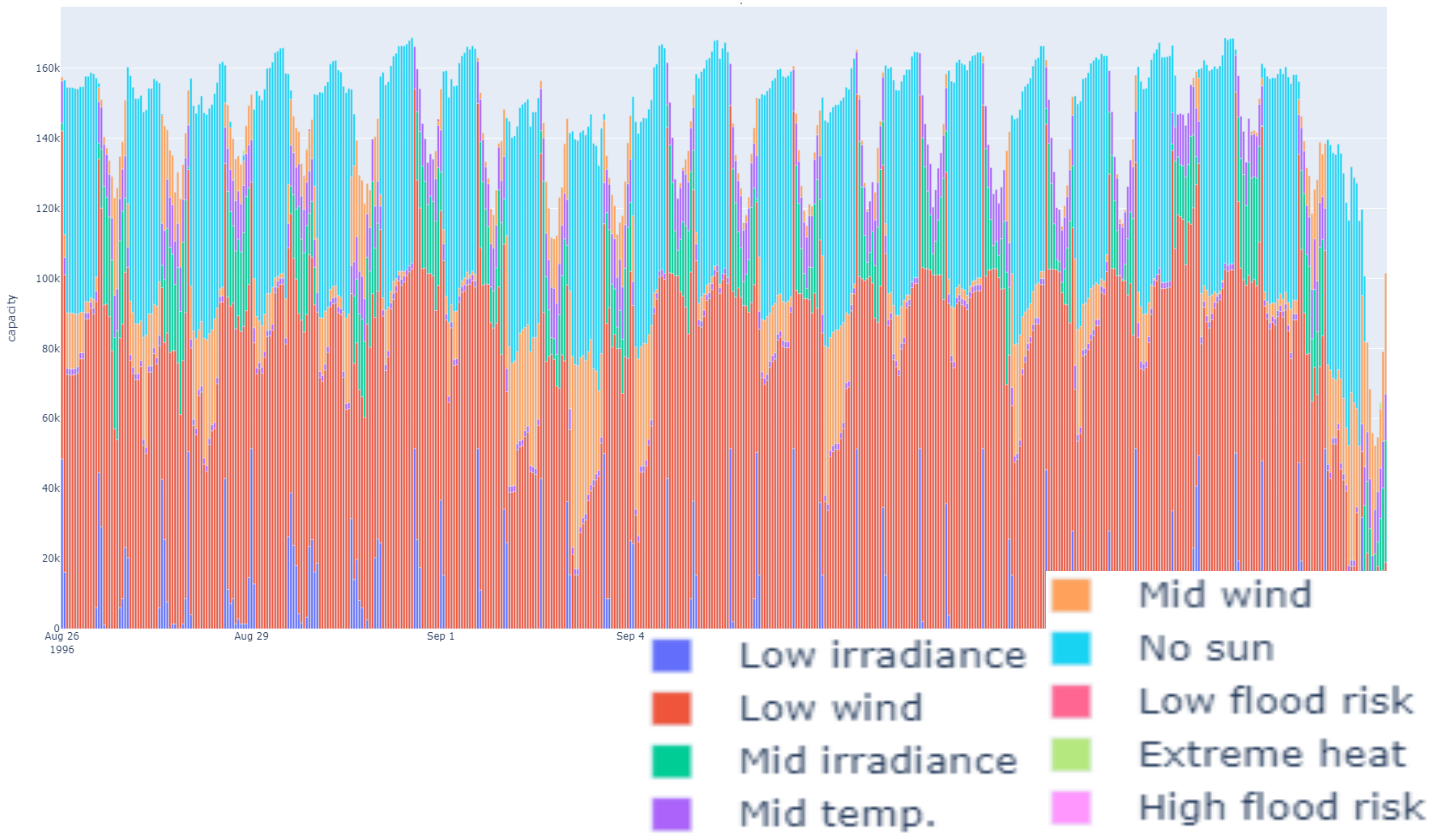
Avg Capacity at Risk: 146,348 MW

Max Capacity at Risk: 168,674 MW

Description:

High temperatures in late Aug, early sept coinciding with low wind output.

Capacity at risk (MW)



W1: Winter low wind and low irradiance

Event Description

Event Raw Ranking: 174

Date: Feb 5 – Feb 26

Max 3-day risk date: Feb 20-Feb 26

Weather year: 1968

Cluster: W1 (15% of events)

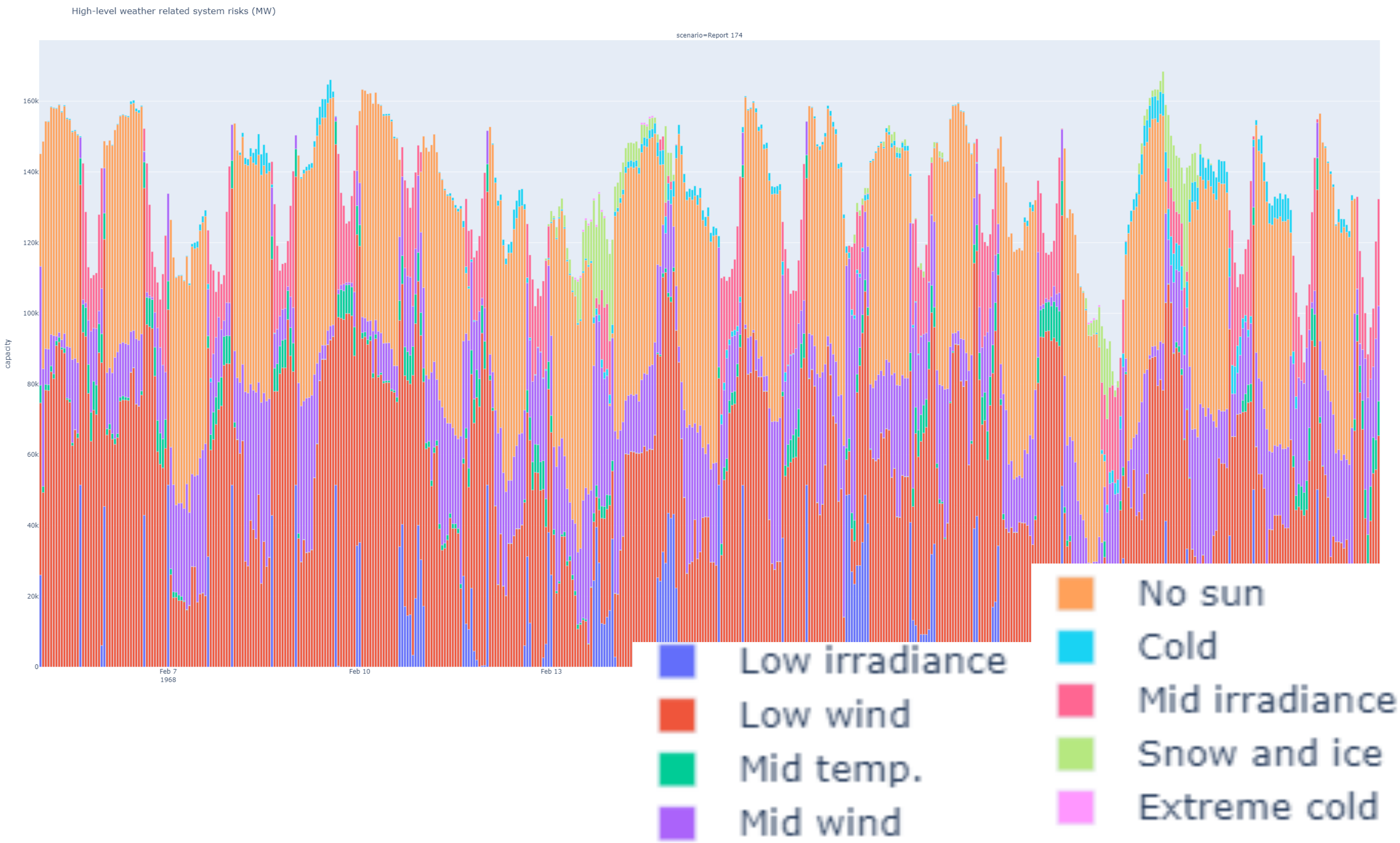
Avg Capacity at Risk: 134,910 MW

Max Capacity at Risk: 168,408 MW

Description:

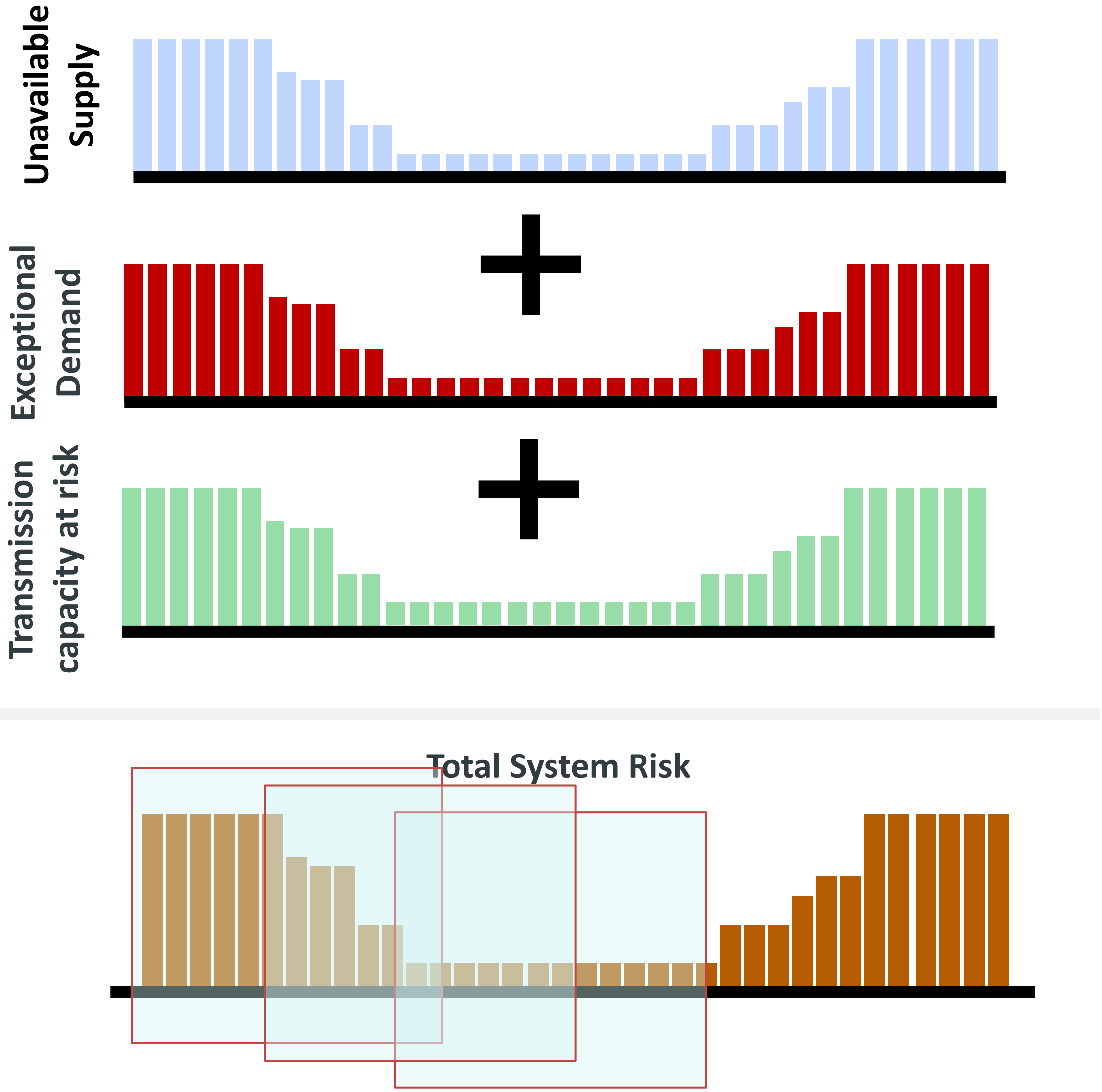
Low irradiance in late Feb coinciding with low wind output.

Capacity at risk (MW)



Risk Screening: Enabling quick evaluation within system planning framework

- Coordination across the workstreams
  - WS1:
    - 5 global climate models and 2 emission pathway models (10 future realizations)
    - 72 historical weather years (reanalysis)
    - Results in 720 synthetic climate projected weather years
  - WS2:
    - Weather dependent asset vulnerabilities and adaptation performance stats
  - WS3:
    - Iterative updates between expansion planning (informs capacity at risk) and risk screening
    - Assessment of adaptation options to reduce system risk



Our climate data pipeline

Future Climate Conditions

Natural variability
Climate change
Uncertainty

Localized climate variables and threats

Distribution planning

Risk Screening Tool

Fast, *approximate* method for identifying time periods and events of interest

Define acute destructive events

Down-selection of time periods

Fit-for-purpose data to feed into each model

Long-term planning

Resource adequacy

Production cost modeling

Recent Deliverables Across all Workstreams

- A Starting Point for Physical Climate Risk Assessment and Mitigation: Future Resilience and Adaptation Planning
- READi Insights: Extreme Heat Events and Impacts to the Electric System
- Costs and Benefits of Proactive Climate Adaptation in the Electric Sector
- Grounding Climate Risk Decisions: Physical Climate Risk Assessment Scientific Foundation and Guidance for Companies – Initial Key Company-Level Insights, Technical Principles, and Technical Issues
- Climate 101: Physical Climate Data
- READi Insights: Extreme Winter Weather Challenges for the Power System
- Climate-Informed Planning and Adaptation for Power Sector Resilience
- READi Insights: Types of Climate Data and Potential Applications within the Electric Power Sector
- READi Insights: Unpacking Climatological and Power System Operating Extremes
- READi Insights: Physical Climate Data 101 Course Overview
- Climate Vulnerability Considerations for the Power Sector: Nuclear Generation Assets
- Climate Vulnerability Considerations for the Power Sector: Health and Safety, Environmental Justice, and Ecological Patterns
- Climate Vulnerability Considerations for the Power Sector: Transmission and Distribution Infrastructure
- Climate Vulnerability Considerations for the Power Sector: Non-Nuclear Generation Assets

Find all this and more at www.epri.com/READi

Thank you!

Andrea Staid
astaid@epri.com