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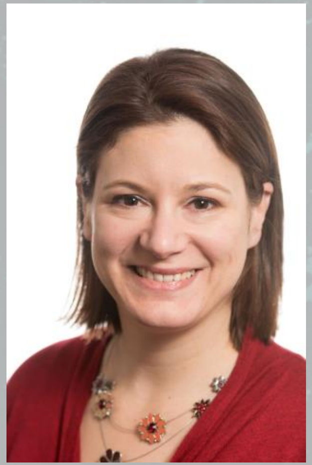

DEEP DIVE THREE: Vulnerability of the Decarbonized Grid to Energy Droughts and Climate Extremes

Hosted by: Nathalie Voisin

Panelists: Cameron Bracken, Casey Burleyson, and Allison Campbell

July 24, 2023

PNNL

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Vulnerability of the Decarbonized Grid to Energy Droughts and Climate Extremes

Cameron Bracken, Casey Burleyson, Allison Campbell, and the GODEEEP Team

July 24, 2023

GODEEEP Webinar Series, Deep Dive 3

U.S. DEPARTMENT OF ENERGY BATTELLE

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GODEEEP uses PNNL's expertise working across fundamental and operational research in climate, power grid, and multisector dynamics

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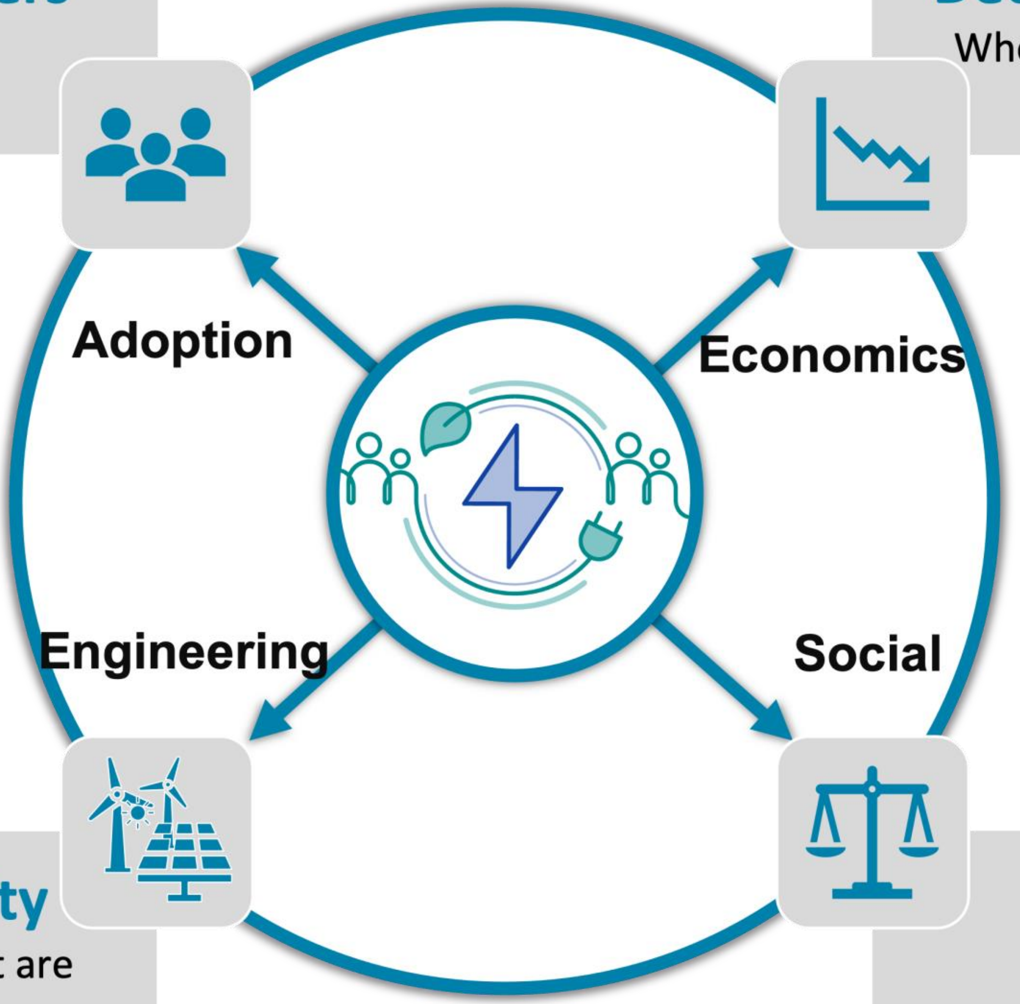
Empowered Stakeholders
Transfer of methods, tools, datasets, and use cases

Decarbonization Pathways
Whole economy decarbonization with interactions across global markets



GODEEEP
Grid Operations, Decarbonization, Environmental and Energy Equity Platform

A $4 million PNNL R&D project

Coordinated research using staff expertise across renowned Climate and Bulk Electric Grid Programs in Fundamental and Applied Research across the Department of Energy's offices

- Atmospheric scientists
- Hydrologists
- Electrical engineers
- Social scientists
- Software engineers
- Stakeholder engagement experts

Resilience and Reliability
Infrastructure and operations that are responsive to climate change

Justice and Equity
Environmental and energy equity impacts of decarbonization

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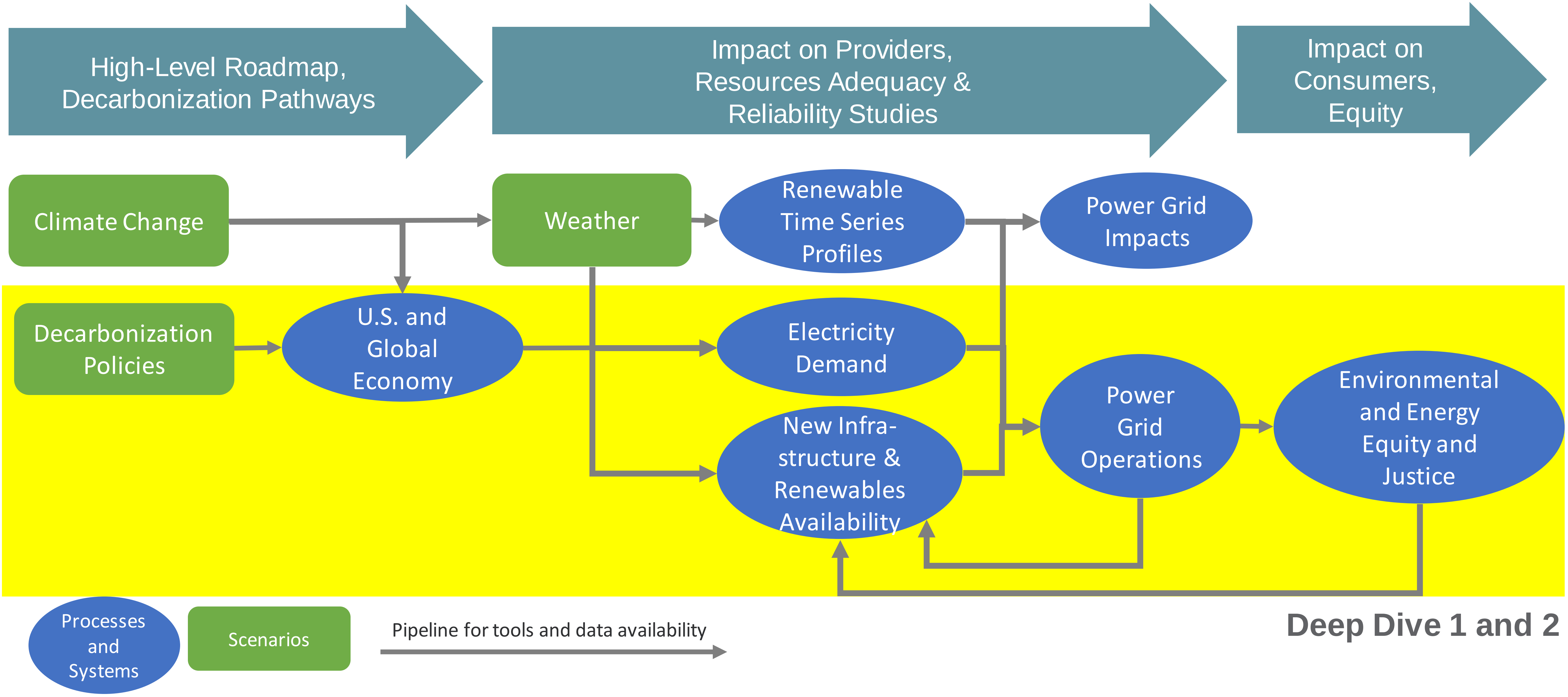
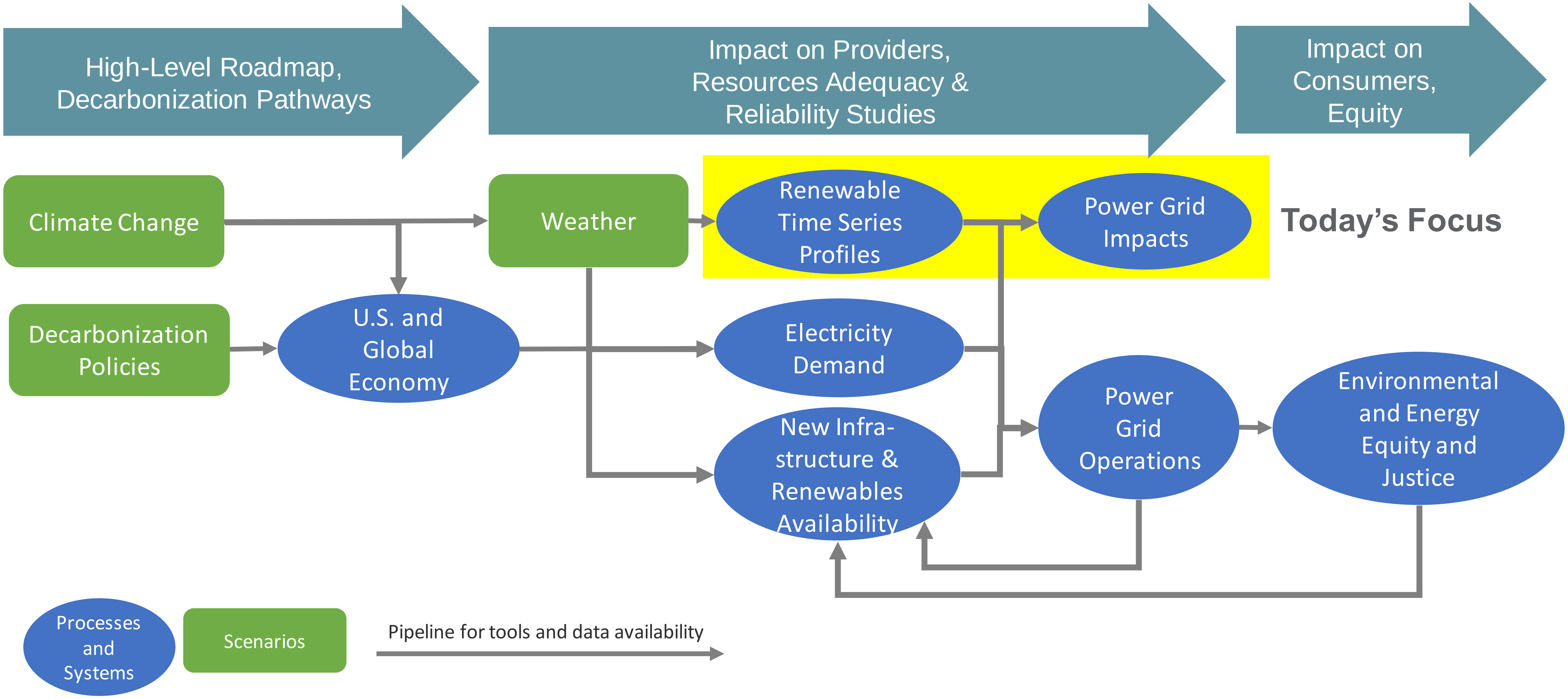
Consistent, open-source, end-to-end framework with intermediate datasets and tools for flexible customization



Deep Dive 1 and 2

Consistent, open-source, end-to-end framework with intermediate datasets and tools for flexible customization



Outline

- Sensitivity of the evolving power grid to wind and solar: what scales matter?
- Development approach and evaluation of the datasets
- A first continuous US benchmark of historical energy droughts
- Applications:
  - Energy droughts for storage and market design
  - Extreme events for reliability studies
- Next Steps

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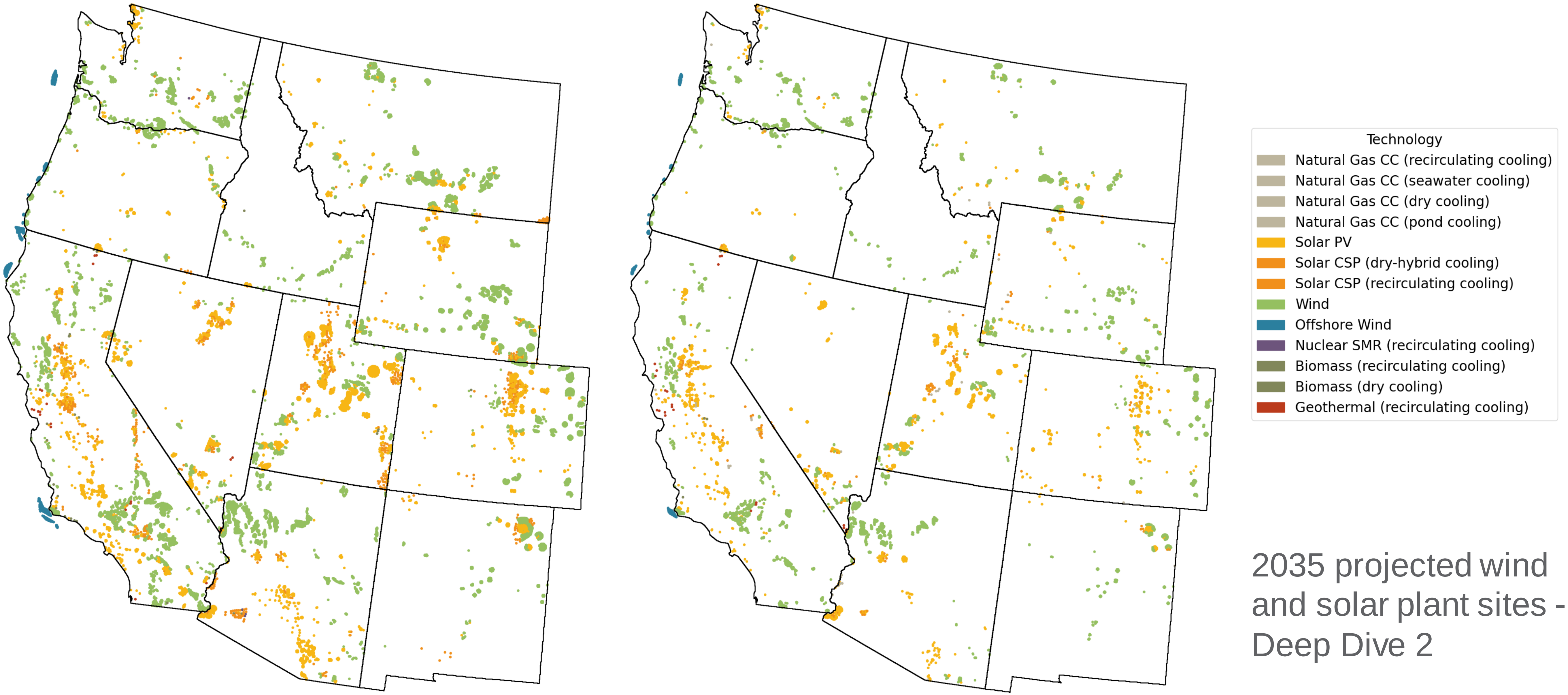
Decarbonization requires a substantial buildout of wind and solar infrastructure

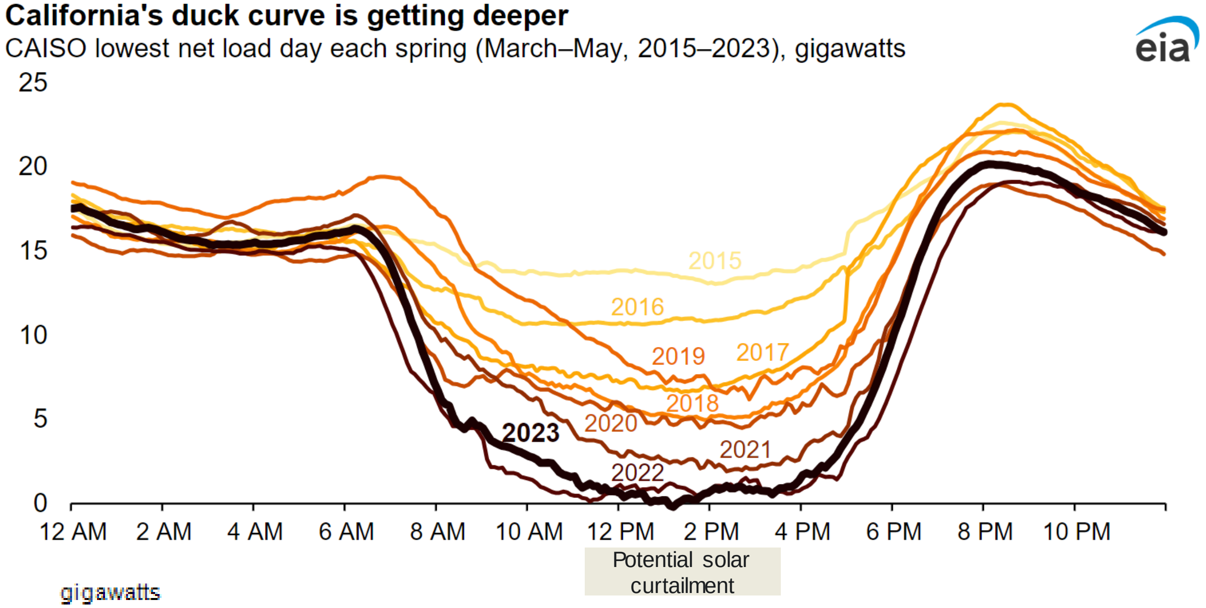
Net-Zero no CCS

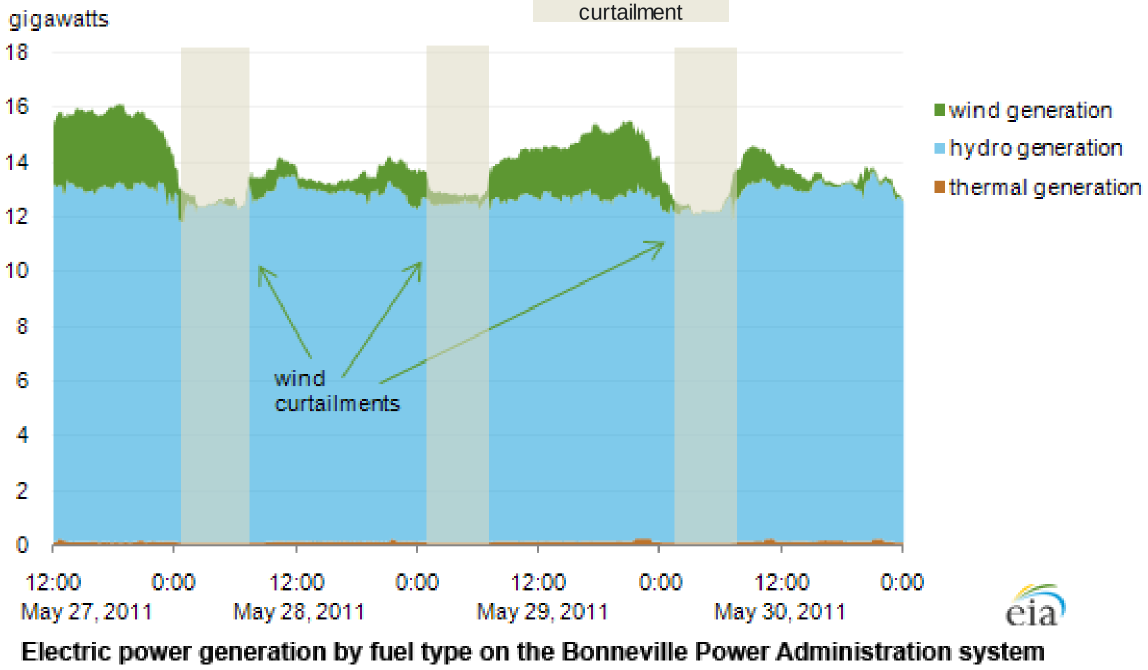
Business-as-Usual



2035 projected wind and solar plant sites - Deep Dive 2

Increased Reliance on Renewables Presents Grid Operational Challenges





Diurnal cycle of solar results in a net load curve (duck curve) that transforms ramping needs of the power grid.

Similarly, wind variations propagate onto other technologies. Some technologies can ramp up and down more than others albeit at a cost.

With the uptake of wind and solar in regional generation portfolios, too much can result in curtailment and too little and a generation shortfall.

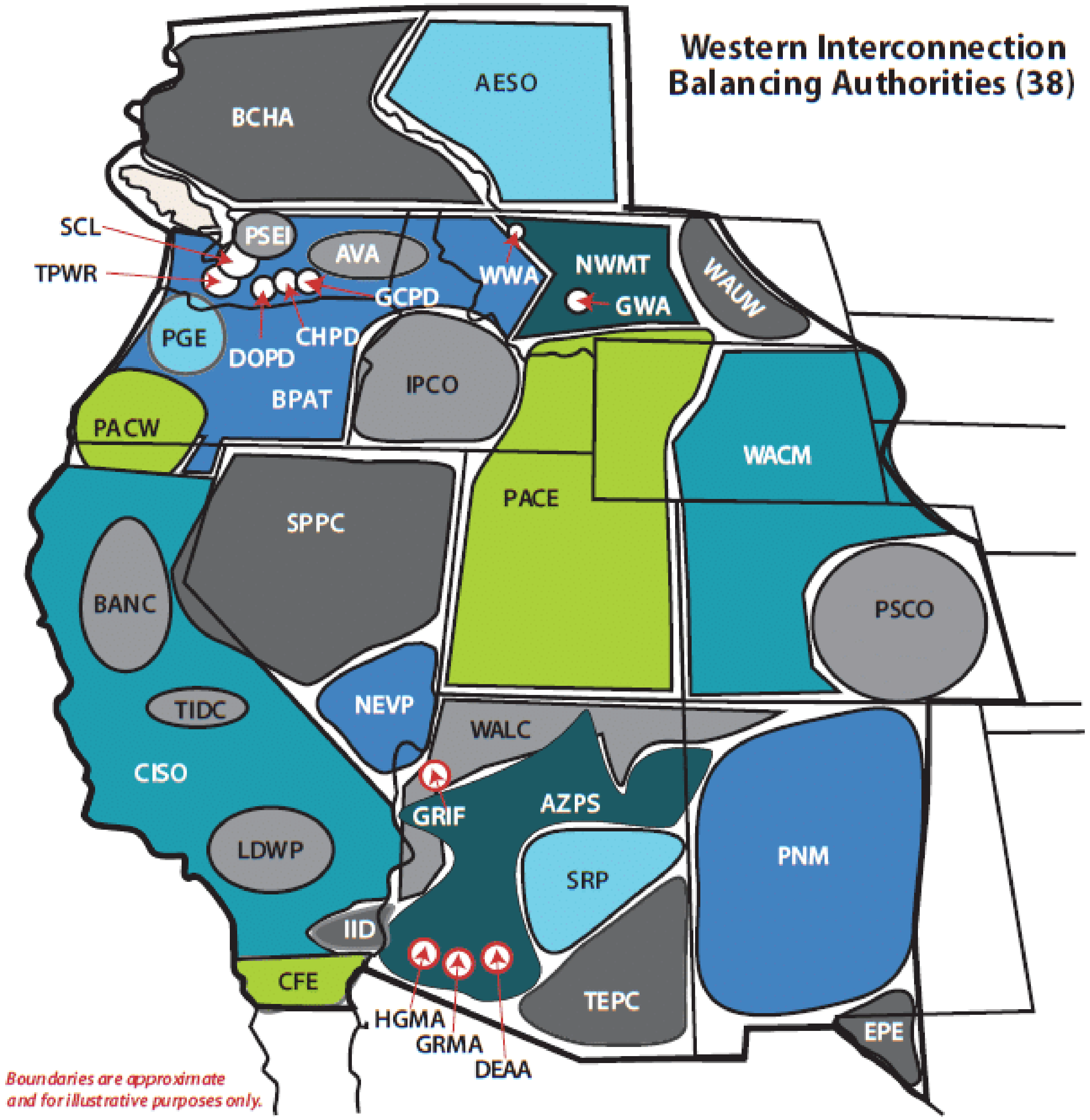
Renewable Integration Happens at the Balancing Authority Scale

Balancing Authority

Wind & solar are "must take"
Wind and solar are "non-dispatchable" without storage

1) Wind + Solar shortfalls: uptake by other regional technologies or imports
2) Wind + Solar > Load : potential curtailment

- BAs are the grid-relevant scale to evaluate energy droughts, and extreme events from a resource adequacy perspective
- Each BA presents unique integration challenges due to regional load differences and renewable profiles

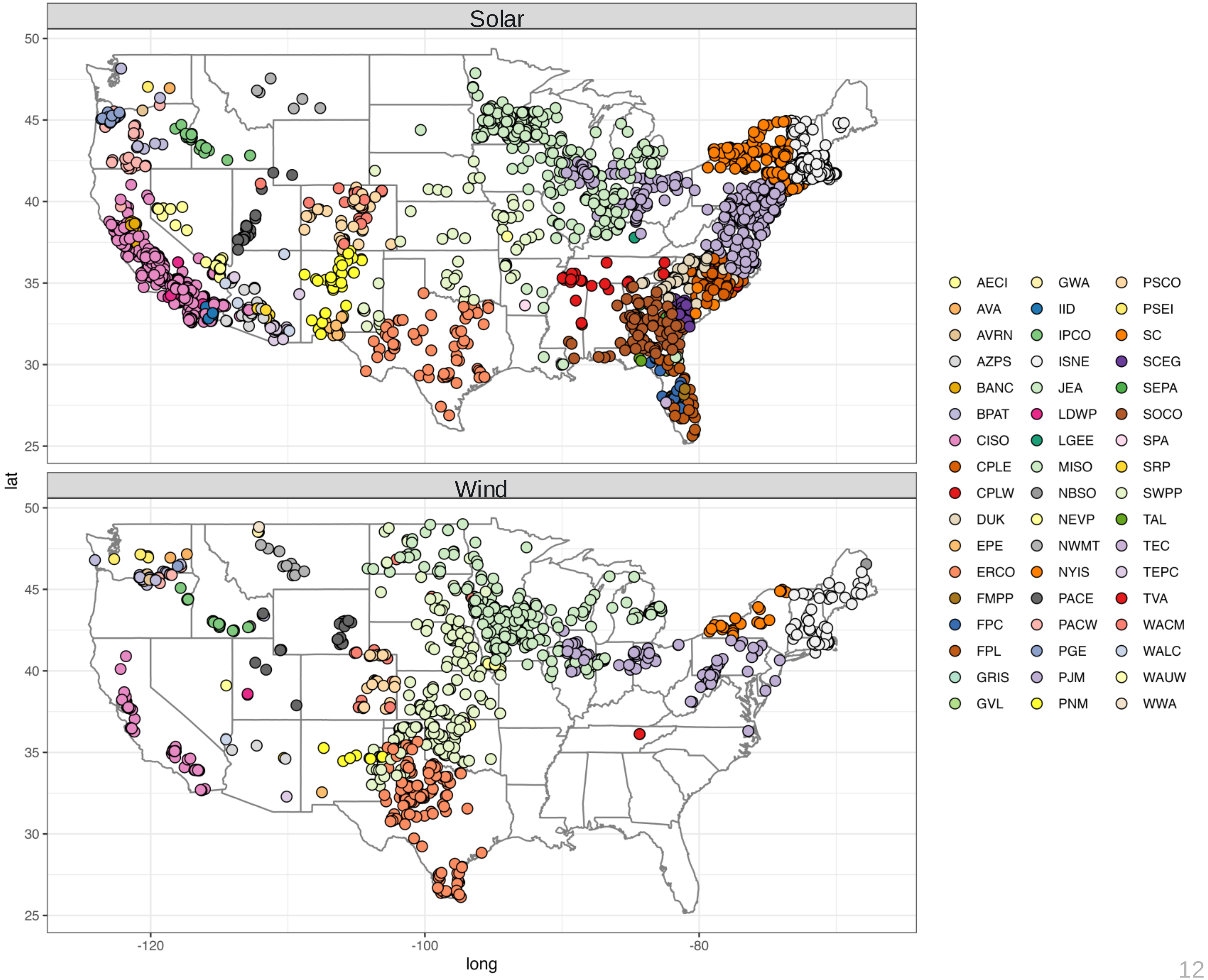


Continental US Utility Scale Wind and Solar

As of 2020:

- 4026 solar plants
- 1395 wind plants
- 69 BAs across the Continental US

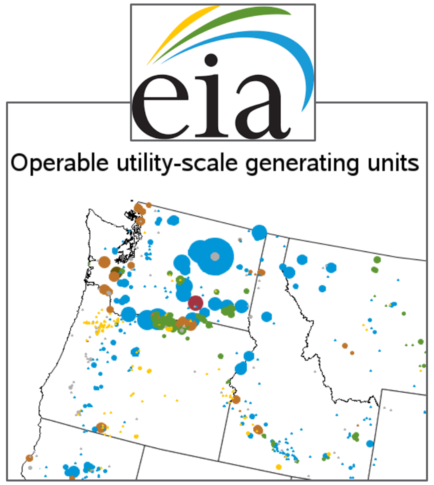
Grid impact assessments require a **long historical baseline** of renewable power production **unique to each power plant** to draw conclusions about future operational challenges



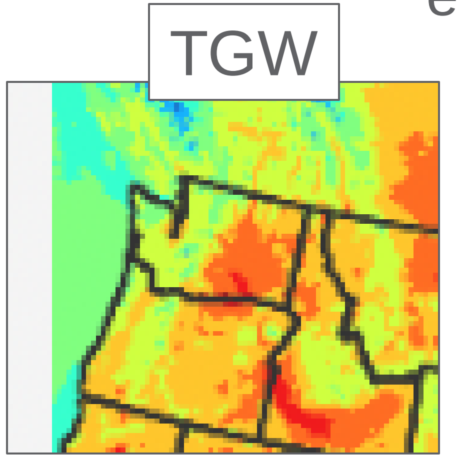
Development and evaluation of hourly wind and solar datasets at the BA scale

To address GODEEEP research questions we need 40-year hourly BA-scale wind and solar power time series that are based on coincident and therefore consistent weather information as load and other weather-sensitive generation technologies.

Step 1: develop a ~10-year historical baseline with historical power plant configuration for evaluation of the process based on observed generation



Step 2: develop a 40-year historical baseline with year 2020 power plant configuration for the energy drought benchmark evaluation



Step 3: develop 40-year future climate hourly time series with infrastructure years 2025, 2030, 2035, 2040, 2045 and 2050 for the evolving energy drought evaluation

Development and evaluation of hourly wind and solar datasets at the BA scale

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Step 1: develop a ~10-year historical baseline with historical power plant configuration for evaluation of the process based on observed generation

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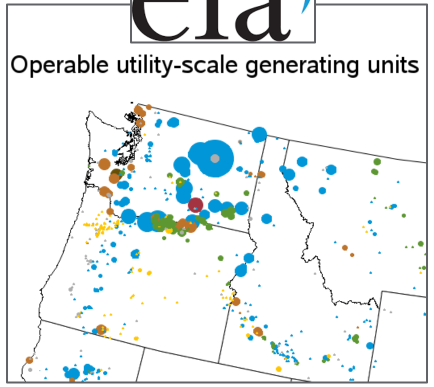
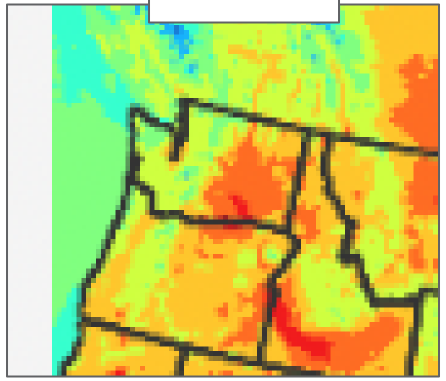
eia

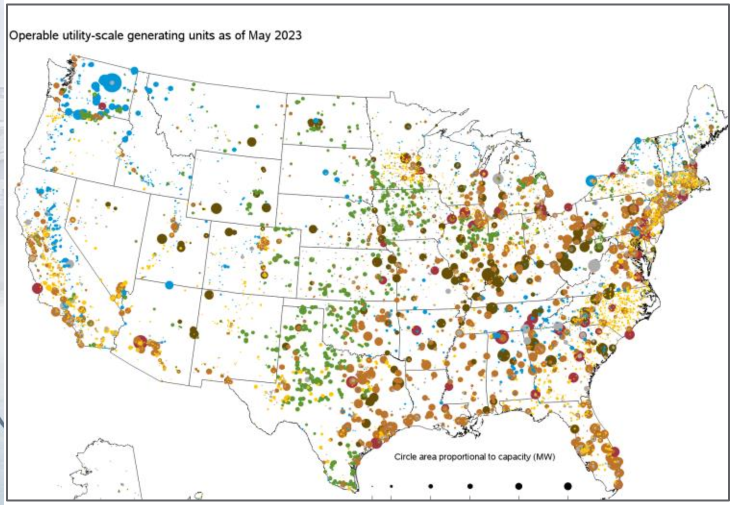


TGW



Wind and Solar Generation Timeseries: Methodology

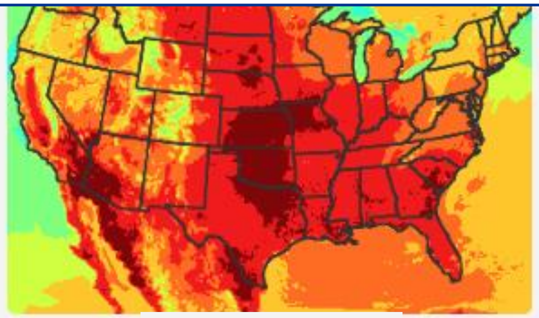
PLANT CONFIGURATION



https://www.eia.gov/electricity/data/eia860/

METEOROLOGY TIME SERIES

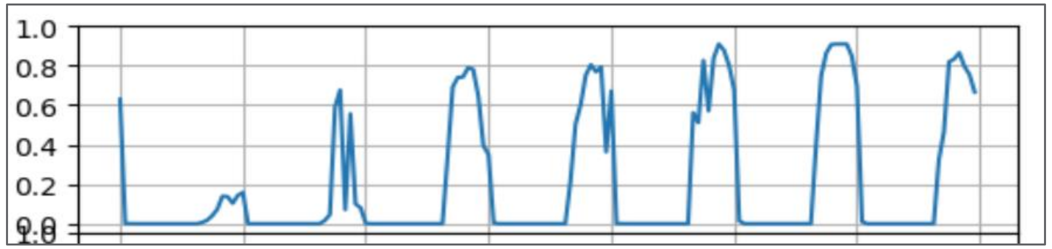
Thermodynamic Global Warming WRF



12km/1hr
1980 - 2022
https://tgw-data.msdlive.org/

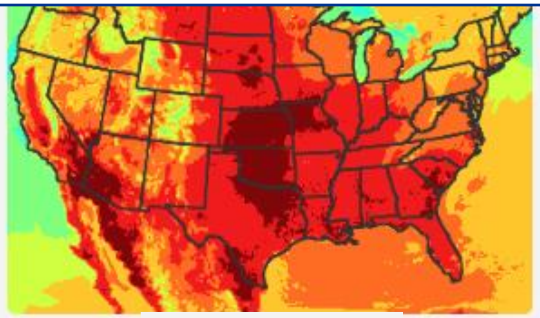
rev

POWER TIME SERIES



Wind Meteorology at Individual Power Plants

Thermodynamic Global Warming WRF



12km/1hr

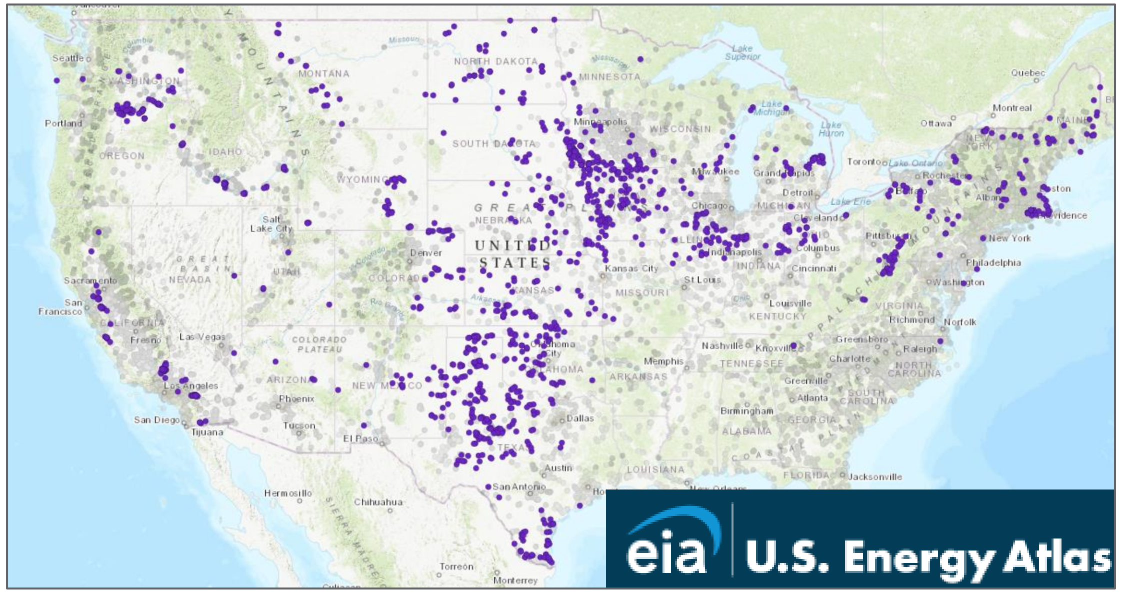
1980 - 2022

https://tgw-data.msdlive.org/

Wind speed, temperature, and pressure are extracted from TGW WRF

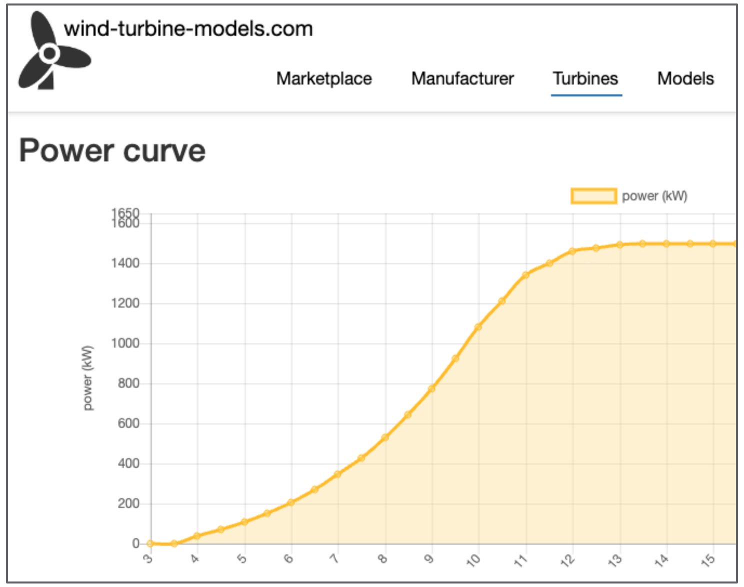
Variable	Description	Temporal Resolution
U	X-wind component	3 Hourly
V	Y-wind component	3 Hourly
T	Temperature	3 Hourly
P	Pressure	3 Hourly

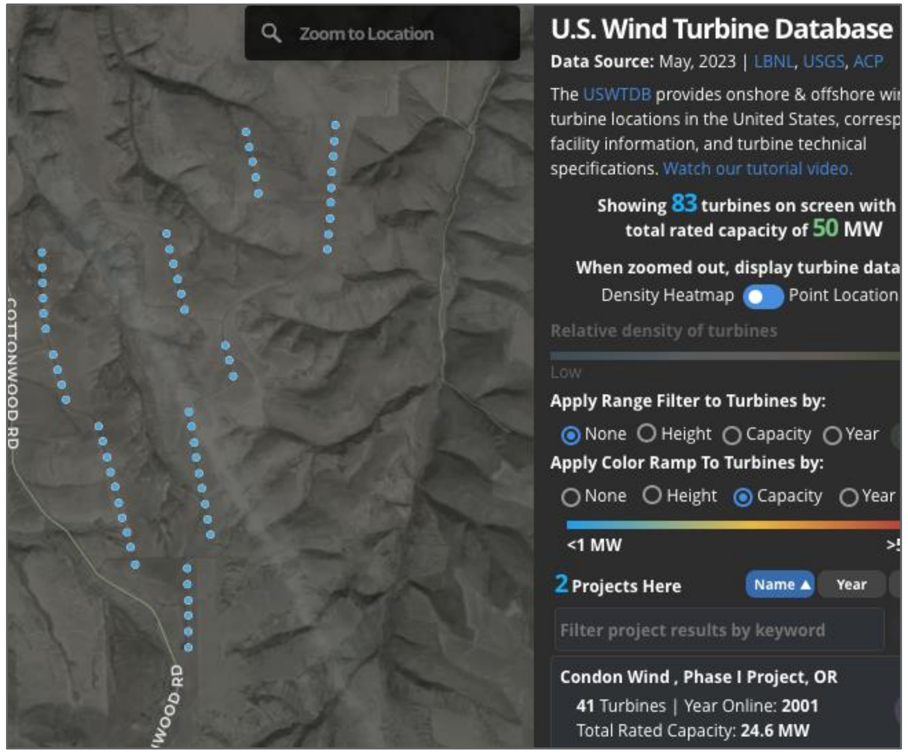
Variables are interpolated temporally to hourly and vertically to wind hub heights at all U.S. wind plant locations



Wind Plant Configurations

reV SAM Plant Config Parameter	Description	Data Source
System Capacity	Installed plant capacity	EIA 860 – Wind spreadsheet
Turbine Power Curve	Converts wind speed to normalized power	Wind-turbine-models.com if available – if not, synthesized from existing power curves
Turbine x, y Coordinates	Locations of all turbines in the generator	U.S. Wind Turbine Database if available – if not, default coordinates created
Turbine Hub Height	Height of hub for most common turbine in generator	EIA 860 – Wind spreadsheet
Turbine Rotor Diameter	Rotor diameter for most common turbine in generator	EIA 860 – Wind spreadsheet

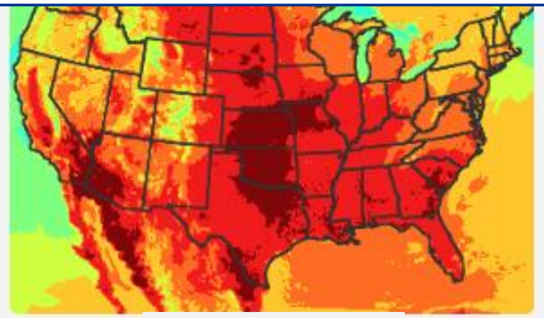




https://eerscmap.usgs.gov/uswtdb/

Solar Meteorology at Individual Power Plants

Thermodynamic Global Warming WRF

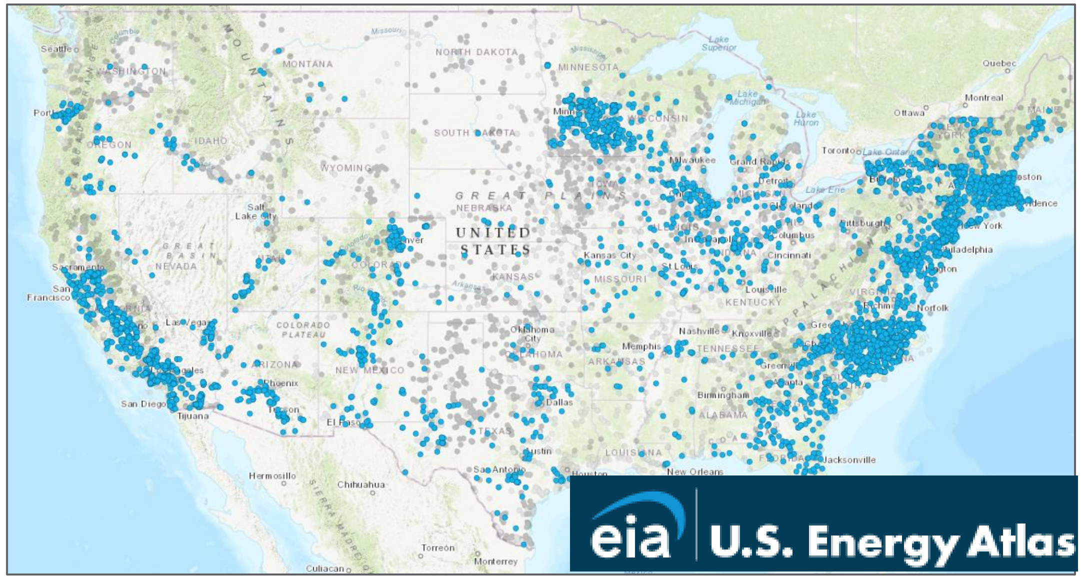


12km/1hr
1980 - 2022
https://tgw-data.msdlive.org/

Surface wind speed, pressure, temperature, and global horizontal irradiance (GHI) are extracted from TGW WRF

Variable	Description	Temporal Resolution
WSPD	Surface wind speed	Hourly
PSFC	Surface Pressure	Hourly
T2	Surface temperature	Hourly
SWDOWN	Downward Short Wave Flux – GHI	Hourly

Direct normal irradiance estimated from GHI using the DISC model, variables prepared at all U.S. solar plant locations

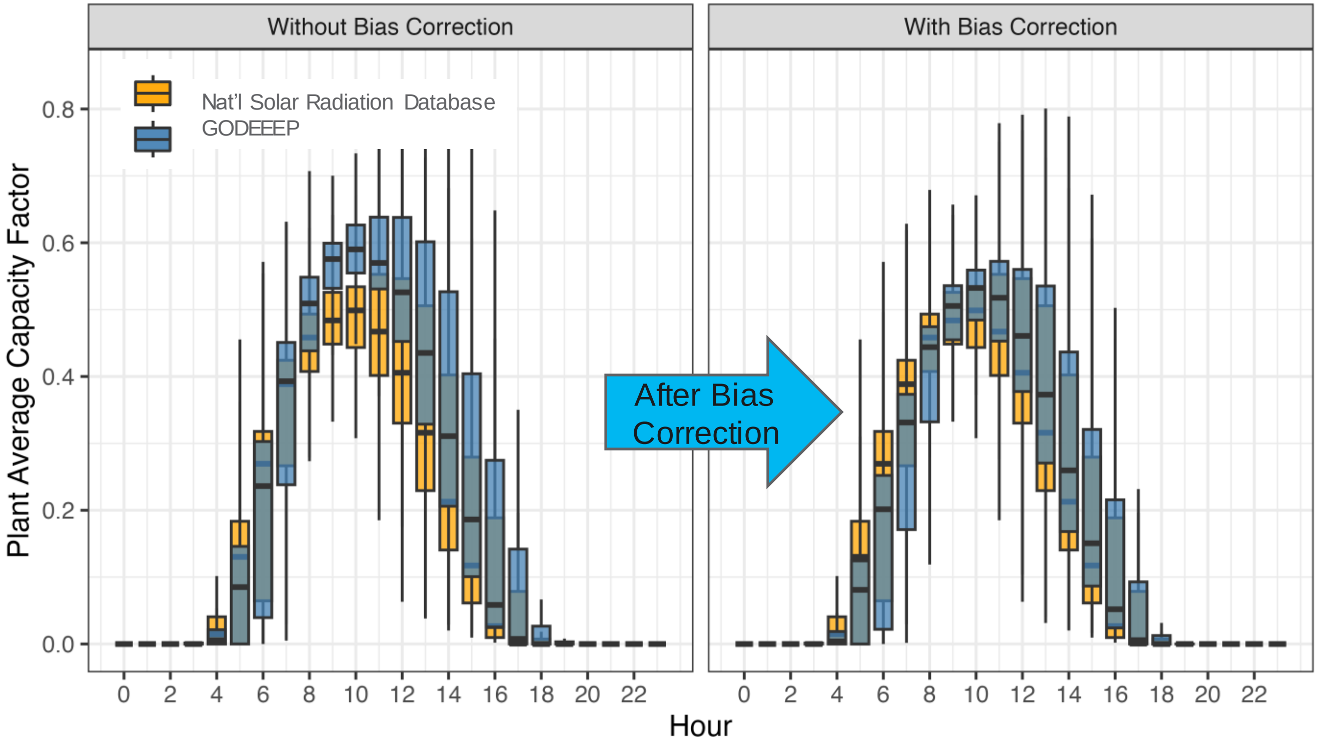


The DISC model is one of many empirical methods to calculate DNI using GHI and surface pressure
https://www.nrel.gov/grid/solar-resource/disc.html

Solar Plant Configurations

reV SAM Plant Config Parameter	Description	Data Source
System Capacity	Installed plant capacity	EIA 860 – Solar spreadsheet
PV Array Type	Fixed tilt, 1 or 2 axis tracking	EIA 860 – Solar spreadsheet
Tilt Angle	Specified or equal to latitude	EIA 860 – Solar spreadsheet
Module Type	Thin film or standard	EIA 860 – Solar spreadsheet
Azimuth Angle	Specified or direct south	EIA 860 – Solar spreadsheet

Solar **power** time series were bias corrected using quantile mapping against the National Solar Radiation Database **converted to power**



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Wind and Solar Datasets Evaluation at the BA scale using BA Observations

Observations

Balancing Authority self-reported power

BA	WIND Available Baseline	SOLAR Available Baseline
ERCOT	2007 – 2020	2011 – 2020
ISONE	2011 – 2020	2011 – 2020
SWPP	2011 – 2020	2014 – 2020
CAISO	2014 – 2020	2014 – 2020
BPA	2007 – 2020	--
MISO	2015 – 2020	--
NYISO	2016 – 2020	--

Dynamics to be evaluated at the BA scale

- Inter-annual variability amidst annual change in infrastructure
- Seasonality
- Intermittency (Wind) & Diurnal Cycle (Solar)

Metrics

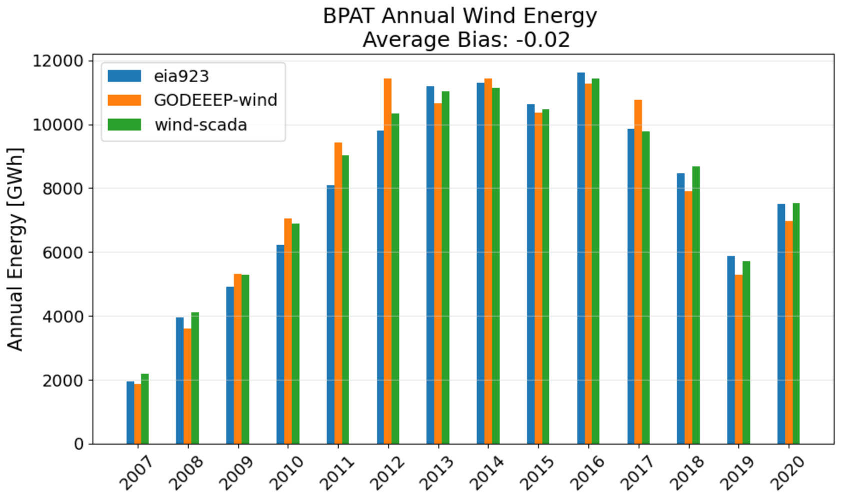
Mean Annual Relative Difference (%)

Mean Monthly Relative Difference (%)

Earth Mover's Distance (difference between two hourly distributions). Applied here, it is a measure of the daily time and magnitude difference between hourly time series (MWh).

Wind Historical Hourly Time Series Evaluation

Annual

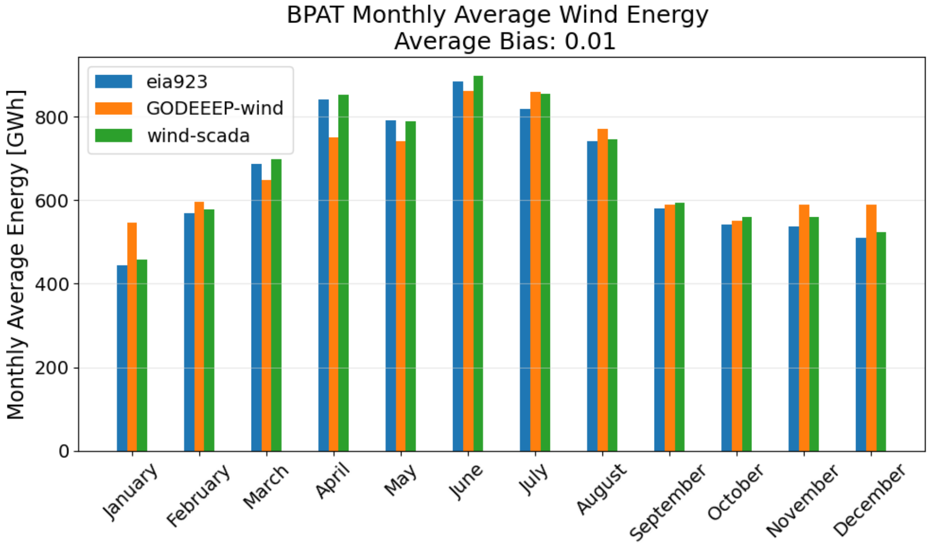


BPA annual average difference: -2%

Across BAs: ~ +7% overestimation

Reasonable representation of combined inter-annual variability and evolving fleet

Monthly

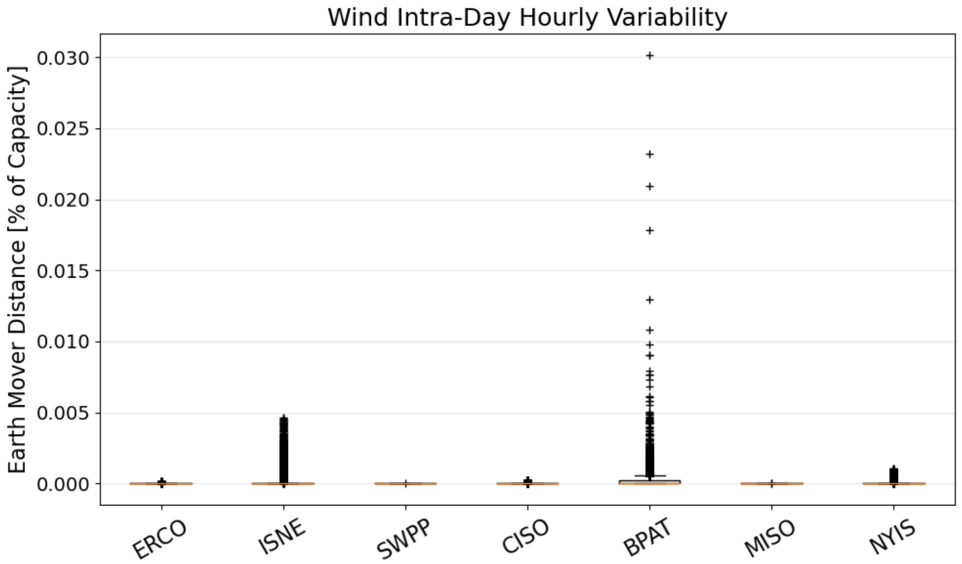


BPA mean monthly relative difference: 1%

Across BAs: ~ +9% overestimation with overestimation in winter months and underestimation in summer months

Future work will address further curation of observation data and deep uncertainties across the whole process

Intra-day hourly variability

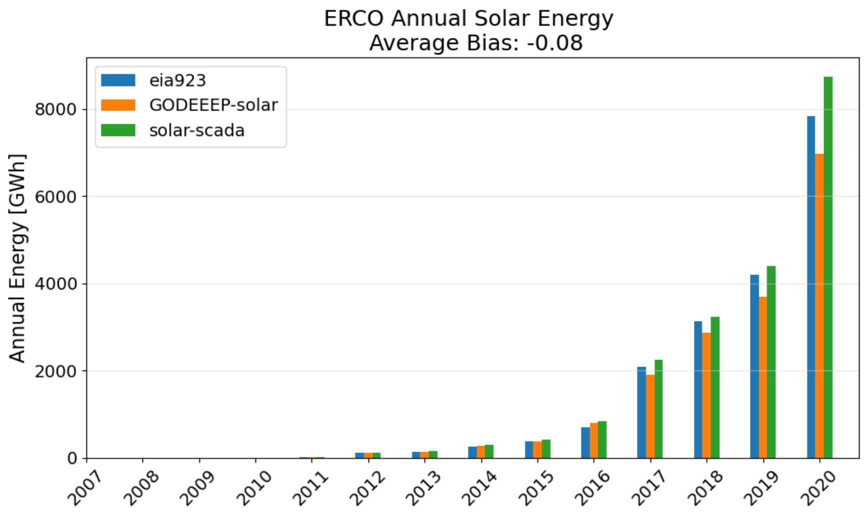


Across BAs, median relative EMD is 0%

For BAs with complex terrain (BPA), the daily spread in EMD can range up to 0.03% of installed capacity

Solar Historical Hourly Time Series Evaluation

Annual

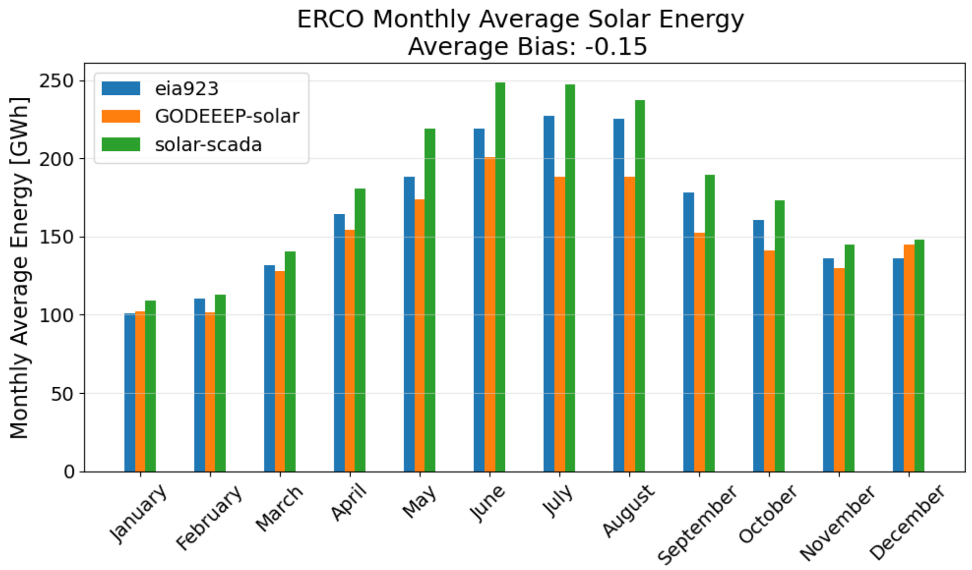


ERCOT annual average difference: -8%

Across BAs: ~ +7% overestimation

Reasonable representation of combined inter-annual variability and evolving fleet

Monthly

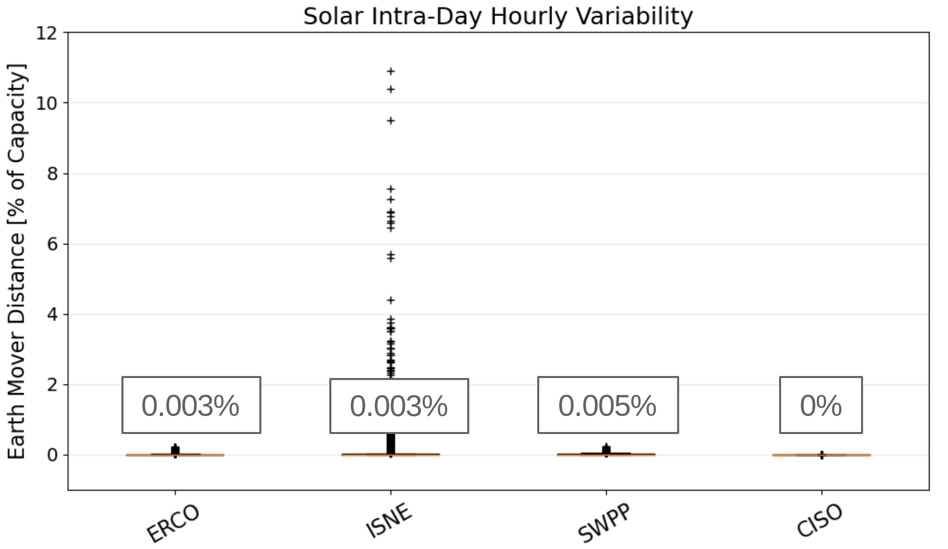


ERCOT mean monthly relative difference: -15%

Across BAs: ~ +4% overestimation with overestimation in winter months and underestimation in summer months

Future work will address further curation of observation data and deep uncertainties across the whole process

Intra-day hourly variability



With respect to the installed capacity, EMD is very small – less than 0.1%

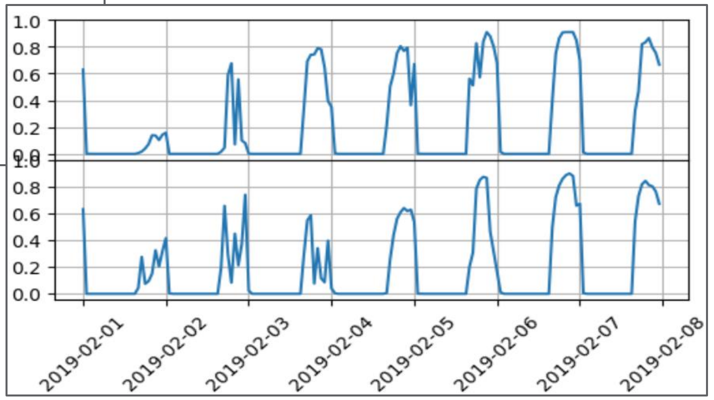
Some days in Eastern Interconnect can range higher than 10%

EMD needs to be benchmarked with other datasets to address future steps in some regions

Wind and Solar Hourly Profiles and Generation Datasets on Zenodo

Hourly wind and solar generation profiles for every EIA 2020 plant in the CONUS

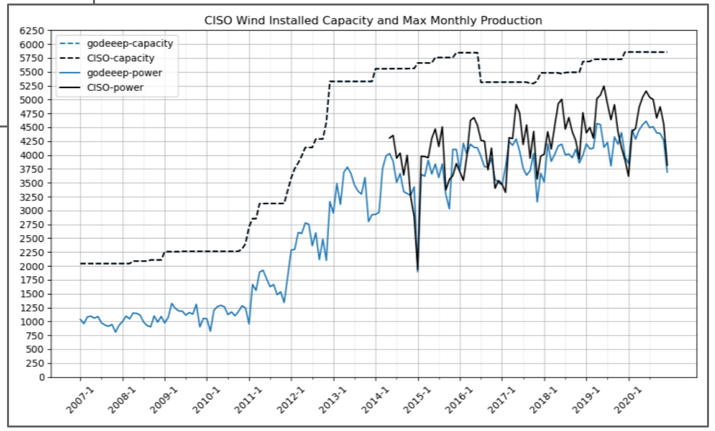
Bracken, Cameron; Underwood, Scott; Campbell, Allison; Thurber, Travis B; Voisin, Nathalie



DOI 10.5281/zenodo.7901615

Balancing Authority Hourly Generation Of Installed Plant Capacities in CONUS

Campbell, Allison; Bracken, Cameron; Underwood, Scott; Thurber, Travis B; Voisin, Nathalie



DOI 10.5281/zenodo.7991871

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Short Q&A

A first continuous US benchmark of historical energy resources droughts

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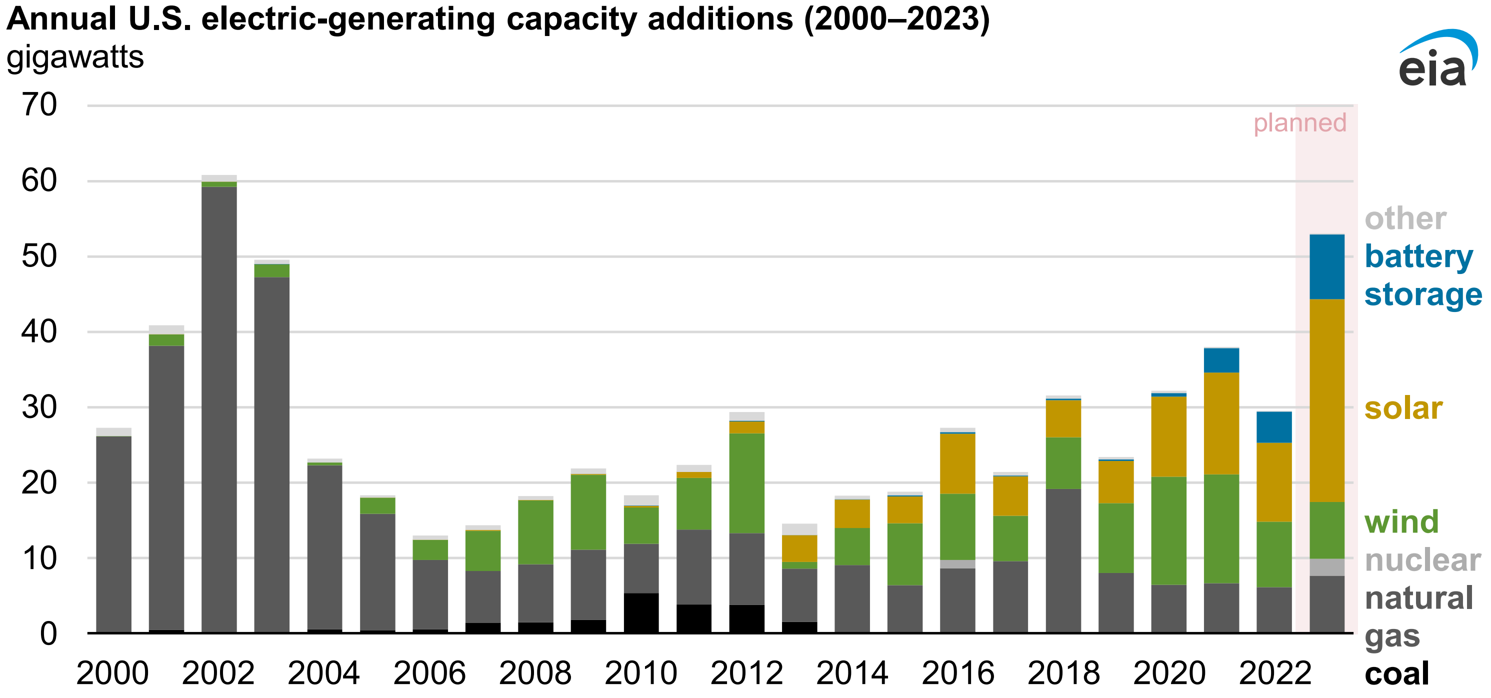
Hydrologic Drought — Months to Years

Energy Drought — Hours to Days

Increased reliance on renewables brings increased risk of weather driven wind and solar shortages



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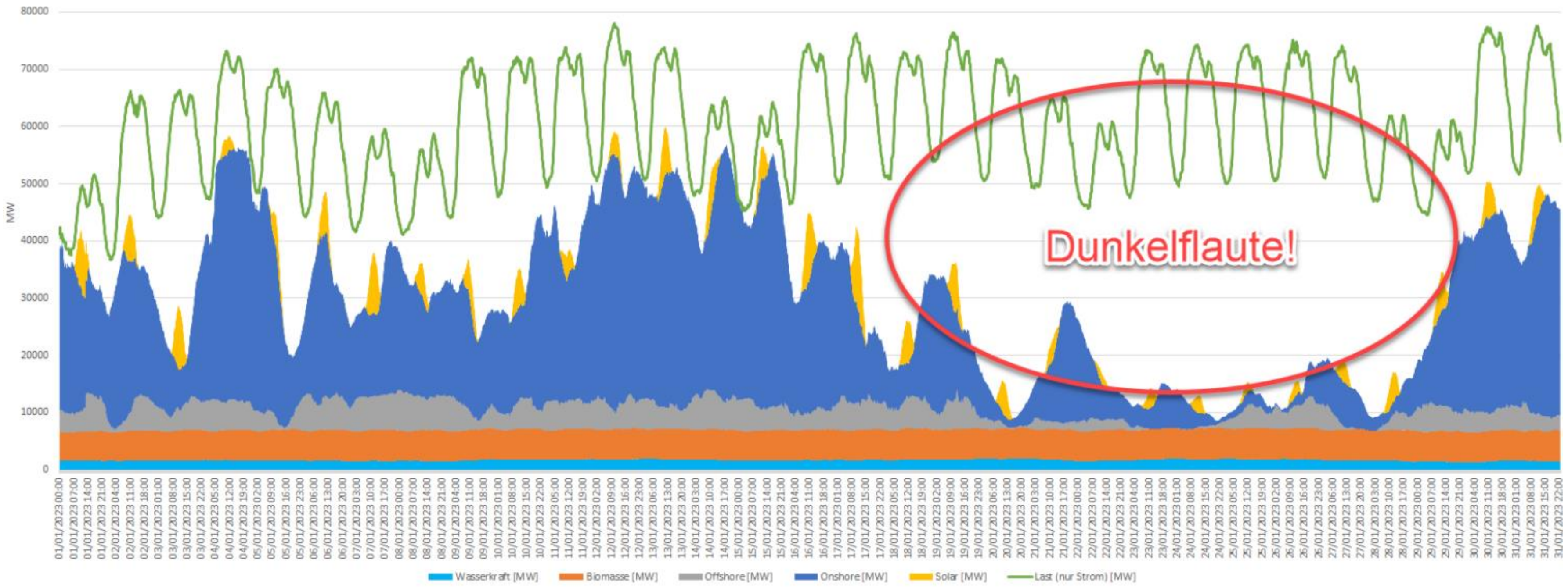
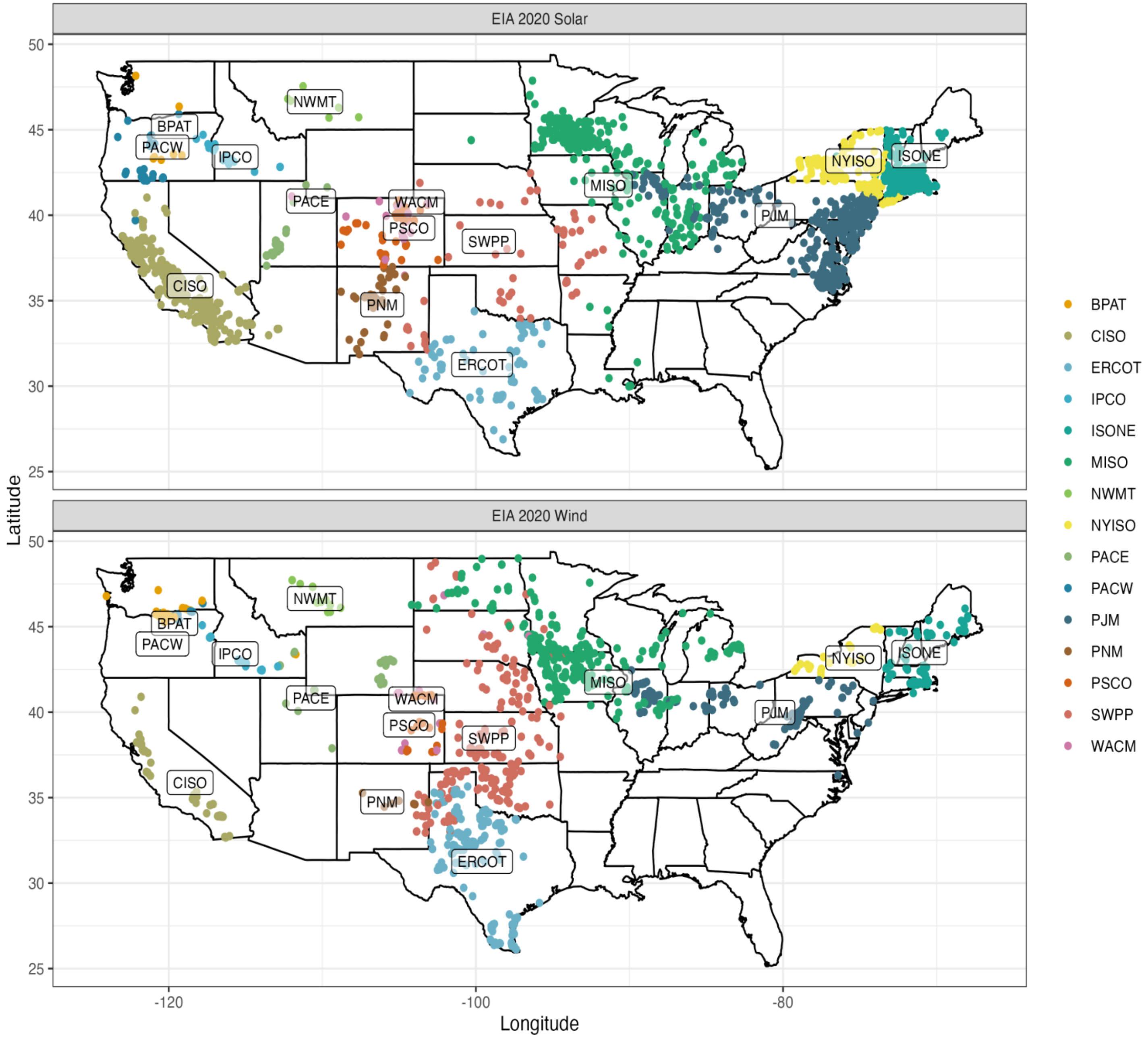
What are Compound Energy Droughts?

- **Compound Wind and Solar Energy Droughts** – Periods in which both wind and solar are simultaneously low
- **Compound Wind and Solar Energy Droughts + High Load** – Low wind and solar coincident with high load
- Wind and solar generation are weather dependent, so we are really asking how certain aspects of the weather system co-vary over large regions
- We are interested in energy droughts at a spatial scale where it matters for the grid, Balancing Authority level



Energy Drought Study Region – BA Scale

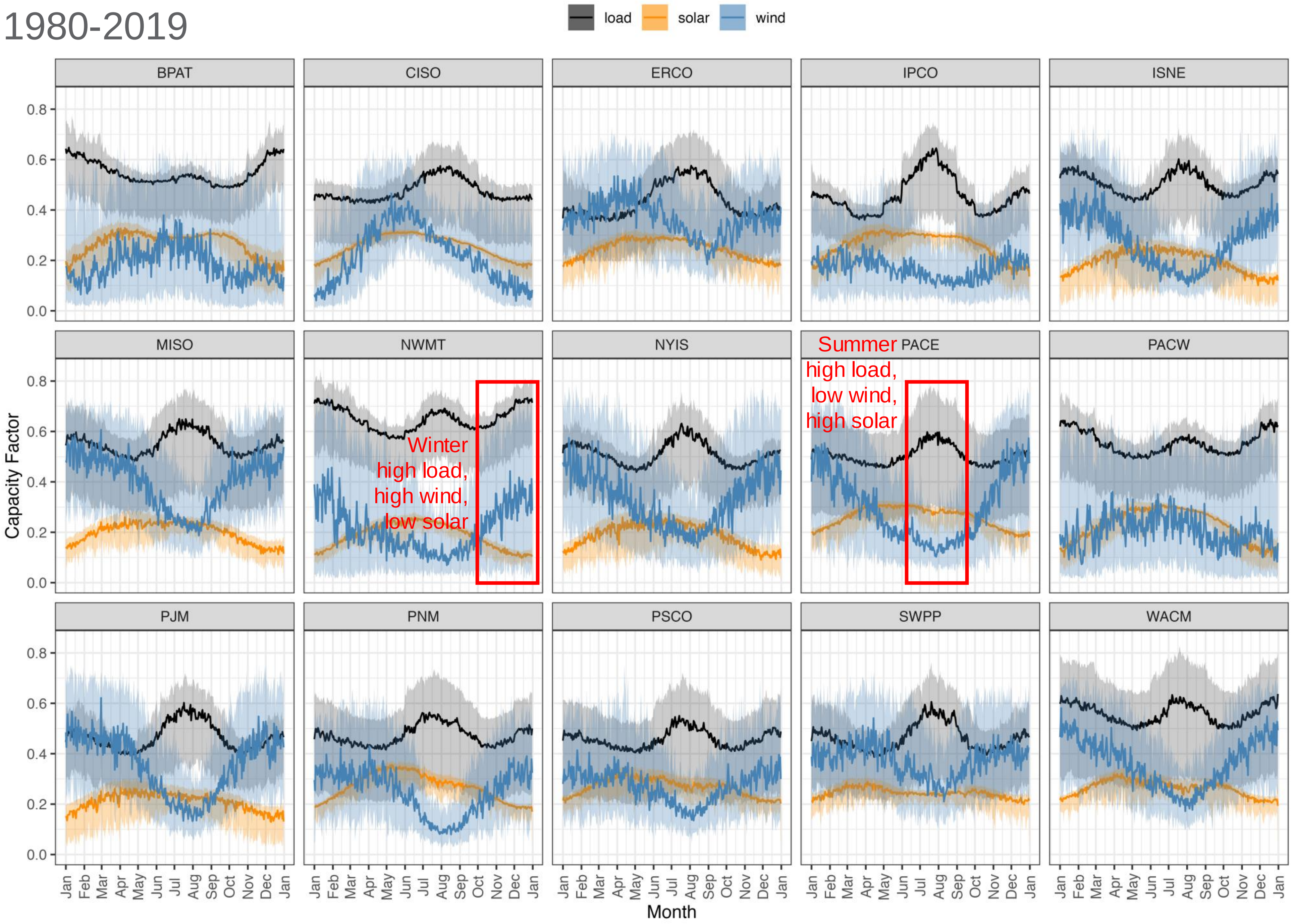
- 15 BAs across the Continental US
- Only BAs with at least 5 wind and solar plants are considered
- Plants are from EIA 860 2020
- All plants within a BA are aggregated at an hourly timestep
  - Not scaled to historical BA gen
- Coincident hourly wind, solar and load from 1980-2019



Wind solar and load cycles vary depending on the region and season

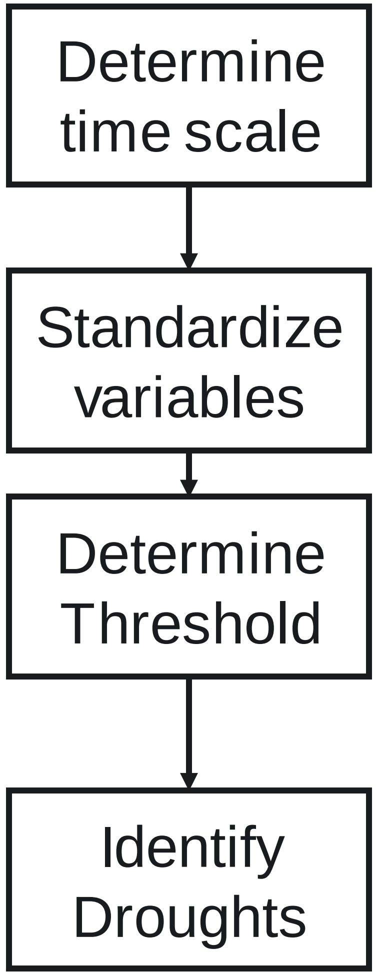
At the seasonal time scale, there is often complementarity between wind and solar to address high load periods. For seasonal droughts, hydro, natural gas and transmission also need to be considered.

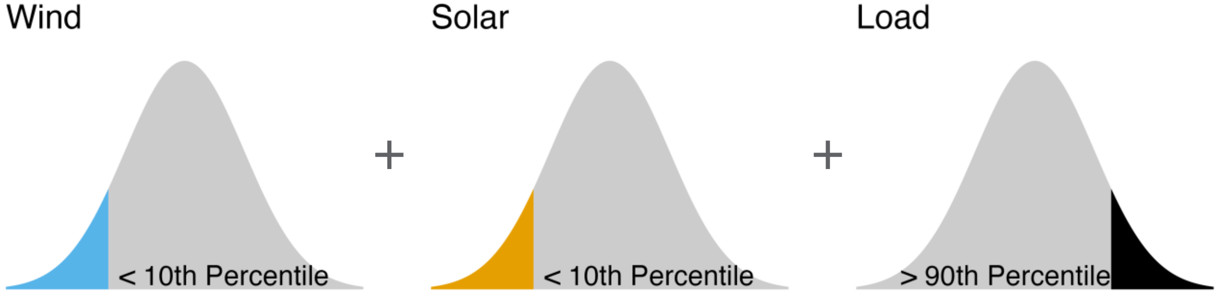
1980-2019



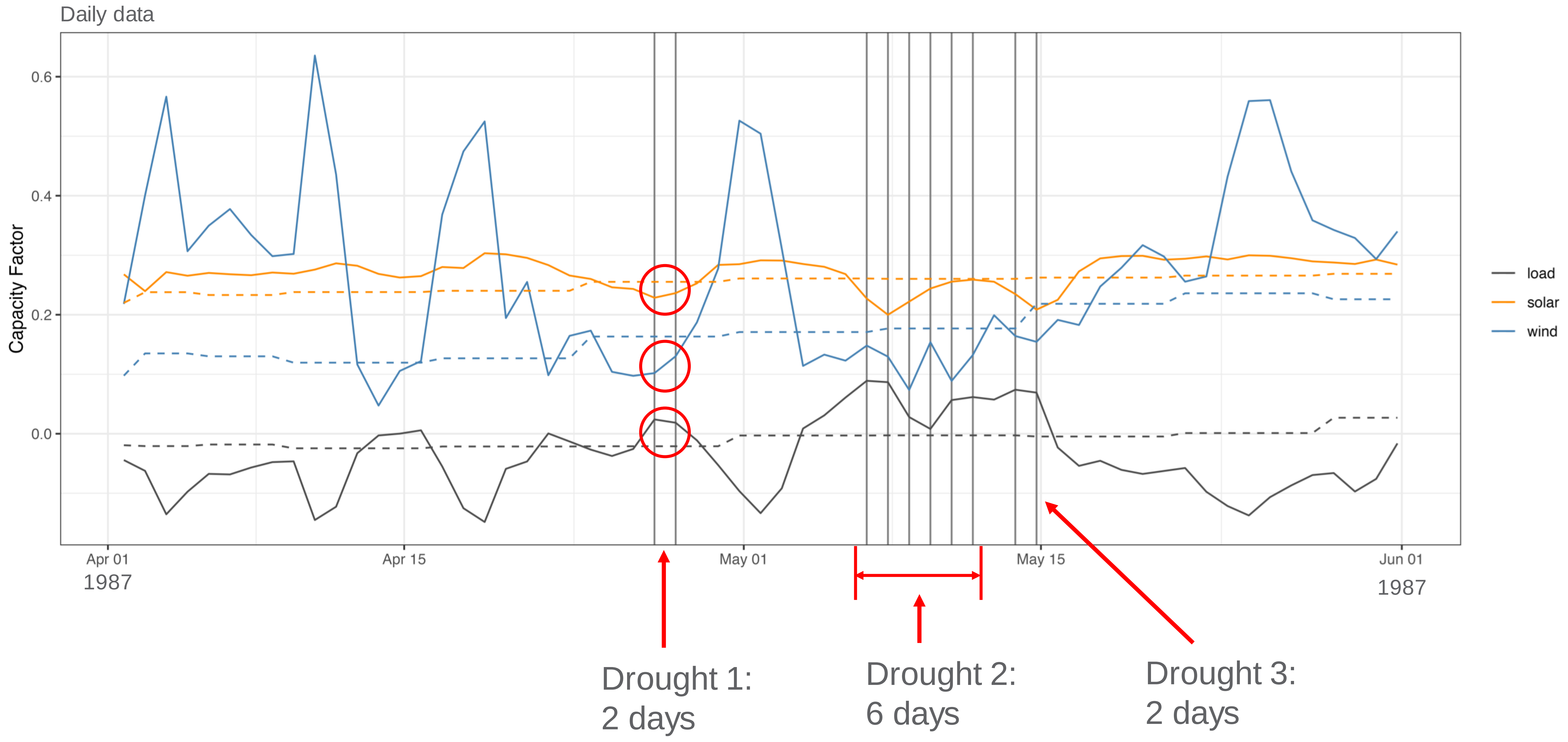
Compound Energy Drought: Definition and Metrics

- Total the generation for several time scales
  - 1-hour, 4-hour, 12-hour, 1-day, 2-day, 3-day, 5-day
  - Sub-daily time scales are important for grid reliability
- Develop standardized indices
  - SREPI – Standardized Renewable Energy Production Index
  - SLRI – Standardized Residual Load Index
- Determine dynamic drought threshold
- Compound Wind and Solar Droughts
  - $SREPI(W_t) < 10^{th}$ percentile and $SREPI(S_t) < 10^{th}$ percentile
- Compound Wind, and Solar Droughts + High Load
  - $SREPI(W_t) < 10^{th}$ percentile and $SREPI(S_t) < 10^{th}$ percentile and $SRLI(L_t) > 90^{th}$ percentile





Energy Drought Definition : Daily Example



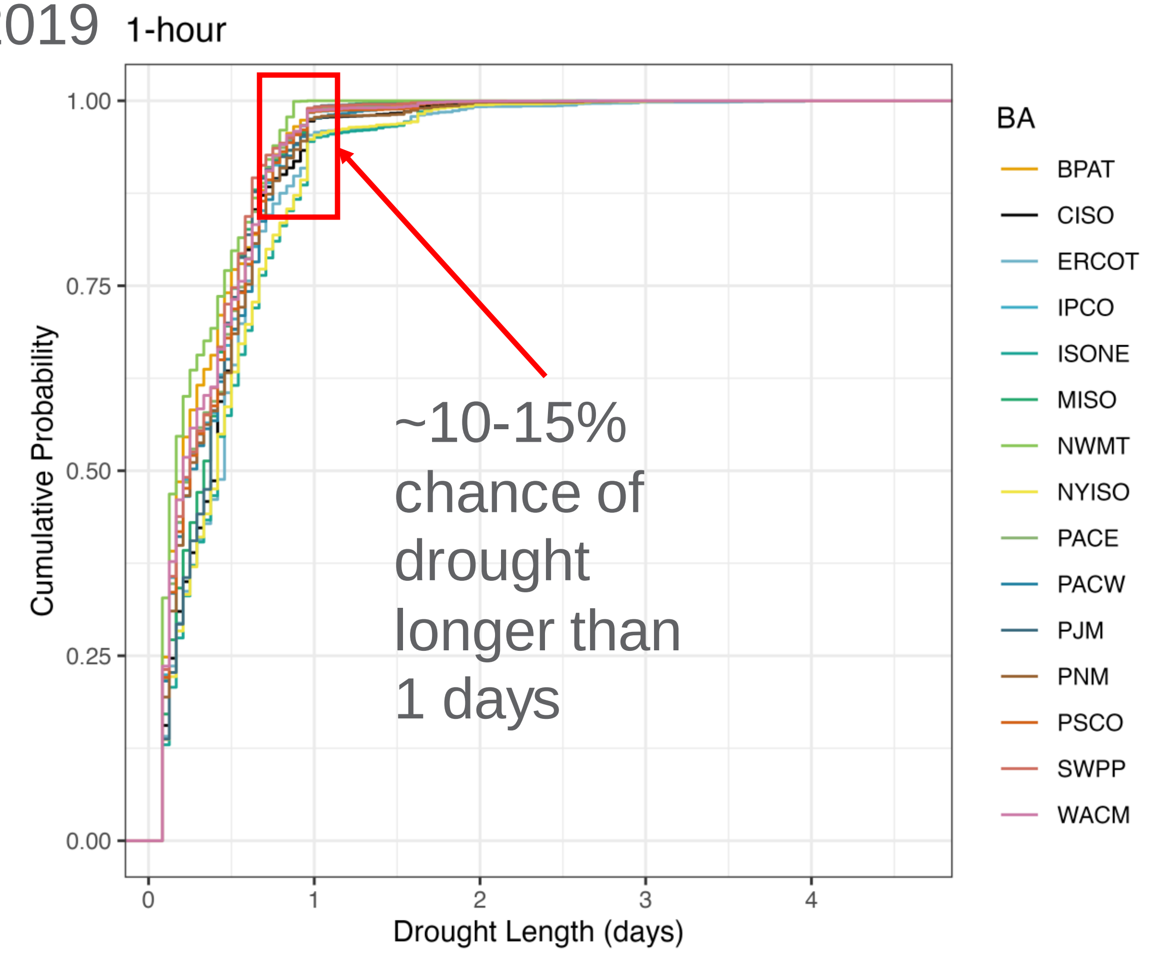
Non-Compound Solar Drought: Duration

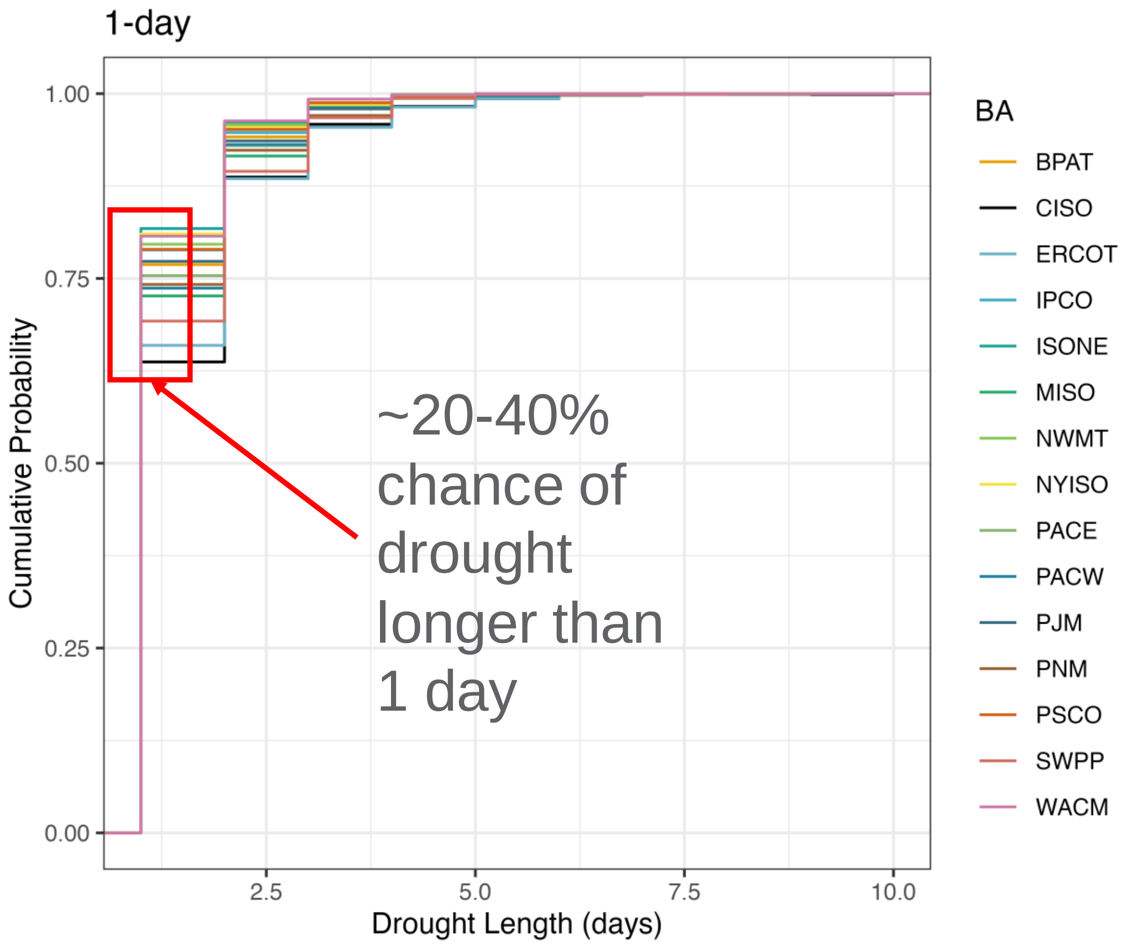
What is the chance that a drought will last 1 day or more?

Hourly droughts last up to 3 days

Daily droughts last up to 5-7 days

1980-2019



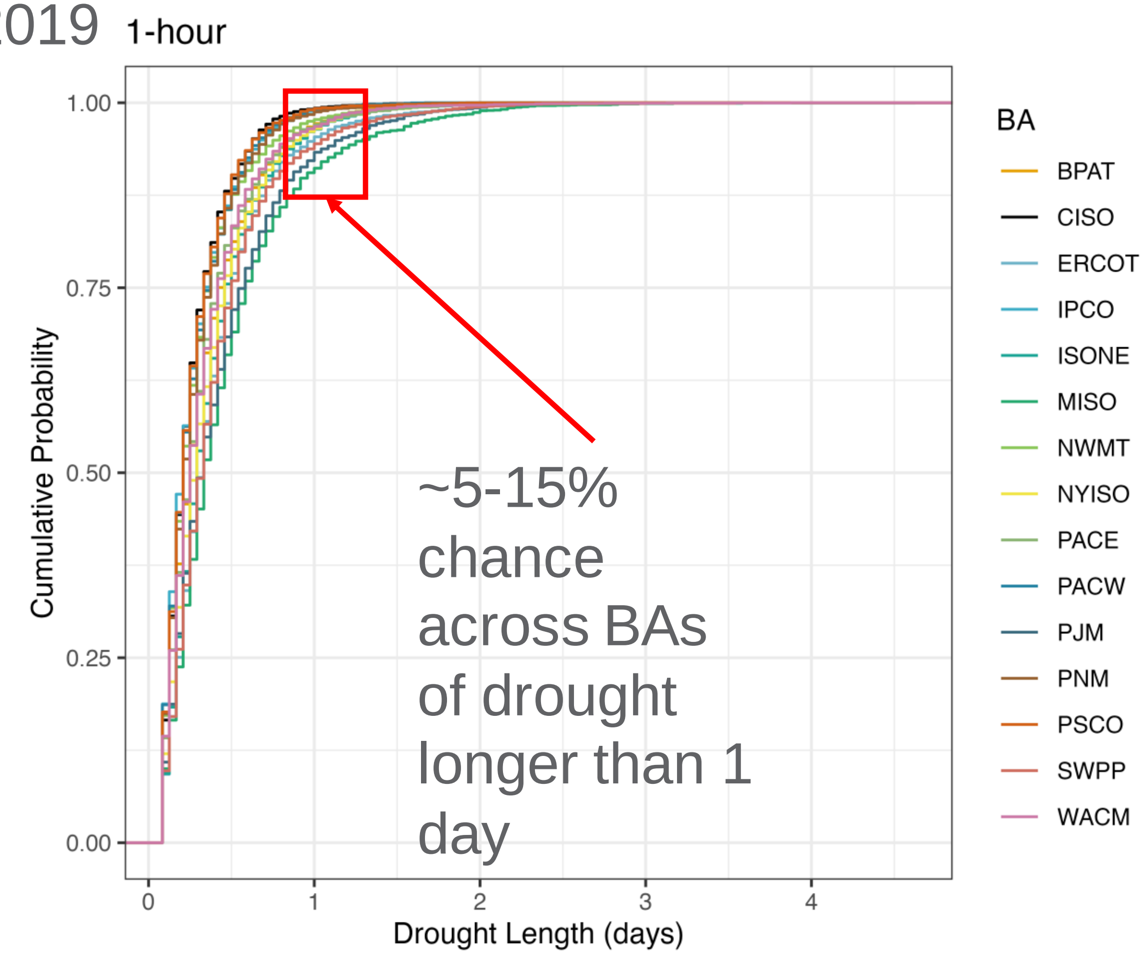


Non-Compound Wind Drought: Duration

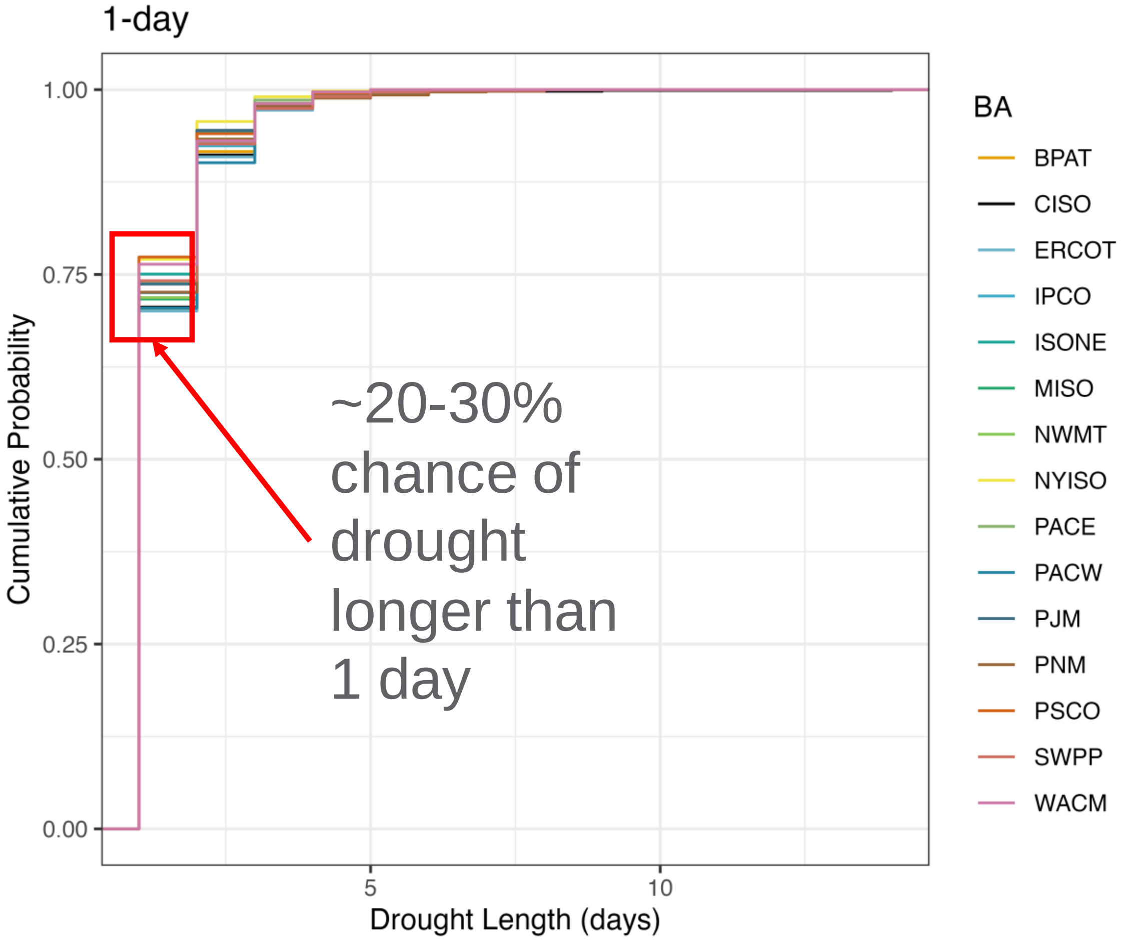
What is the chance that a drought will last 1 day or more?

Hourly droughts last up to 3 days

1980-2019



Daily droughts last up to 10 days

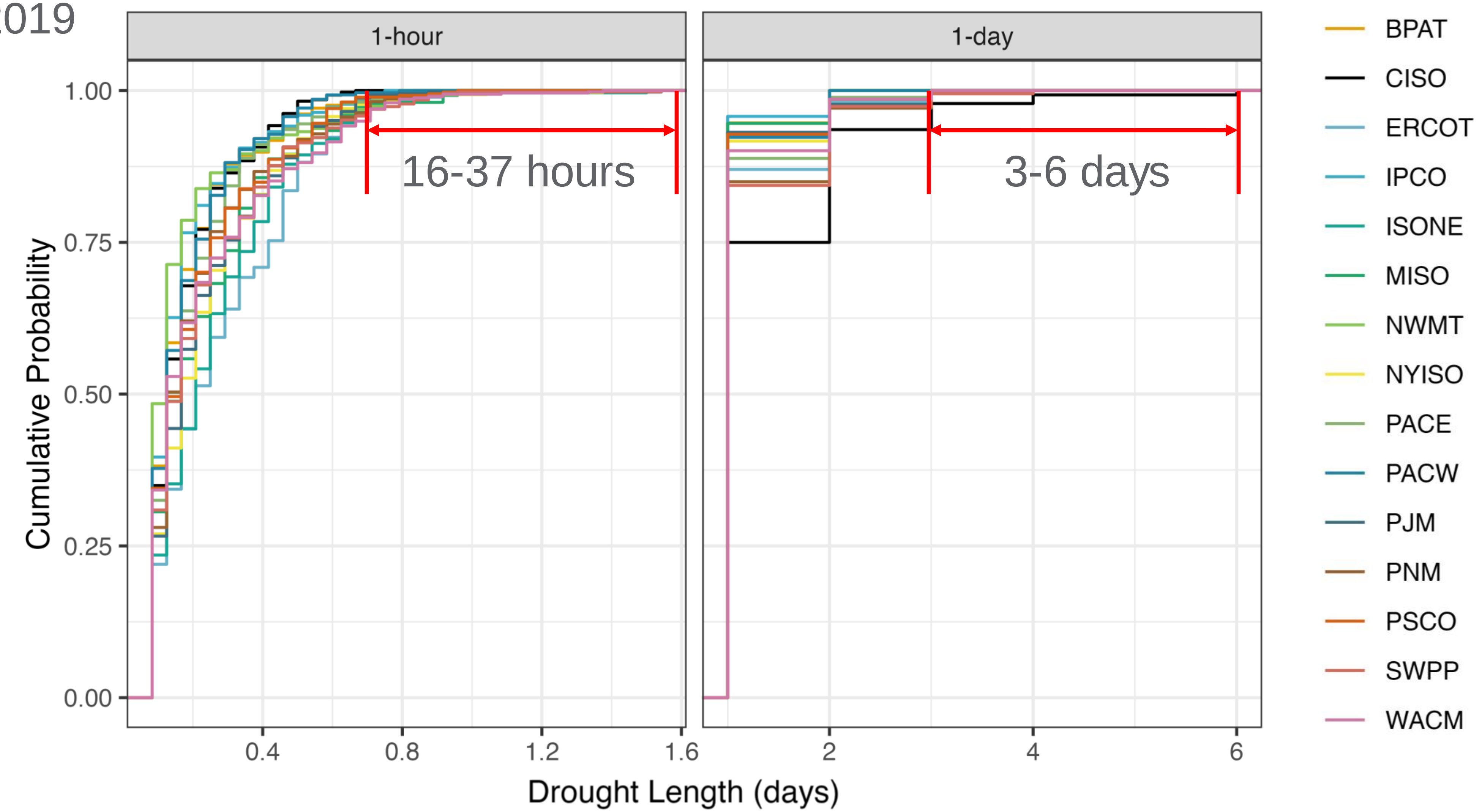


Compound wind and solar drought: duration

Longest hourly droughts last 16 to 37 hours across BAs

All daily droughts last 6 days or less

1980-2019



Hourly and daily compound droughts have distinct characteristics

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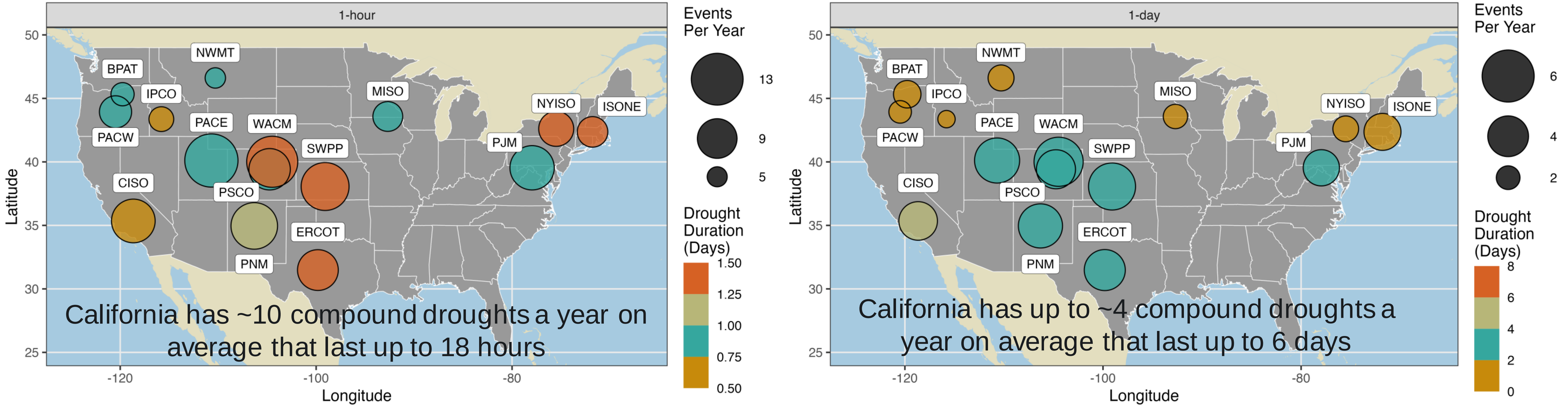
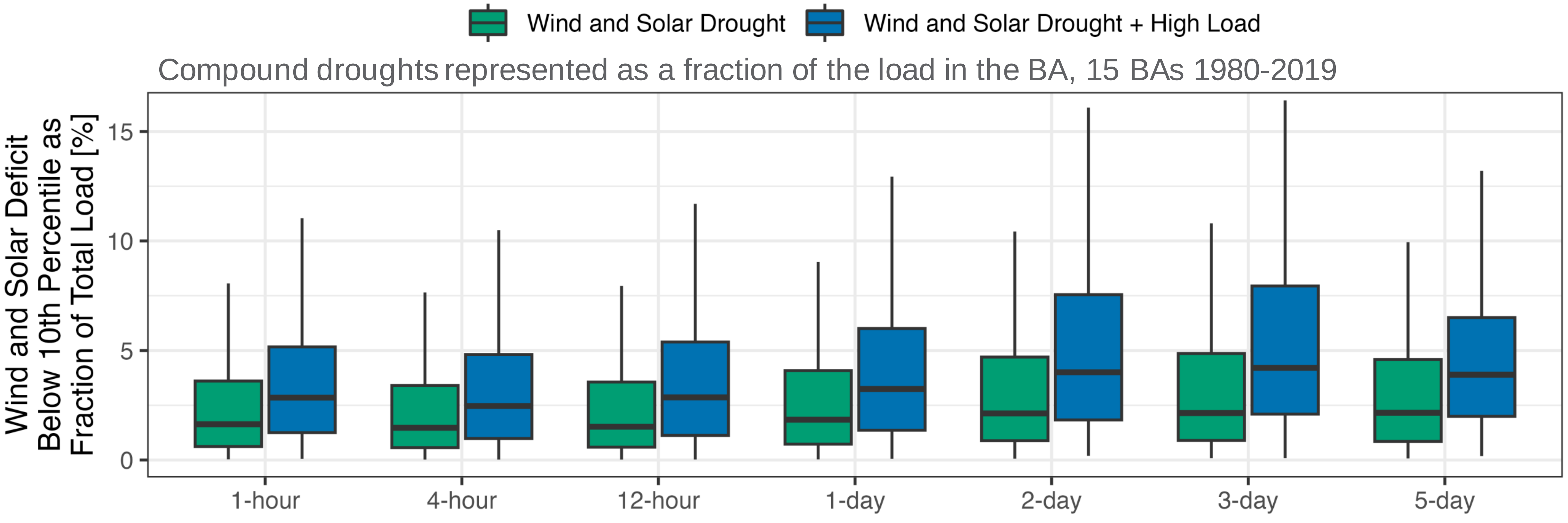
1980-2019 average frequency and maximum wind and solar drought duration



Spatial drought patterns change with time scale

- Frequency of droughts decreases with longer time scales
- California has the shortest hourly compound droughts, but the longest daily droughts

While less frequent, compound wind and solar drought with high load represent up to 10-15% of peak load



- Compound Wind and Solar droughts + High Load are less frequent but more severe on average

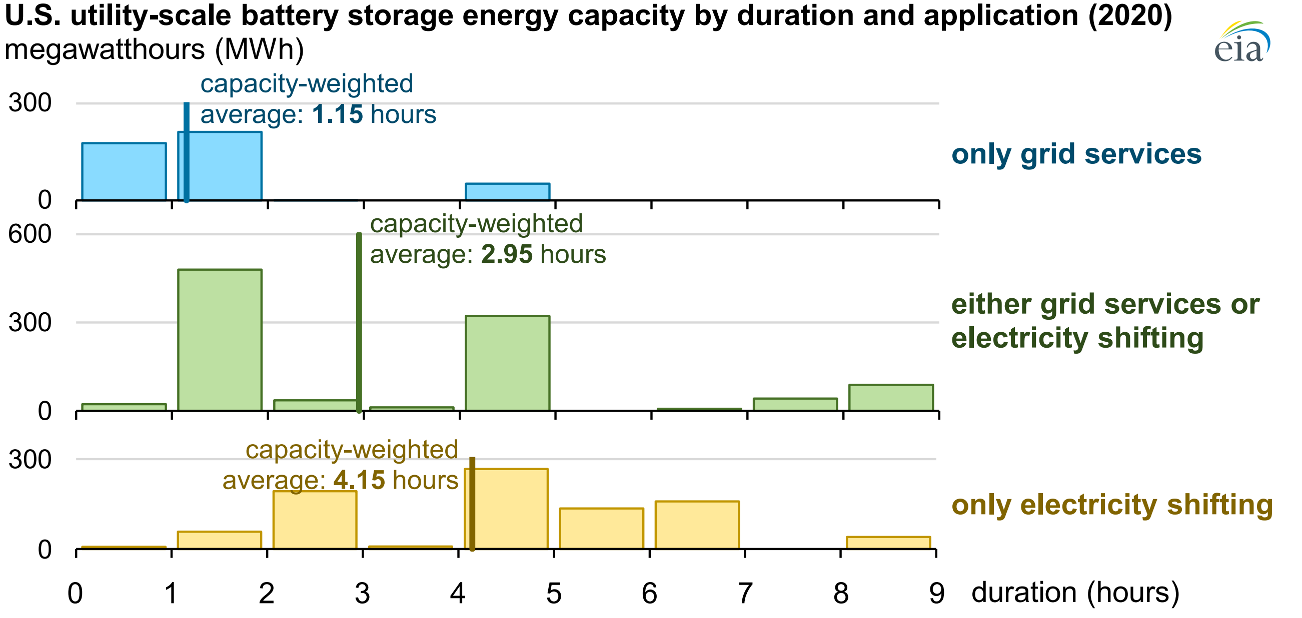
Existing battery storage is intended for short term use

Battery storage durations:

- 1 - 2 hours: grid stability, non spinning reserve, intraday storage management
- 4 - 8 hours: Load shifting, storage management for charge/recharge

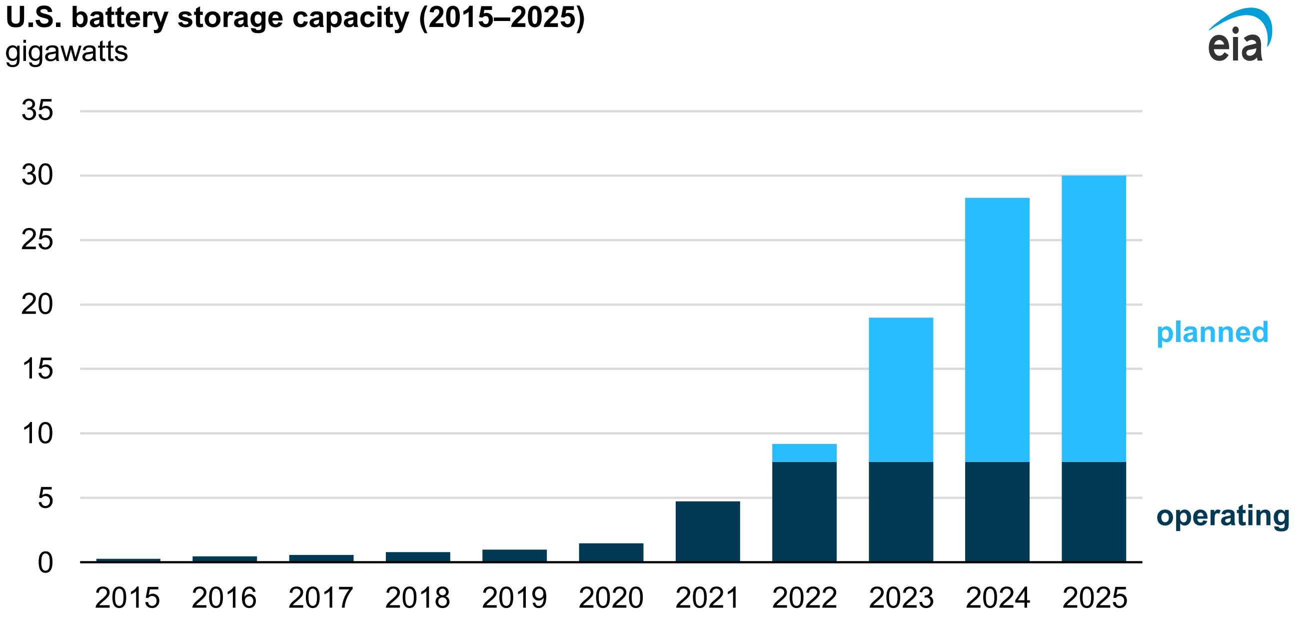
60% of new battery storage installation is intended to be hybridized with wind and solar plants

U.S. utility-scale battery storage energy capacity by duration and application (2020)
megawatthours (MWh)



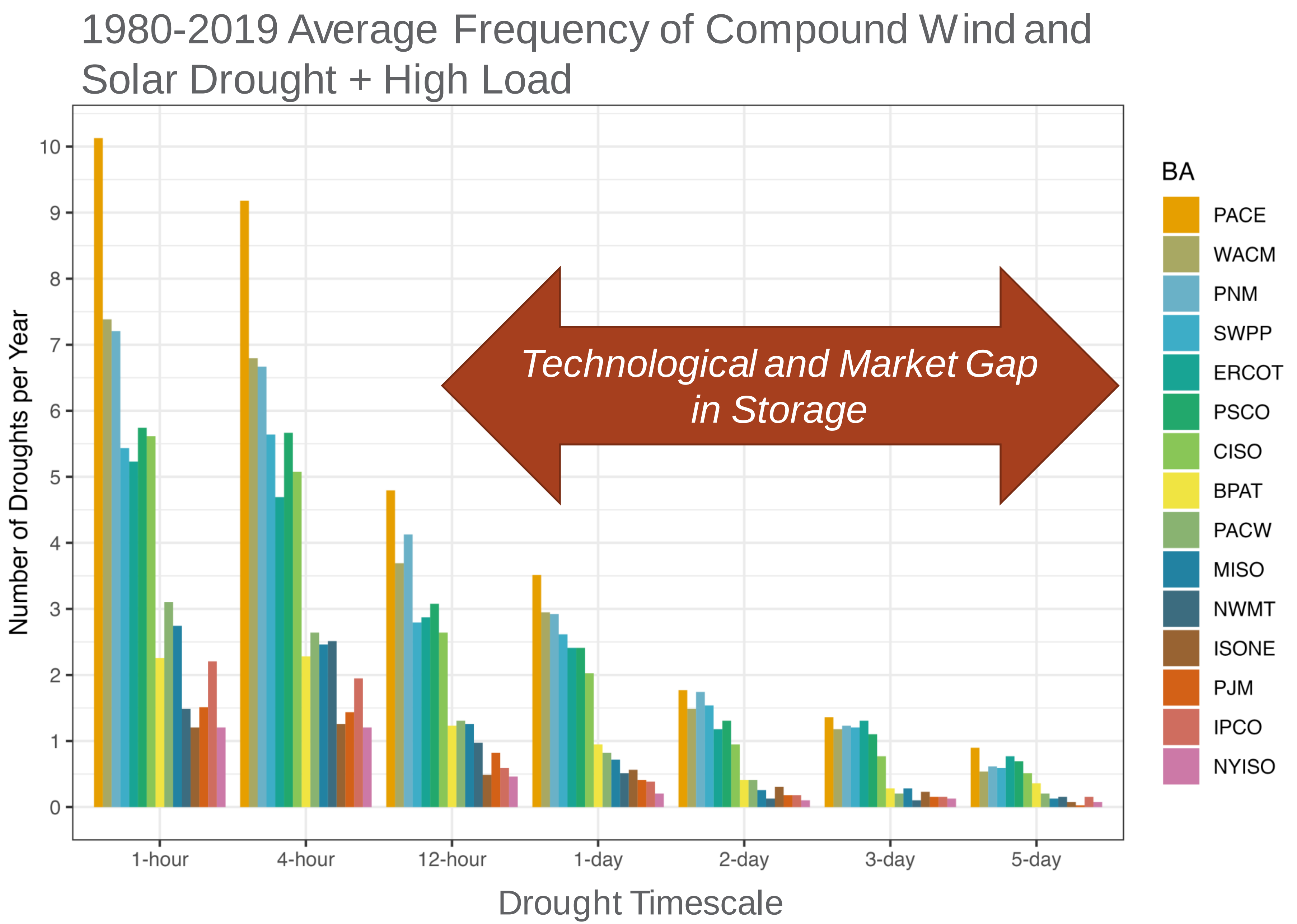
https://www.eia.gov/todayinenergy/detail.php?id=51798

U.S. battery storage capacity (2015–2025)
gigawatts



https://www.eia.gov/todayinenergy/detail.php?id=54939

Existing and planned storage is not adequate to mitigate long duration energy droughts



Energy Droughts – Takeaways

- Compound energy droughts vary widely across spatial and temporal scales, unique regional challenges
- The longest compound energy droughts can last from 16 to 37 continuous hours while the longest daily droughts can last up to 6 days
- Compound wind and solar droughts + high load are less frequent but more severe on average
- Availability of Datasets
  - Historical Wind and Solar – 1980-2022 – coincident, based on 1/8th degree TGW data – 2020 infrastructure
    - https://zenodo.org/record/7901615
  - Energy Drought Data – 1980-2019 – 15 CONUS BAs – 2020 infrastructure
    - https://zenodo.org/record/8008034
- Preprint
  - Bracken et al. 2023, submitted, https://eartharxiv.org/repository/view/5575/

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Short Q&A

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WECC's 10- and 20-Year Extreme Heat and Extreme Cold Working Groups

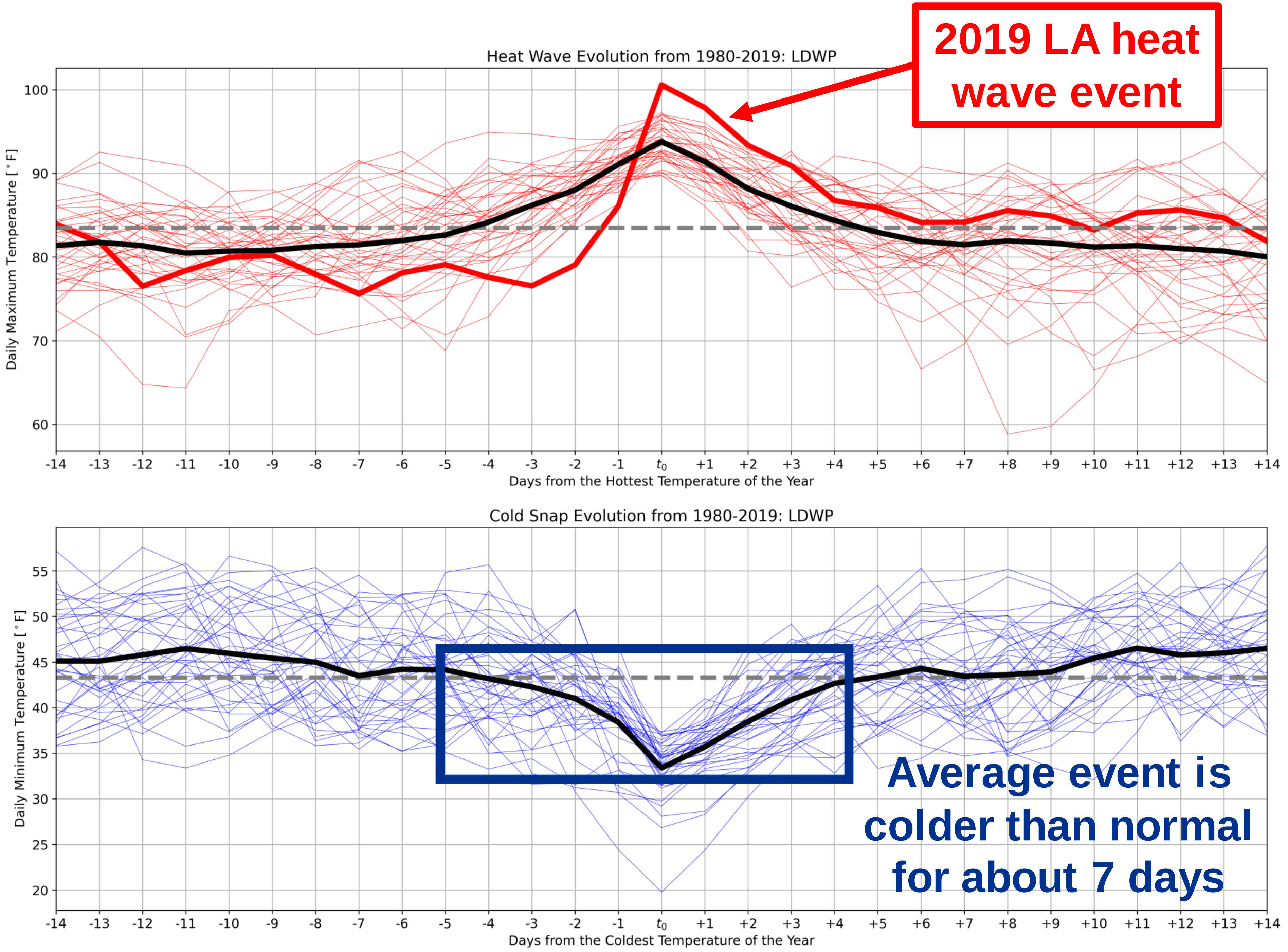
Purpose: Assess the reliability of the projected western U.S. electric grid on 10- and 20-year time horizons under extreme cold and extreme heat conditions.

GODEEEP's Contributions:

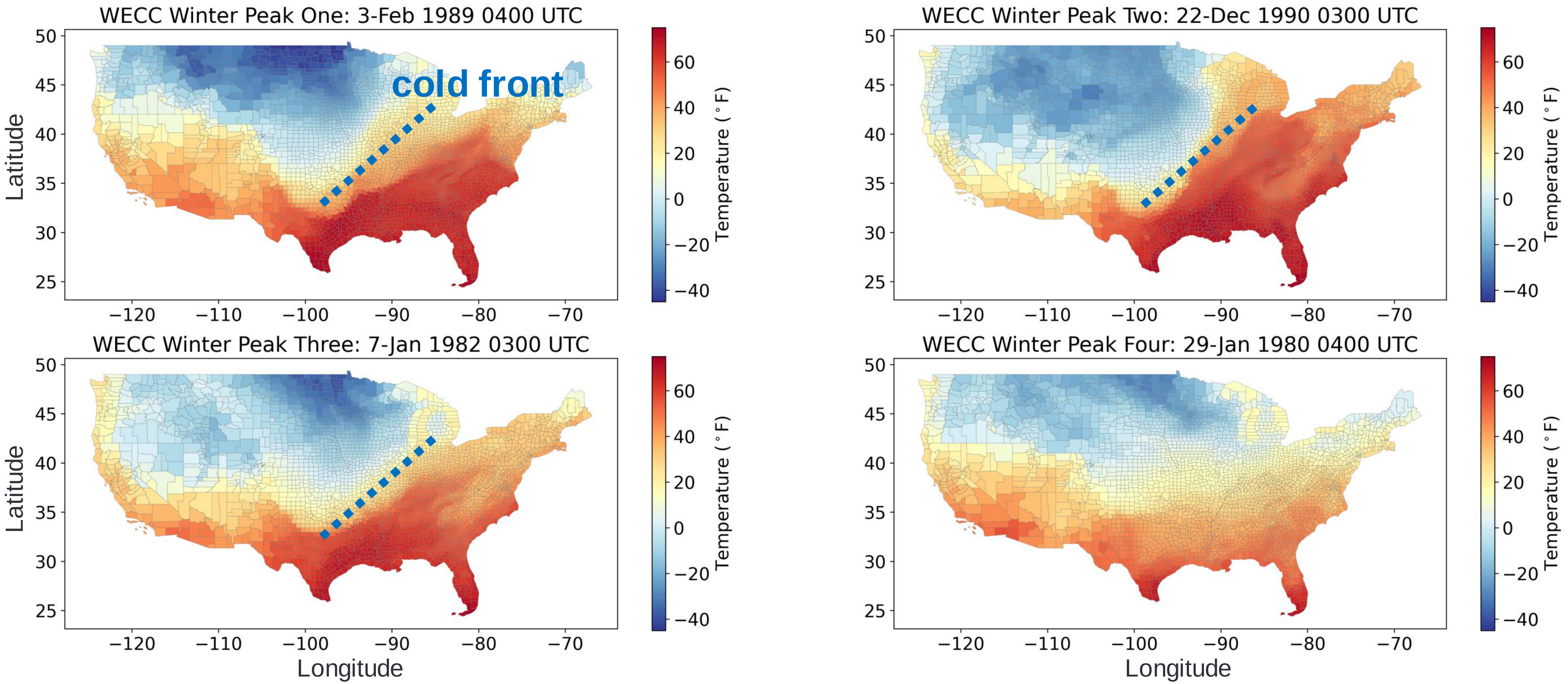
- What is a typical duration for heat waves and cold snaps impacting the WECC? Does the duration vary across BAs?
- Where do heat waves and cold snaps typically occur in the WECC? How does their location impact the resulting loads?
- How does renewable energy potential change during a typical heat wave or cold snap?

Heat Wave and Cold Snap Duration

- Analyzed the hottest and coldest day of each year (1980-2019) in each BA in the WECC
- Typical heat waves and cold snaps last ~6-7 days and are, on average, symmetric about the maximum/minimum temperature day
- We used these event dates and meteorology time series to select extreme hot/cold events to study

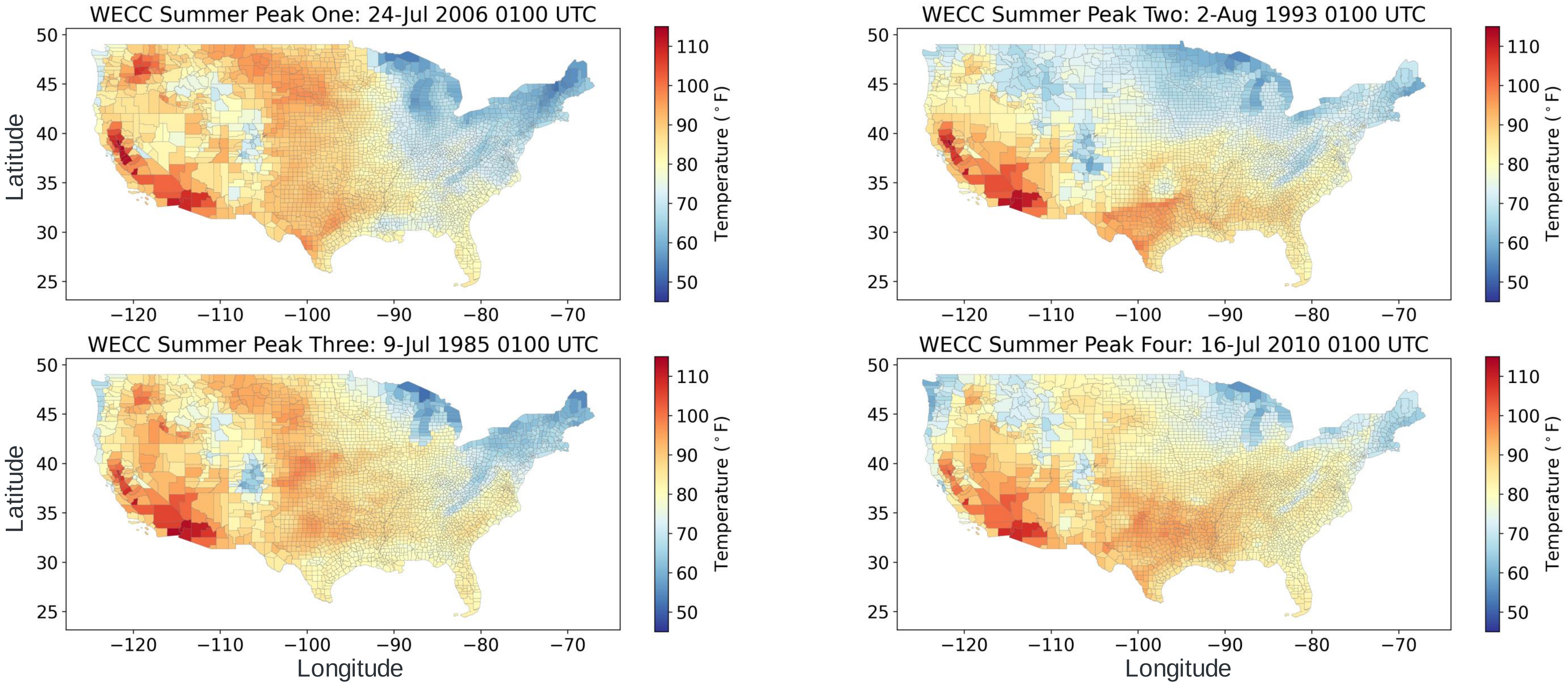


Four Highest Historical Winter Loads



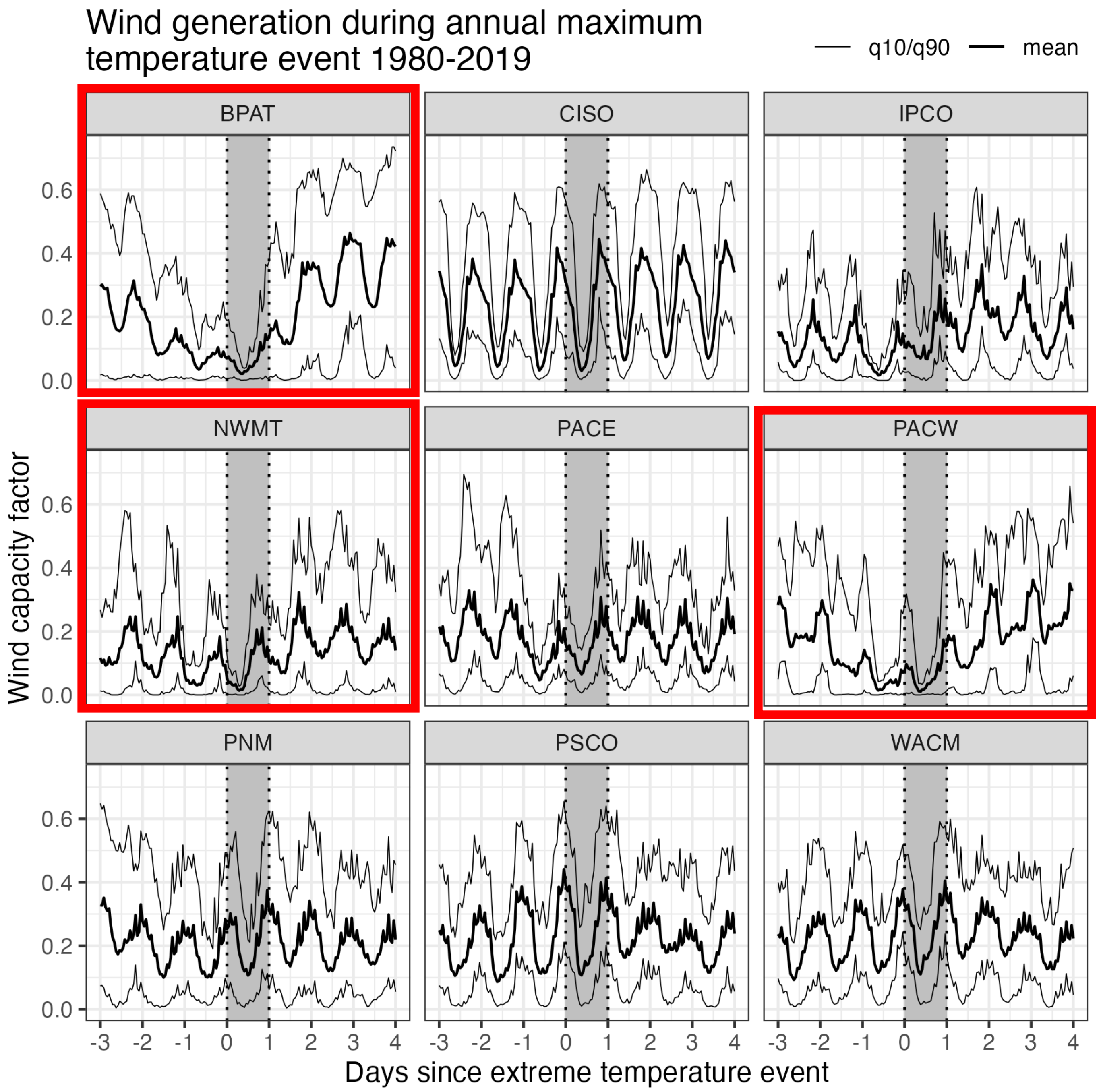
- Cold snaps tend to be focused on the PNW and extend eastward into the Dakotas
- Temperatures during extreme cold snaps tend to be moderate in the SW and California

Four Highest Historical Summer Loads



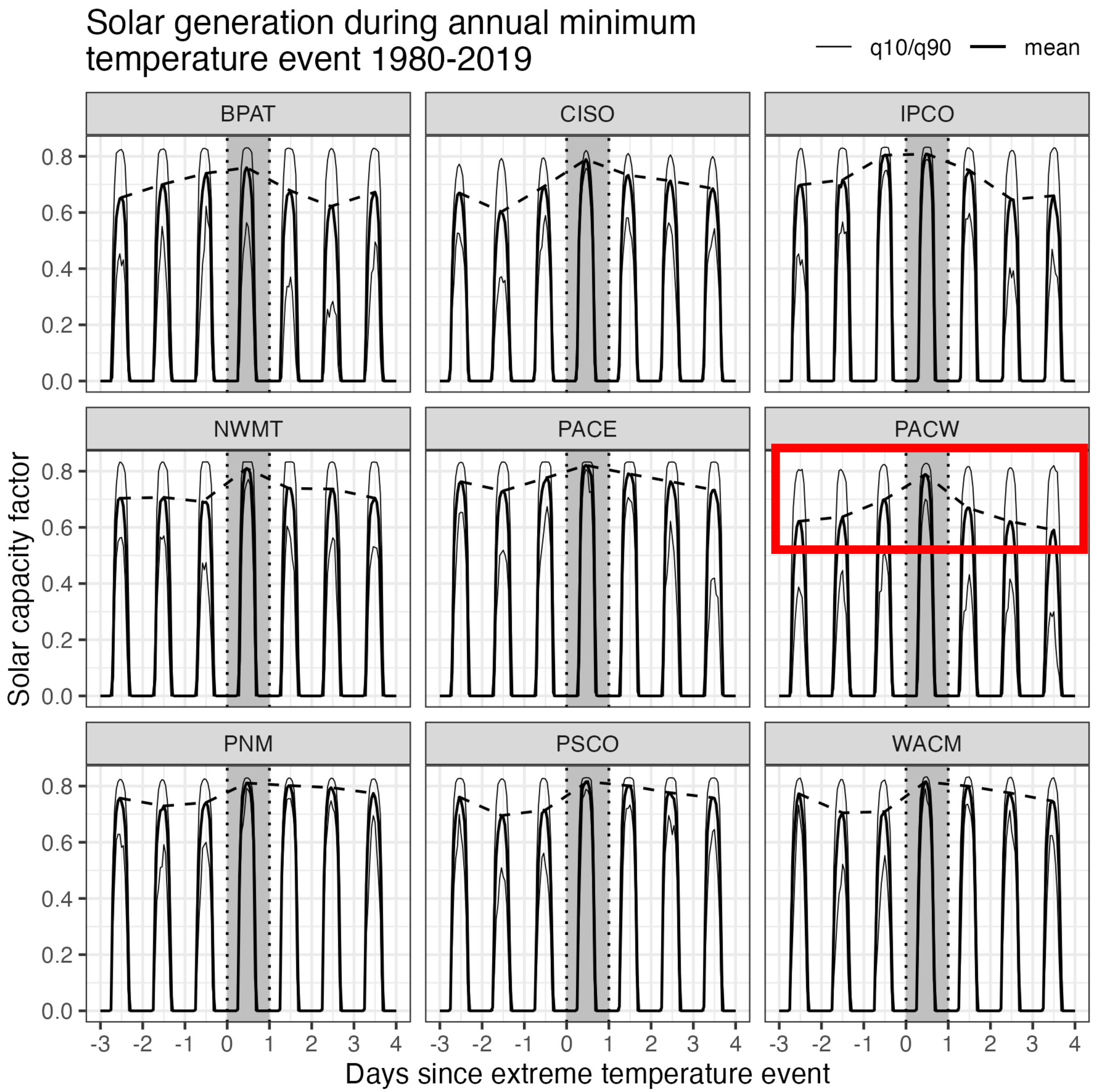
- Heat waves are spatially broader
- Hottest in the SW, but extreme heat expands from the PNW through the midwest and Texas

Potential Wind Generation During Heat Waves



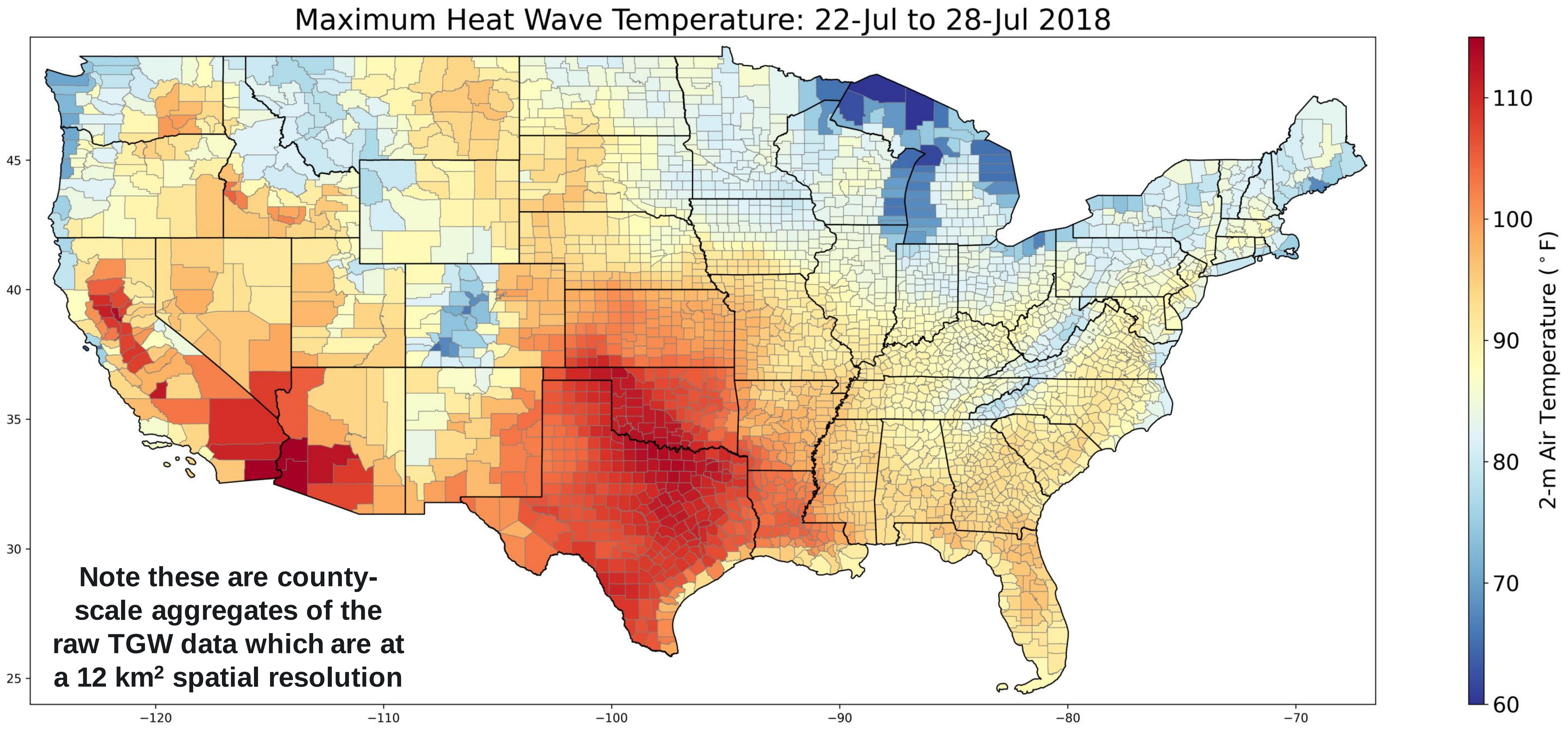
- BAs in the PNW show notable suppression of wind during heat wave events (e.g., BPAT, PACW, and NWMT)
- Normal wind response from other WECC BAs during heat waves

Potential Solar Generation During Cold Snaps



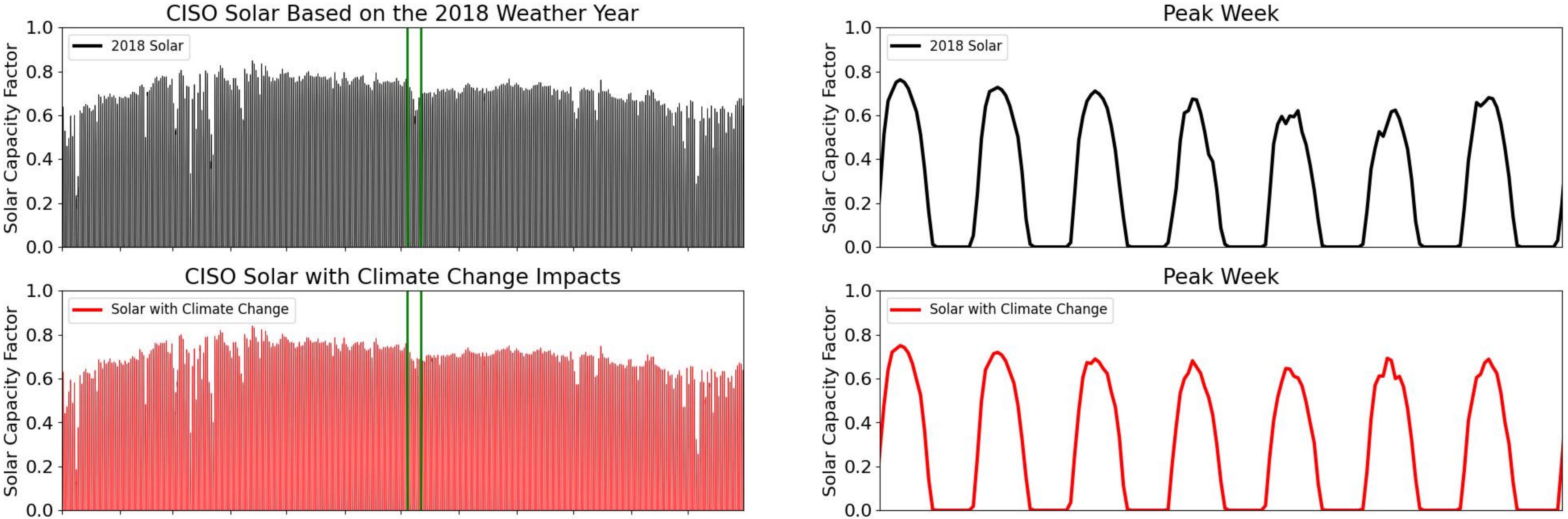
- Solar generation tends be lower before and after cold snaps
- High solar production on the coldest days
- High overall production due to less panel derating

Selecting a Heat Wave Case Study



Note these are county-scale aggregates of the raw TGW data which are at a 12 km^2 spatial resolution

Capturing the Impact of Extreme Heat and Cold



- Can look at the historical heat wave event through the context of our 40-year historical load, wind, and solar dataset.
- Can also explore how the same event may look in the future under climate change.

Designing Stress Cases for the National Transmission Planning Project

Purpose: Explore how increased transmission can potentially alleviate grid stress during extreme events such as heat waves.

GODEEEP's Contributions:

- Create hourly time series of load, wind, and solar based on the 2015 and 2018 weather years that can be used as input to the GridView production cost model.
- Loads and wind and solar generation are scaled to match the baseline NTP system projection for 2035.

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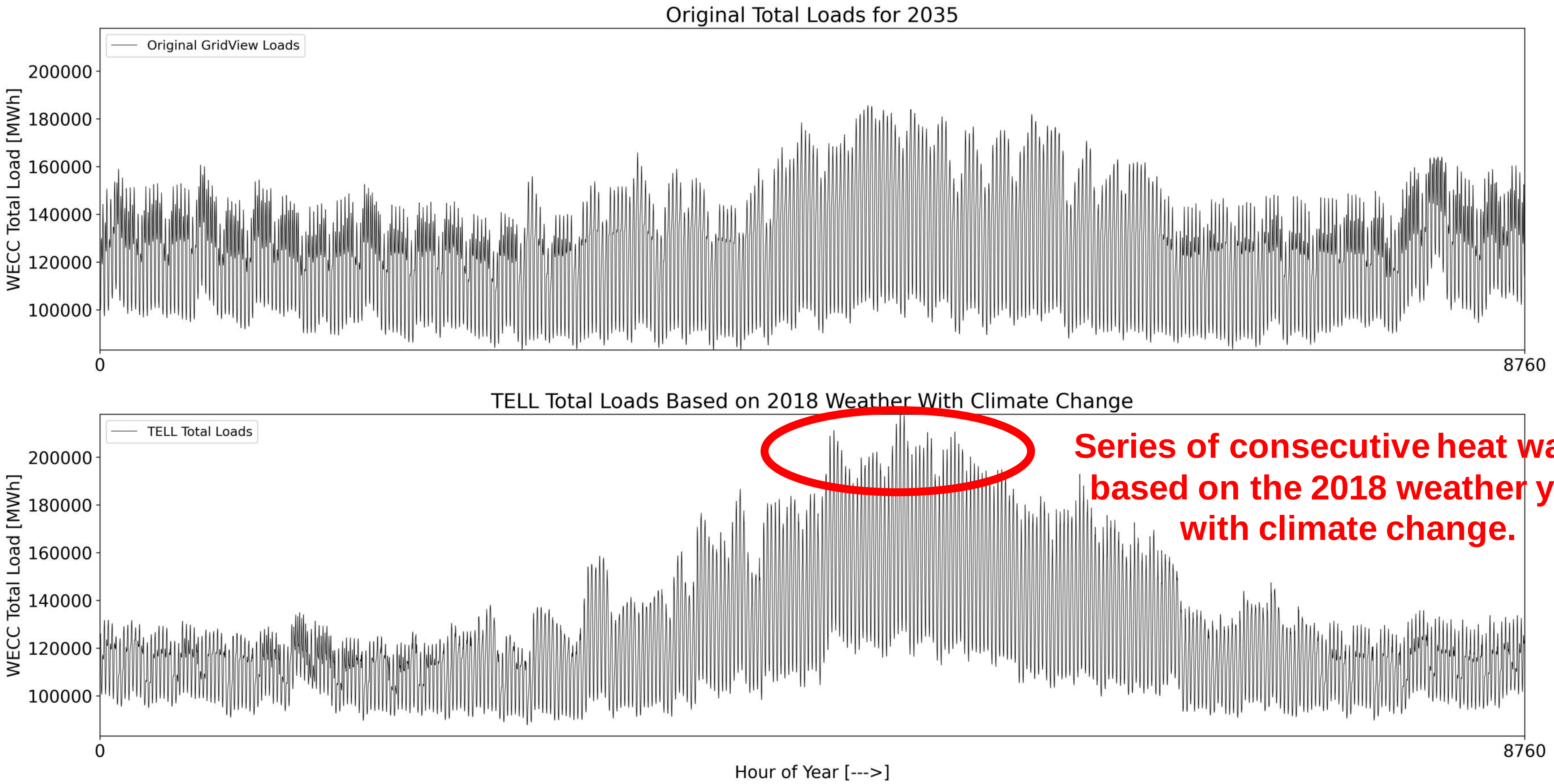
Designing Stress Cases for the National Transmission Planning Project



Series of consecutive heat waves based on the 2018 weather year with climate change.

Next Steps: Energy Droughts and Decarbonization

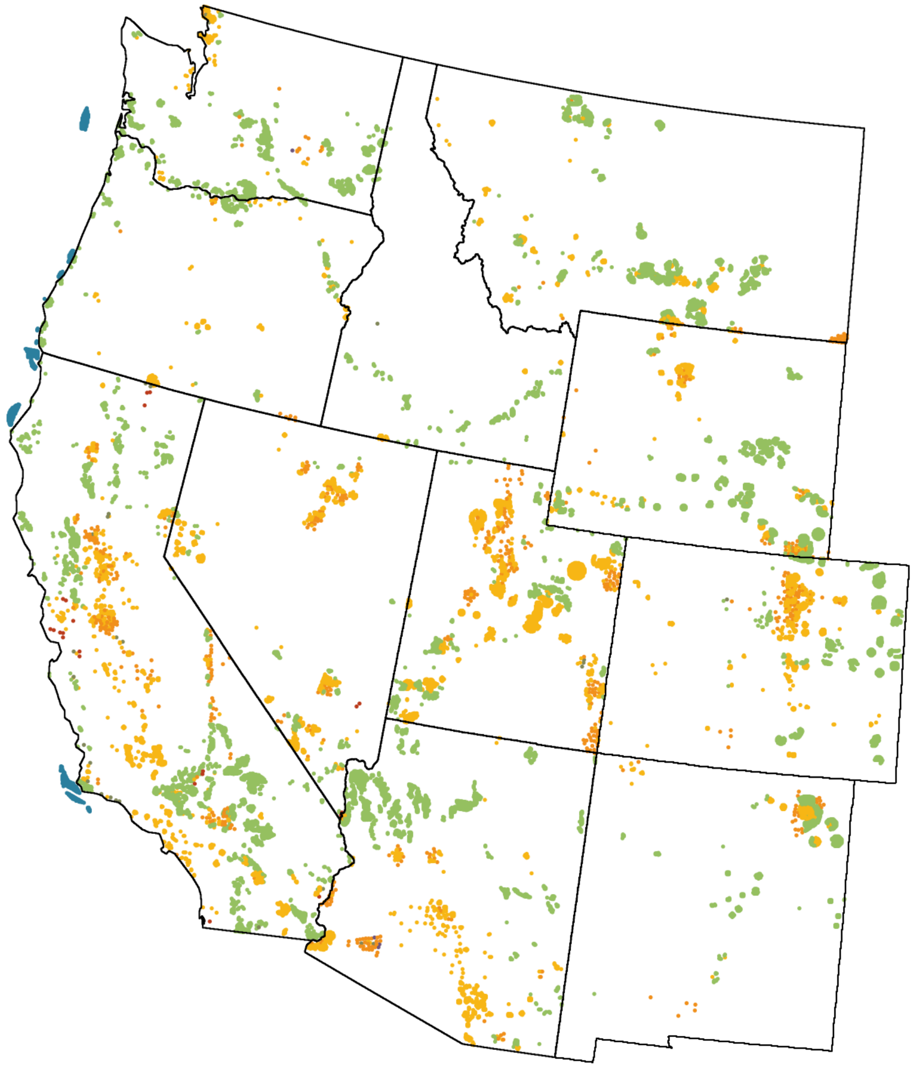
Multi-Scenario Climate Projections
TGW Simulations

Decarbonization Scenarios
Net-Zero, Business as Usual

Future Plant Sitings
CERF + GridView

Future Energy Droughts, Extremes
Grid Impacts and Storage Needs 2025-2050

Net-Zero no CCS



2035 projected wind (green) and solar (orange) power plant sitings

Data and code are all publicly available

Key Datasets

- **Climate Forcing**
  - Jones, A. D., Rastogi, D., Vahmani, P., Stansfield, A., Reed, K., Thurber, T., Ullrich, P., & Rice, J. S. (2022). IM3/HyperFACETS Thermodynamic Global Warming (TGW) Simulation Datasets (v1.0.0) [Data set]. MSD-LIVE Data Repository. https://doi.org/10.57931/1885756
- **Wind and Solar Generation**
  - Bracken, Cameron, Underwood, Scott, Campbell, Allison, Thurber, Travis B, & Voisin, Nathalie. (2023). Hourly wind and solar generation profiles for every EIA 2020 plant in the CONUS (v1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7901615
  - Campbell, Allison, Bracken, Cameron, Underwood, Scott, Thurber, Travis B, & Voisin, Nathalie. (2023). Balancing Authority Hourly Generation Of Installed Plant Capacities in CONUS (v1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7991871
- **Total Electricity Load Profiles by Balancing Authority**
  - Burleyson, Casey, Thurber, Travis, Acharya, Samrat, & Ghosal, Malini. (2023). Total Load Profiles by Balancing Authority in the Western United States for GODEEEP (v1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8067472
- **Energy Droughts**
  - Bracken, Cameron, Voisin, Nathalie, Burleyson, Casey D, Campbell, Allison M, Hou, Z Jason, & Broman, Daniel. (2023). Solar and Wind Energy Drought Data for 15 BAs in the CONUS (v1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8008034

Code: https://github.com/GODEEEP

Takeaways

- Wind and solar power datasets, with consistent with existing infrastructure
  - Evaluation against BA-reported power
- Standardized definition of compound energy drought and benchmark across the U.S.
- Datasets of coincident wind, solar and load are flexible and are actively being used for other studies:
  - NTP – Grid stress tests
  - WECC – Extreme event characterization
  - NAERM – Reliability studies
- Next steps:
  - Evolving infrastructure and climate
  - Seasonal drought (hydro)
  - Storage technologies, market development

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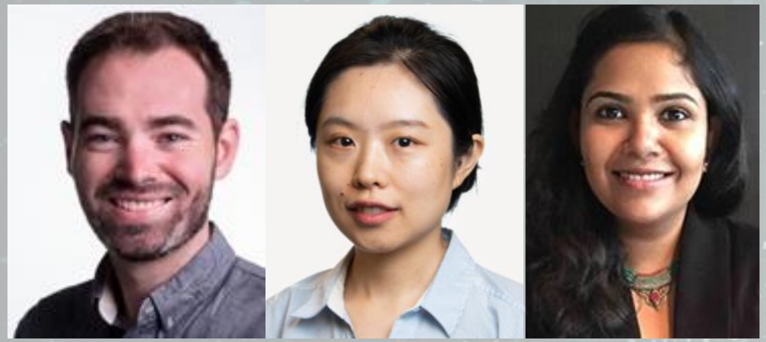
UPCOMING WEBINAR



DEEP DIVE FOUR

Decarbonization Impacts on Disadvantaged Communities

Presented by Stefan Rose, Ying Zhang, and Sumitrra Ganguli

Monday, August 7, 10 a.m. PT

Aug 7

PNNL

REGISTER FOR WEBINARS: https://www.pnnl.gov/events/godeeep-webinar-series

Q&A

On behalf of the whole **GODEEEP** team, thank you!

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Allison.M.Campbell@pnnl.gov
Casey.Burleyson@pnnl.gov

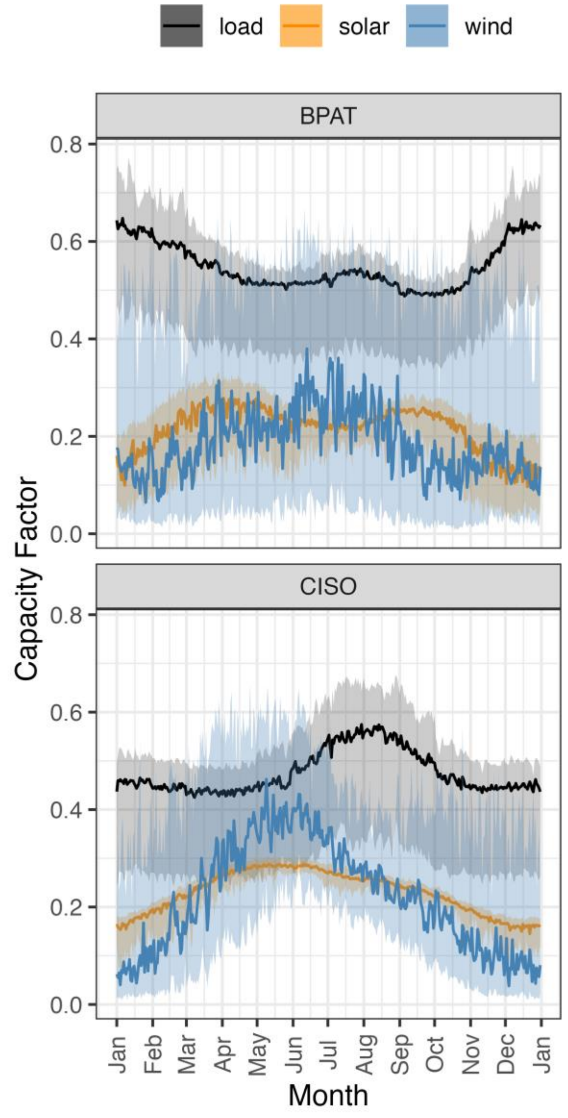
https://godeeep.pnl.gov/

Backup Slides

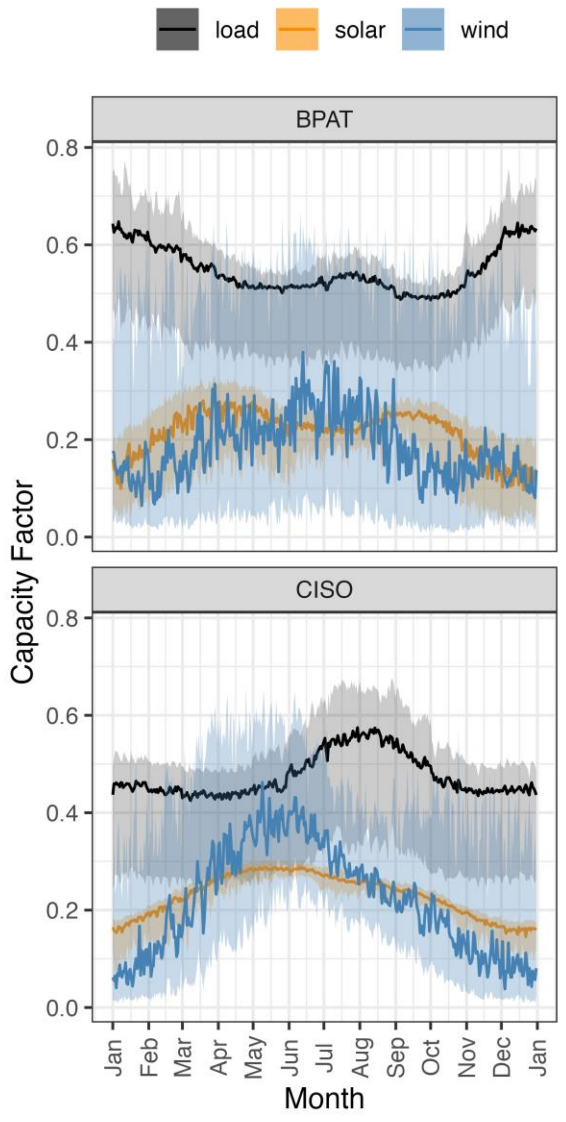
Thank you

Wind and Solar Droughts Frequency – seasonally

Some BA have seasonal signal in droughts even with a dynamic threshold

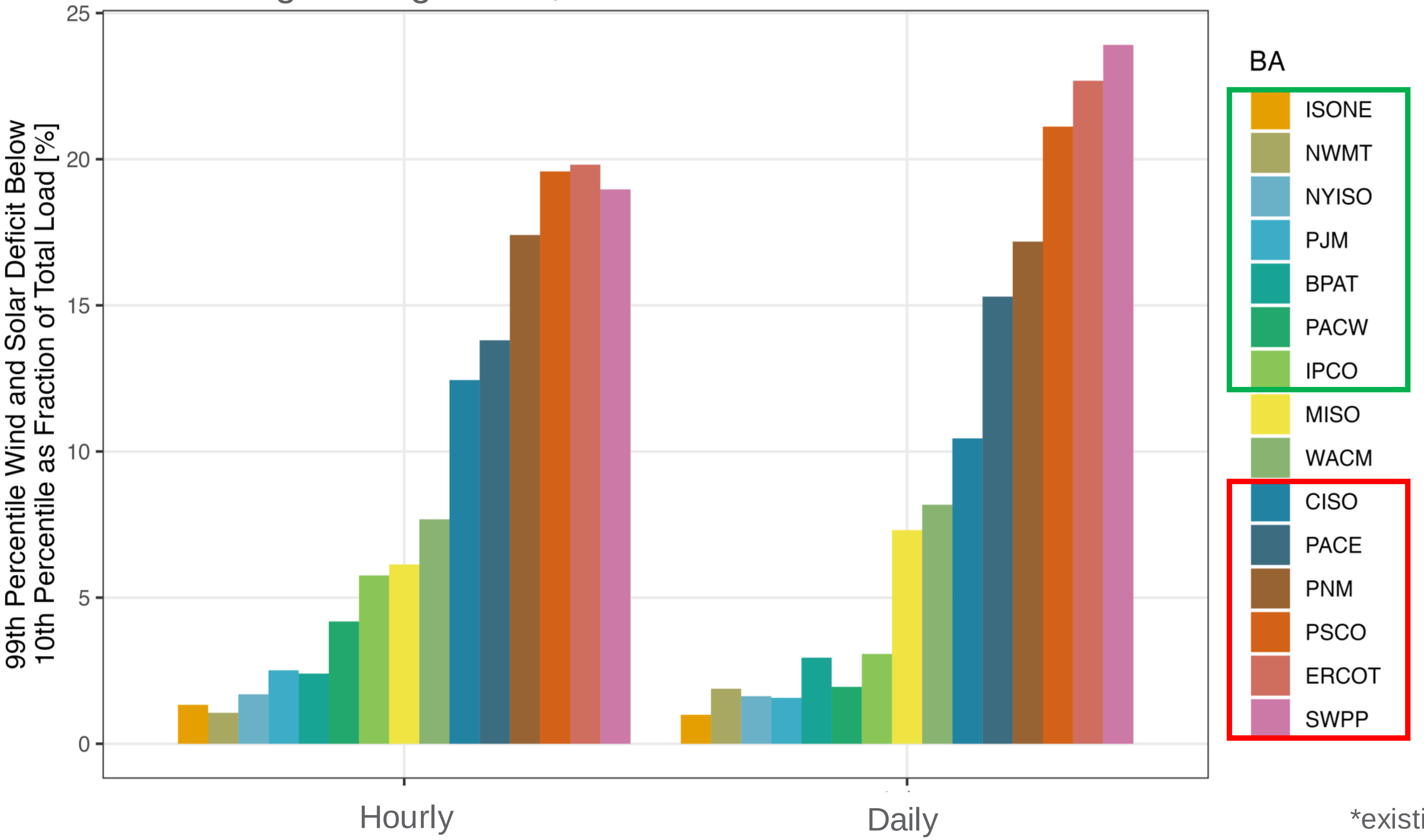


Wind and Solar Droughts + High Load Frequency – seasonally



Extreme energy droughts require improved storage capacity

1980-2019 99th Percentile Deficit of Compound Wind and Solar Drought + High Load, 2020 infrastructure



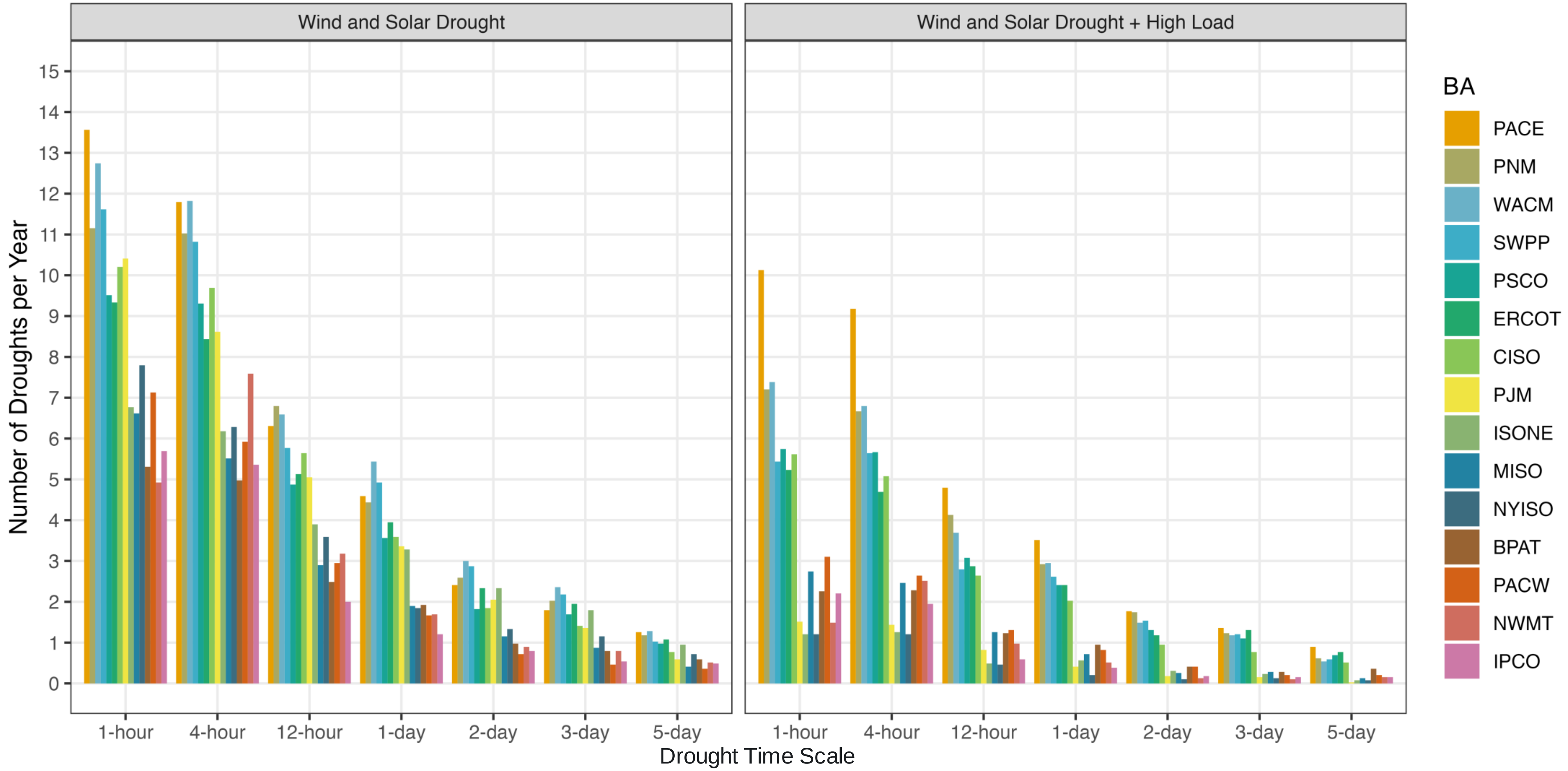
Low Risk:
Pacific Northwest, Northeast

High Risk:
California, Midwest, Southwest, Texas

*existing storage not taken into account

Wind and Solar Droughts are Not Independent from High Load Events

1980-2019



- If high load was independent from compound wind and solar droughts, we would expect a 90% reduction in drought frequency
- Actual reduction is 10-50%

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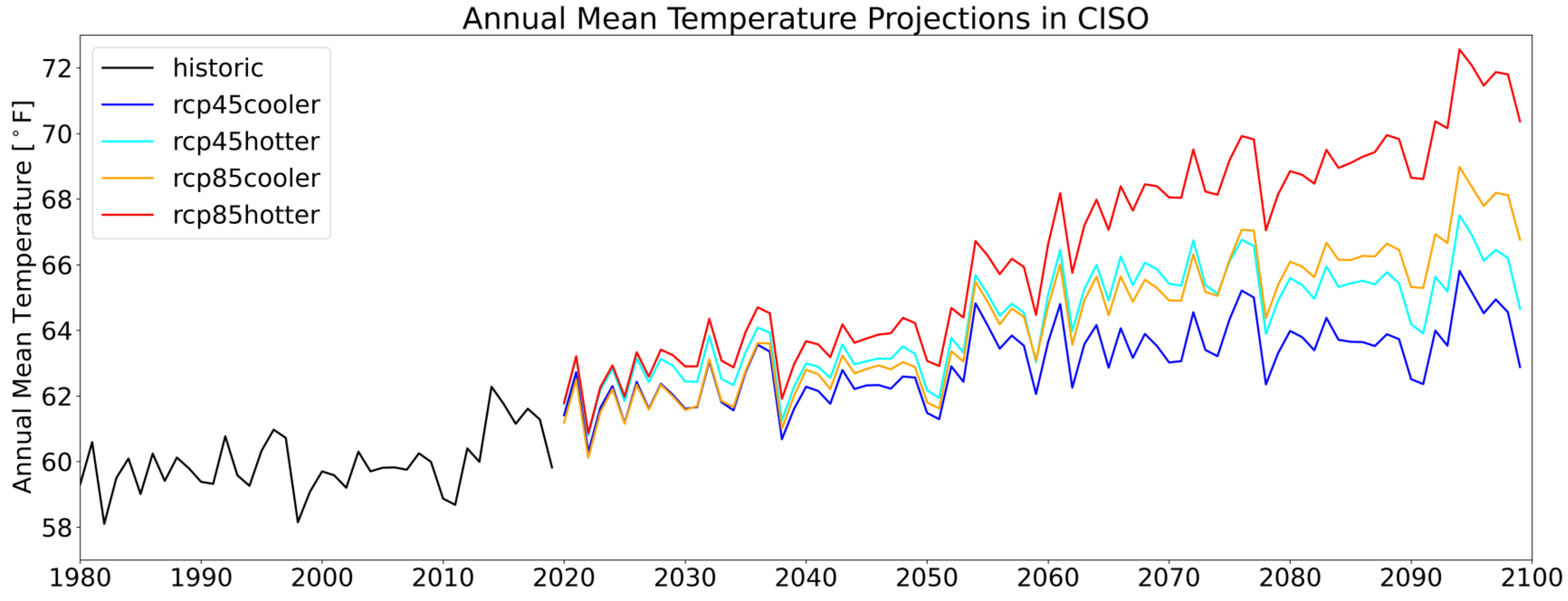
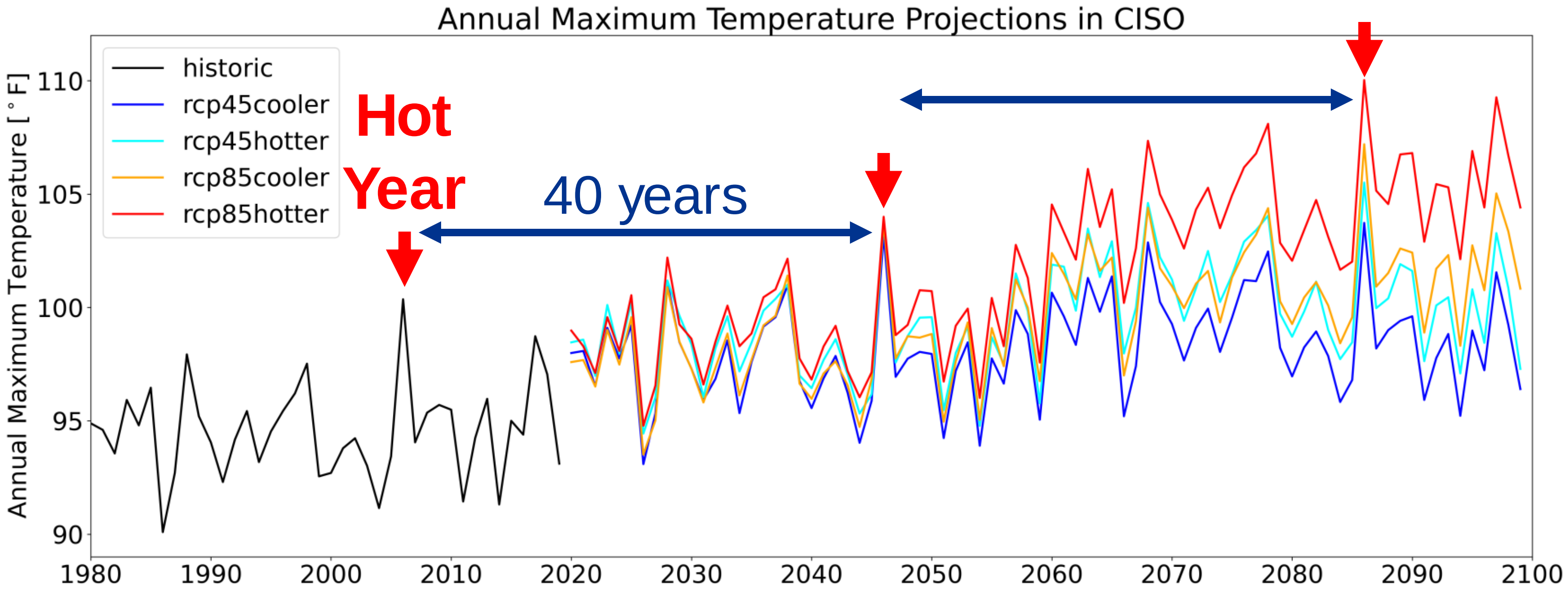
U.S. Climate Projection Dataset



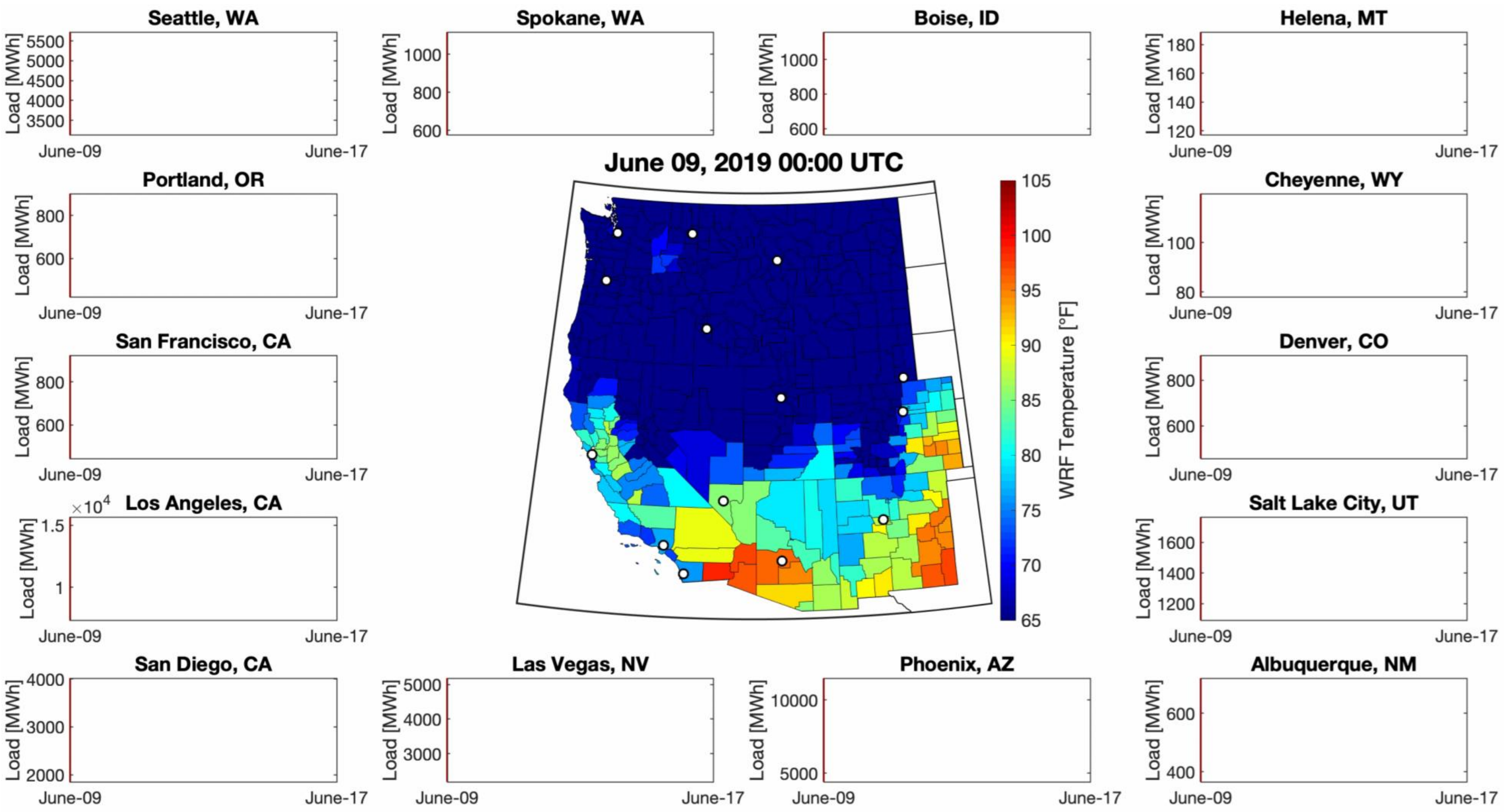


- Historic data reproduces observed sequence of past events (1980–2019)
- Sequence is repeated twice in the future (2020–2059 and 2060–2099) with additional warming gradually applied
- 1/8 deg (~12 km) resolution, U.S., hourly
- 25 hourly and 250+ three-hourly variables
- Output is first spatially-averaged by county then population-weighted to create annual 8,760-hr meteorology time series for 54 BAs across the U.S.

Climate data was developed with DOE Sc funding and is publicly available: https://data.msdlive.org/records/cnsy6-0y610

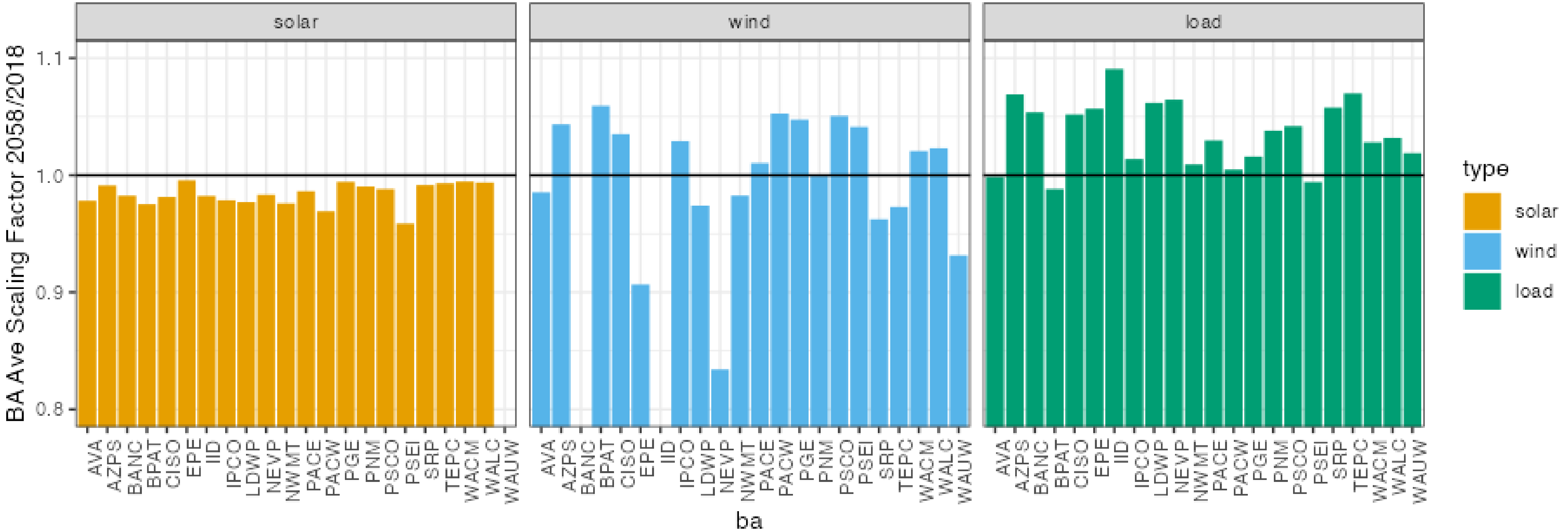
PNNL's Total ELectricity Loads (TELL) model

- Projects the evolution of hourly electricity demand in response to changes in weather and climate
- Based on a series of machine learning models trained on historical loads and meteorology
- Output is projections of **hourly electricity demand** at the county-, state-, and **BA-scale** that are conceptually and quantitatively consistent
- Released as an extensively documented open-source code base: https://github.com/IMMM-SFA/tell



McGrath, C., C. D. Burleyson, Z. Khan, A. Rahman, T. Thurber, C. R. Vernon, N. Voisin, and J. S. Rice, 2022: tell: a Python package to model future electricity loads. Journal of Open-Source Software, 7(79) 4472, https://doi.org/10.21105/joss.04472

Capturing the Impact of Extreme Heat and Cold



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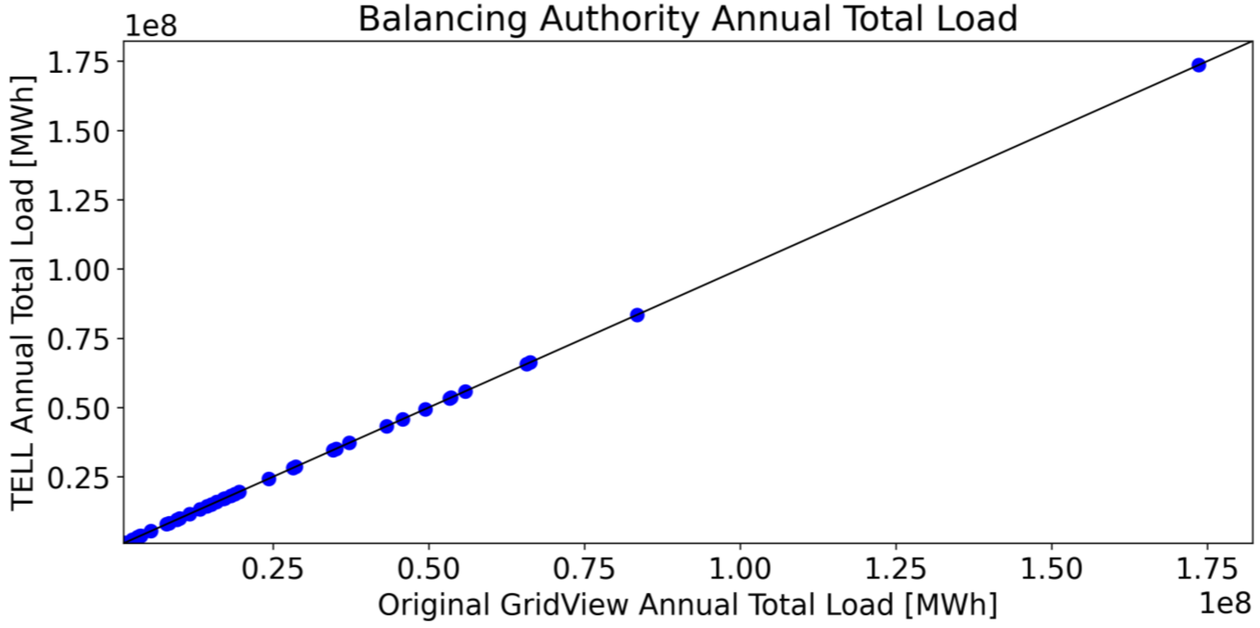
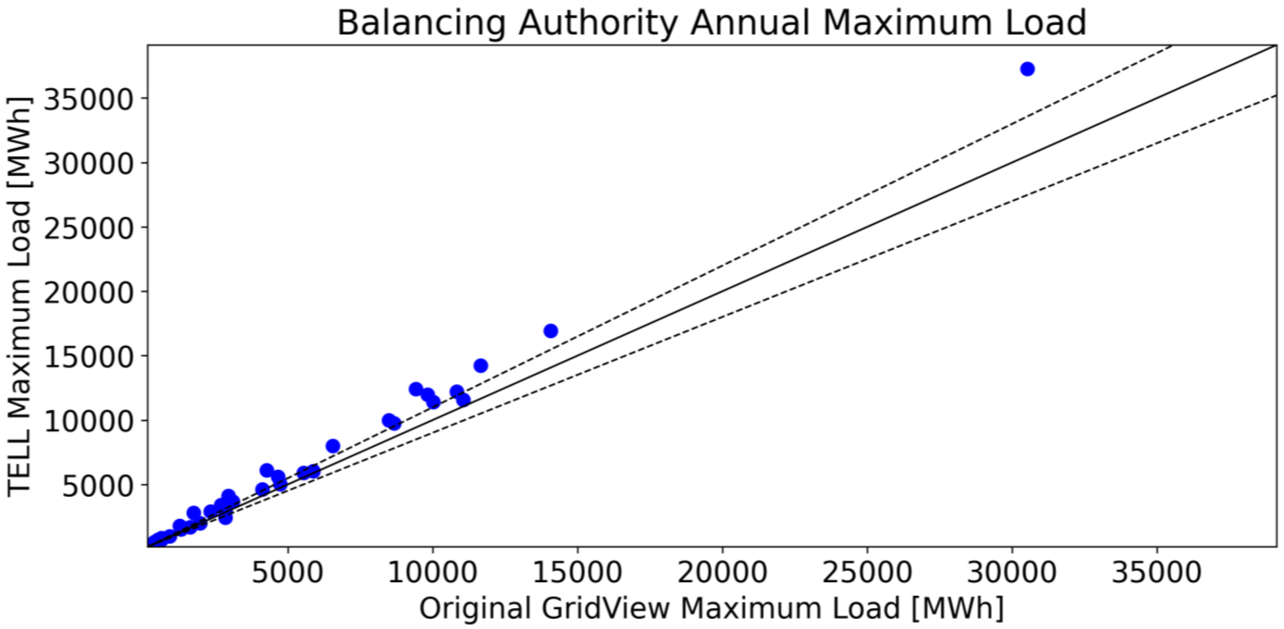
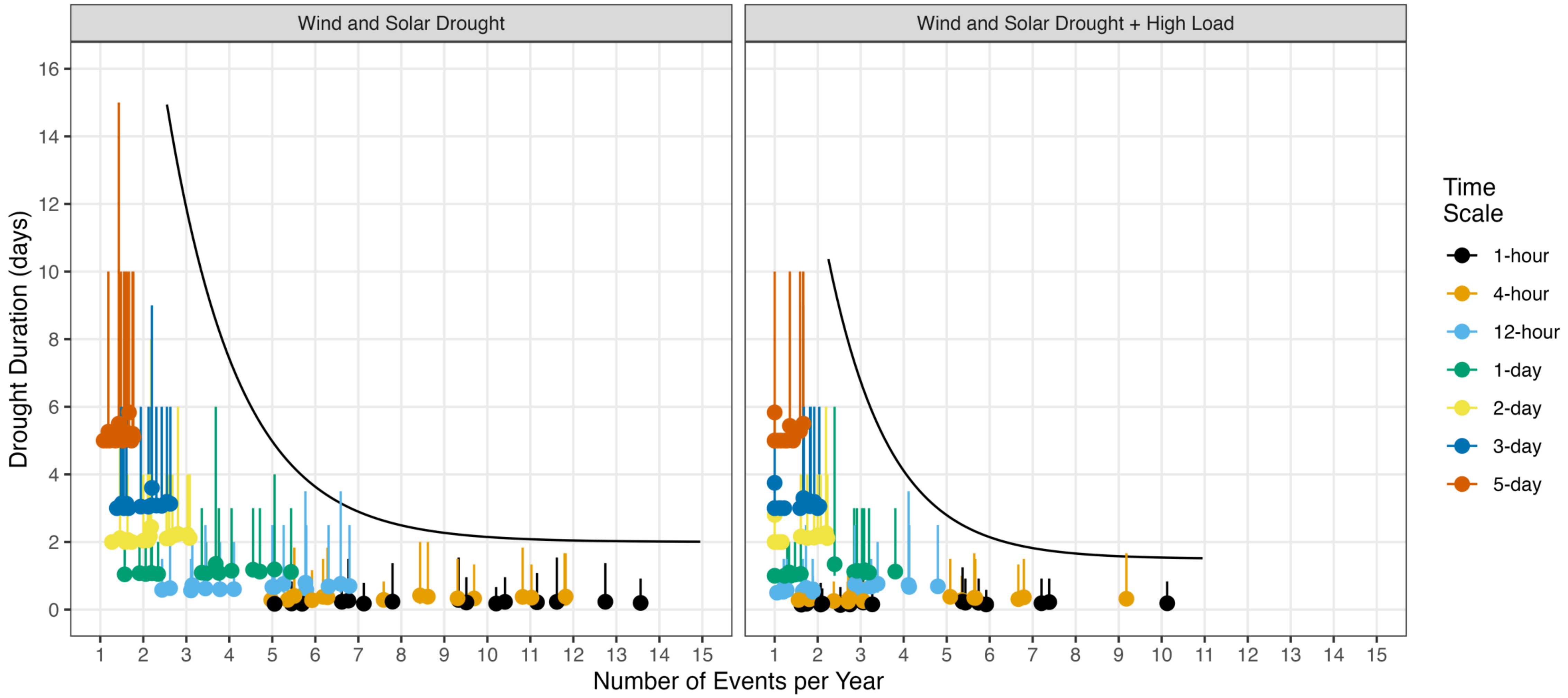
Designing Stress Cases for the National Transmission Planning Project





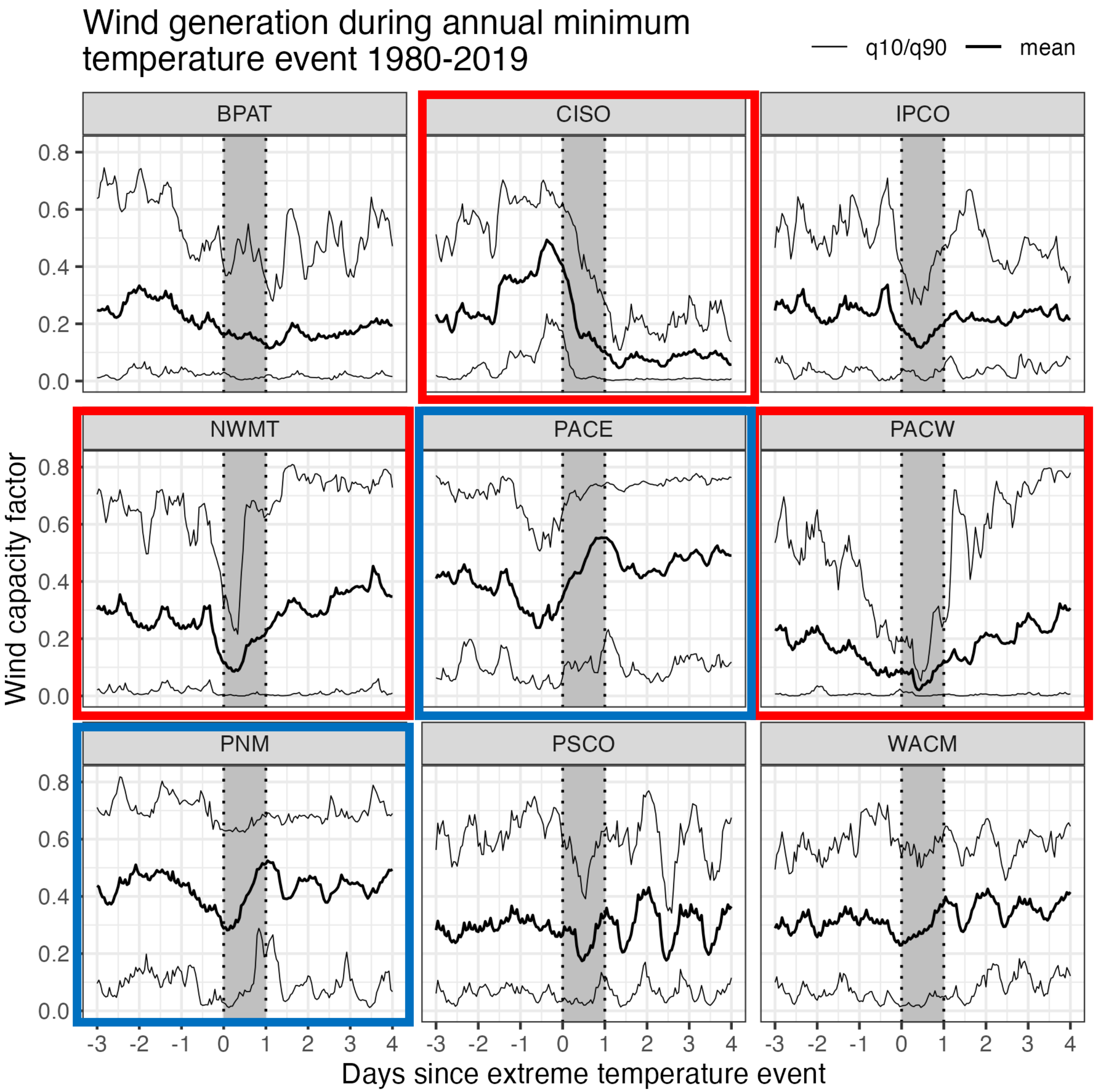
- Annual total loads are consistent with the original NTP 2035 base system projections
- Hourly loads and annual maximum and minimum loads are modified to reflect the temporal variation present in the 2015 and 2018 weather years.
- Annual maximum loads in some BAs increased by >20% making this a great case to test system reliability.

Drought frequency and duration



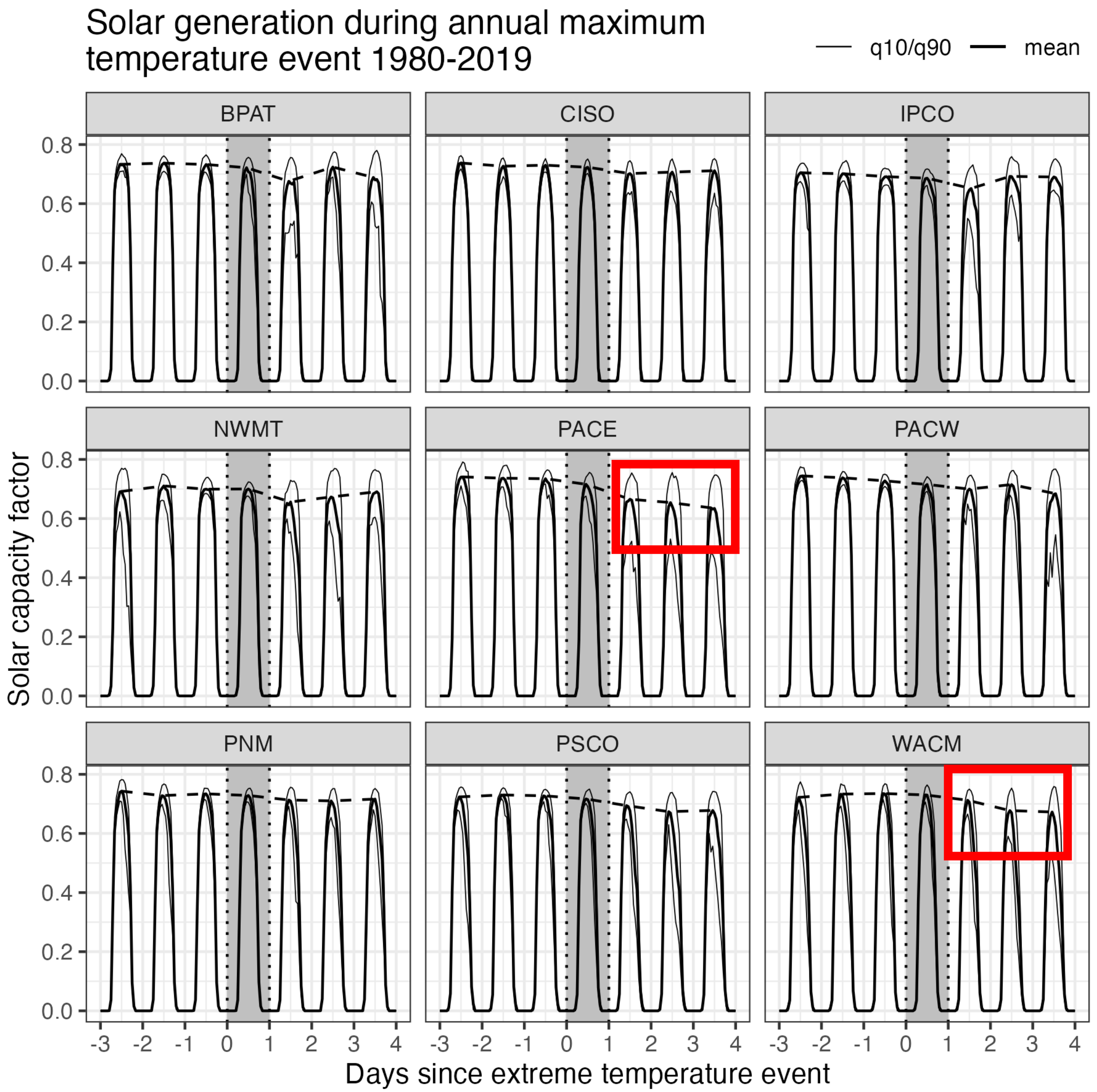
- Drought distributions are bounded
- Wind and Solar drought occur preferentially in periods of high load

Wind Generation During Cold Snaps



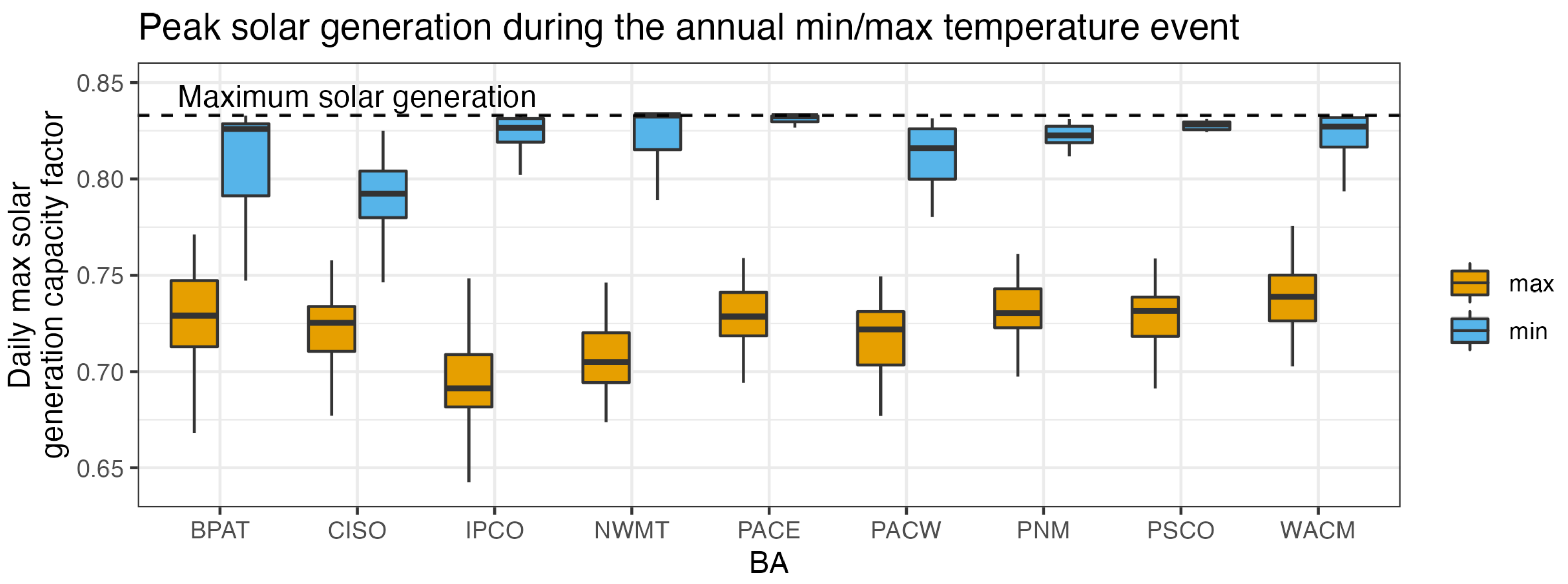
- BA scale wind response during cold events is highly regional
- Wind generation drops off notably in some BAs (e.g., CISO, PACW, NWMT) before and during cold snaps
- Wind generation increases notably in other BAs (e.g., PACE and PNM) on extreme cold days
- Other BA (e.g., BPAT and IPCO) have muted wind response during cold snaps

Solar Generation During Heat Waves



- Peak solar production is largely the same before, during, and after heat waves
- Slight tendency for lower peak production after heat waves in some BAs
- Lower overall production due to panel derating

Peak Solar Generation



- Peak generation during cold snaps is near panel maximum (minus losses) due to limited temperature derating and lack of clouds
- Peak generation during heat waves is reduced due to temperature derating and possibly other meteorological factors (i.e., clouds, haze, and smoke)