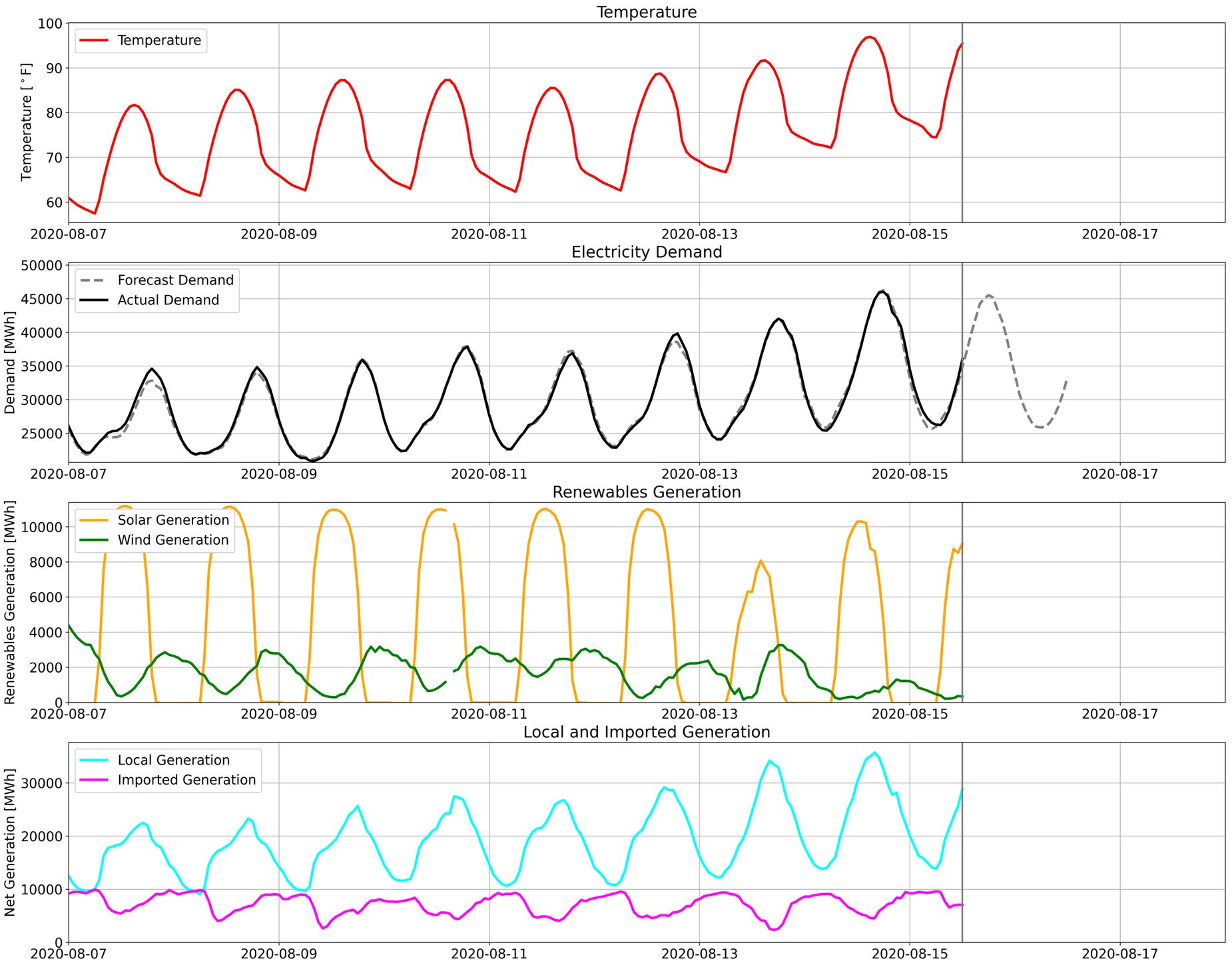
15-August 2020

12:26 pm Pacific

“At 12:26 p.m. the CAISO issued a Warning effective 12:00 p.m. through 11:59 p.m. confirming the Alert issued the day before because conditions had not improved, and the forecasted load was trending higher. The CAISO noted possible reserve deficiencies due to resource shortages between 5 p.m. and 9 p.m., requested additional ancillary services and energy bids, and requested voluntary conservation."

*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

12:26 pm Pacific

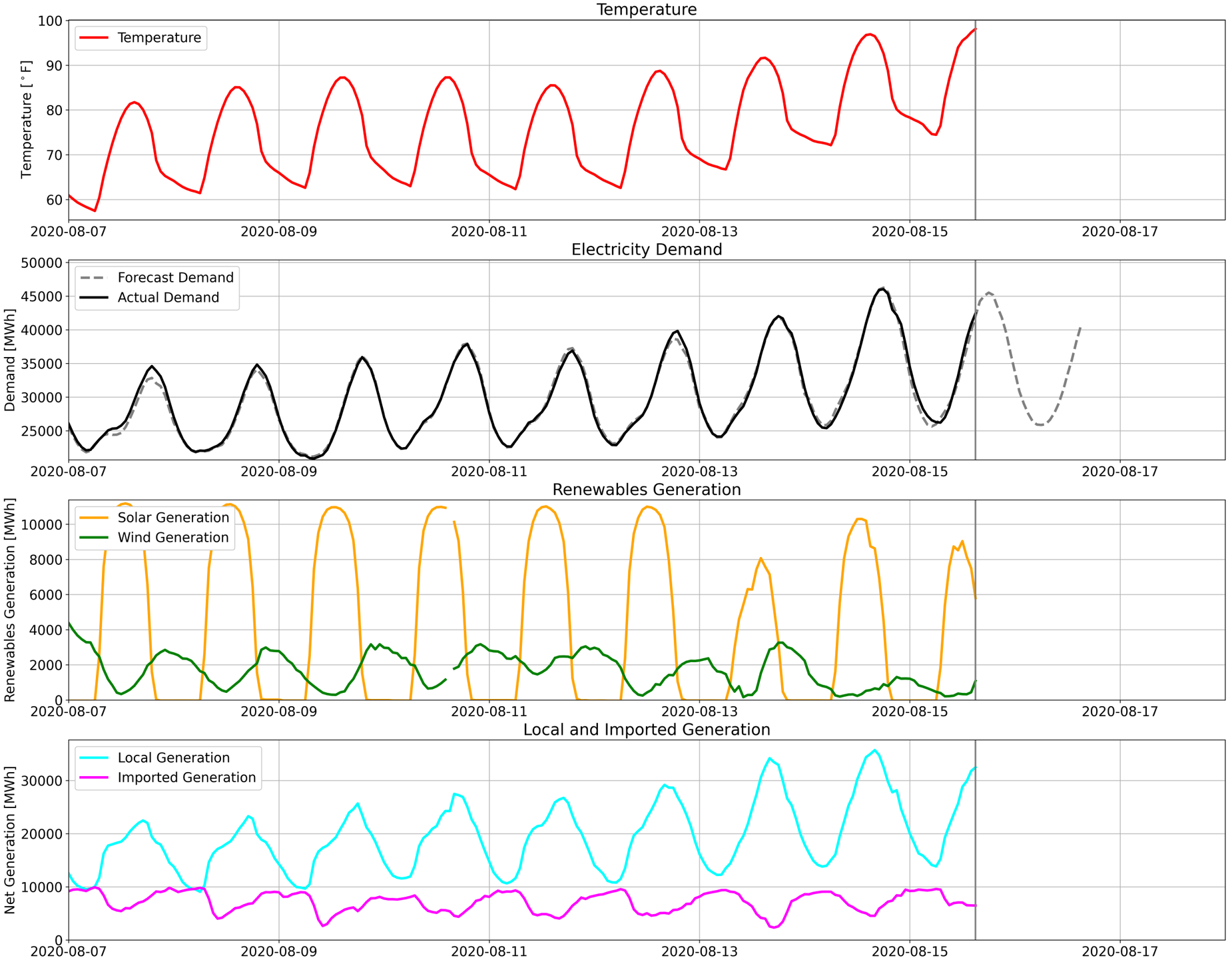


3:00 pm Pacific

“Between 3 p.m. and 5 p.m. CAISO operators continuously canvassed for additional unloaded capacity and for potential emergency assistance from other BAs. CAISO operators requested neighboring BAs to increase the available transmission capacity to allow increased import capability into the CAISO BAA. As a result, the California Oregon Intertie capacity was increased from 3 p.m. to 10 p.m."

*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

3:00 pm Pacific



6:13 pm Pacific

“At 6:13 p.m. a generator unexpectedly ramped down generation from about 394 MW to about 146 MW, resulting in a loss of about 248 MW. This was not an outage, but a ramp down from the CAISO dispatch, which the CAISO now understands to be due to an erroneous dispatch from the scheduling coordinator to the plant."

*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

6:16 pm Pacific

“At 6:16 p.m., the CAISO declared a Stage 2 Emergency because like the day before, consistent with WECC standards, the CAISO was having difficulty maintaining the 6% WECC reserve requirement with generating resources and began to rely on meeting part of its requirement with firm load available to be shed within 10 minutes, counting it as non-spinning contingency reserves."

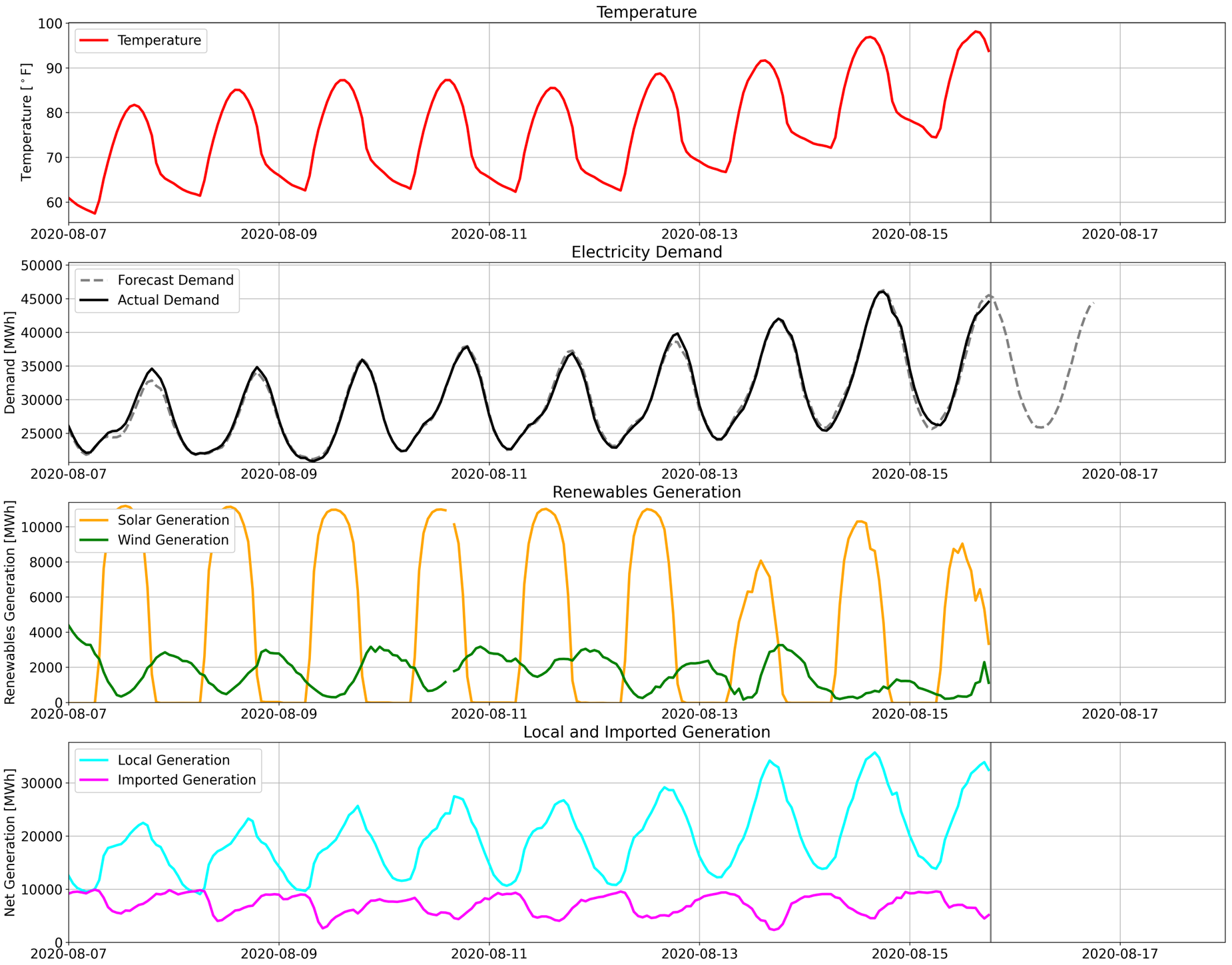
*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

6:28 pm Pacific

“At 6:28 p.m., the CAISO declared a Stage 3 Emergency because it was deficient in meeting its reserves requirement. The CAISO was not able to cure the deficiency with generation because all generation was already online, and solar was rapidly declining while demand remained high…Consequently, the CAISO ordered the distribution utility operators to execute about 500 MW of controlled load shed on their respective distribution systems."

*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

6:28 pm Pacific

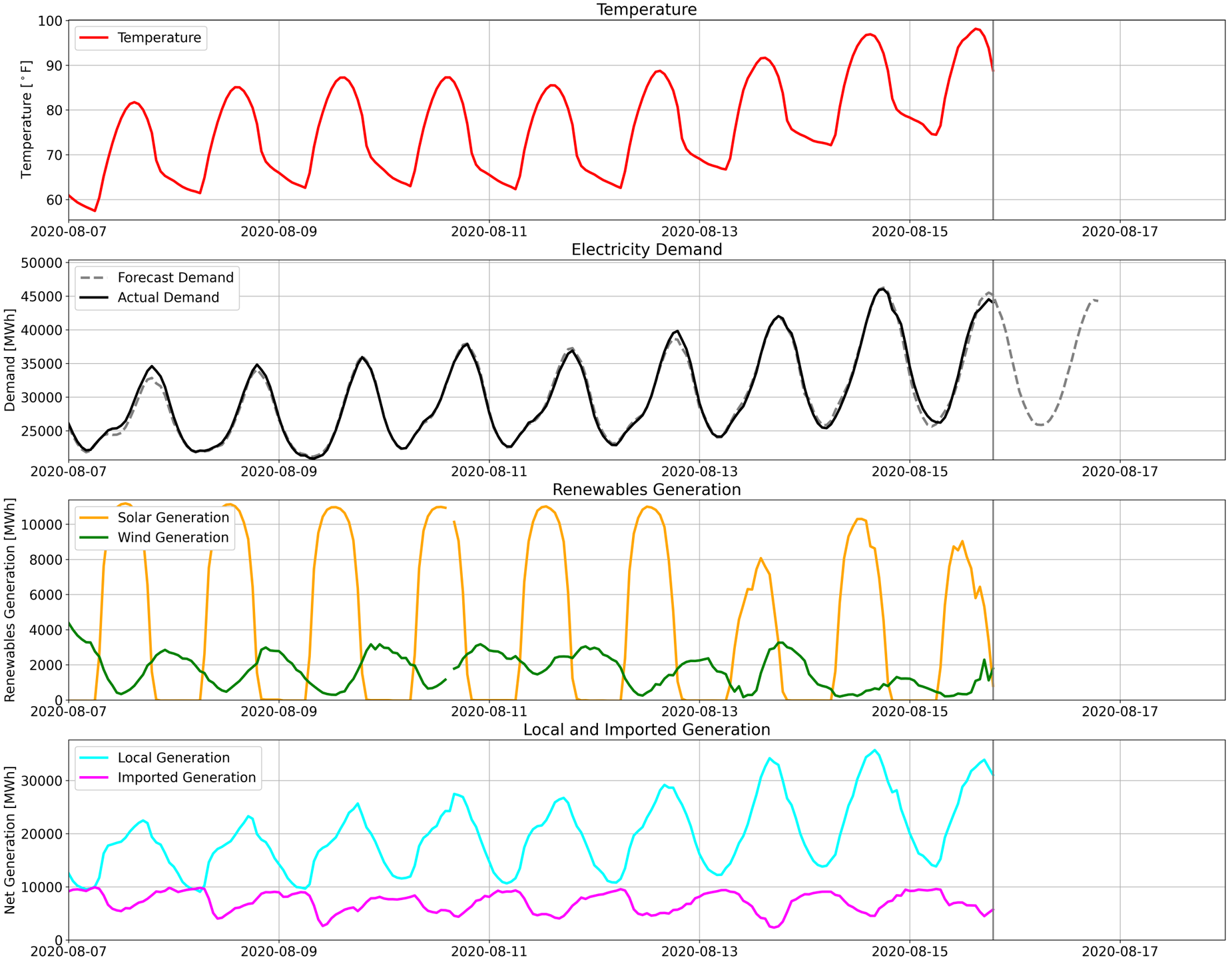


6:48 pm Pacific

“At 6:48 p.m., the Stage 3 Emergency was cancelled because wind production had increased more than 500 MW and the CAISO ordered all previously shed load to be restored. The duration of the controlled load shed was 20 minutes. The CAISO eventually downgraded to a Stage 2, and Stage 2 was cancelled at 8 p.m. The Warning expired at 11:59 pm."

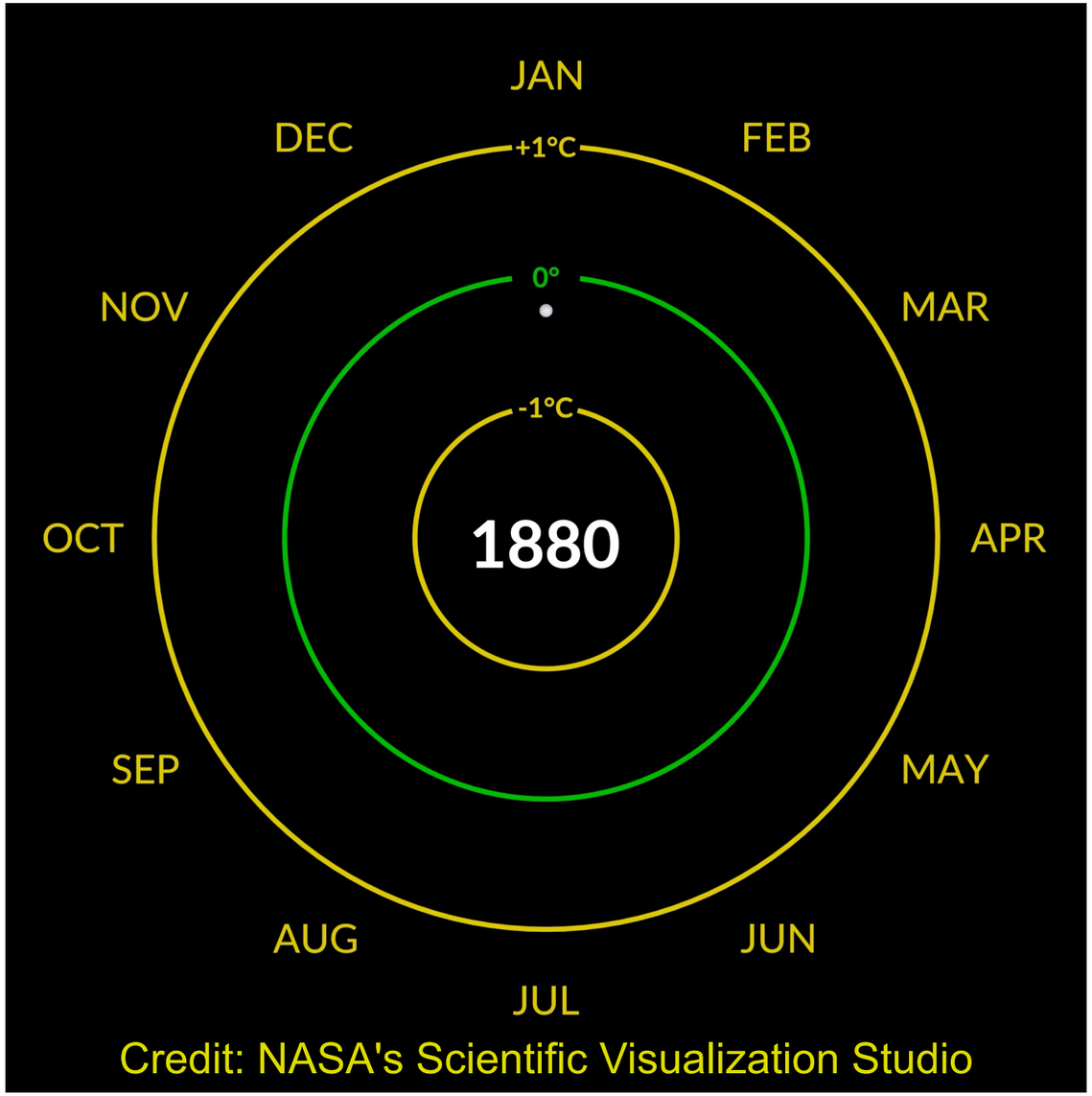
*CAISO Root Cause Analysis: Mid-August 2020 Extreme Heat Wave

6:48 pm Pacific



Assertions

1. The existing grid is weather sensitive.
2. Weather characteristics (e.g., extremes) are changing rapidly.
3. The grid is also changing rapidly.
4. A high renewables grid will be even more weather sensitive.



Credit: NASA's Scientific Visualization Studio

To Put It Another Way…

“There's a heatwave coming at us; Too hot to think straight; Too cold to panic; All of the problems just feel dramatic; And now we're runnin' to the first spot that we find.”
- Beyonce

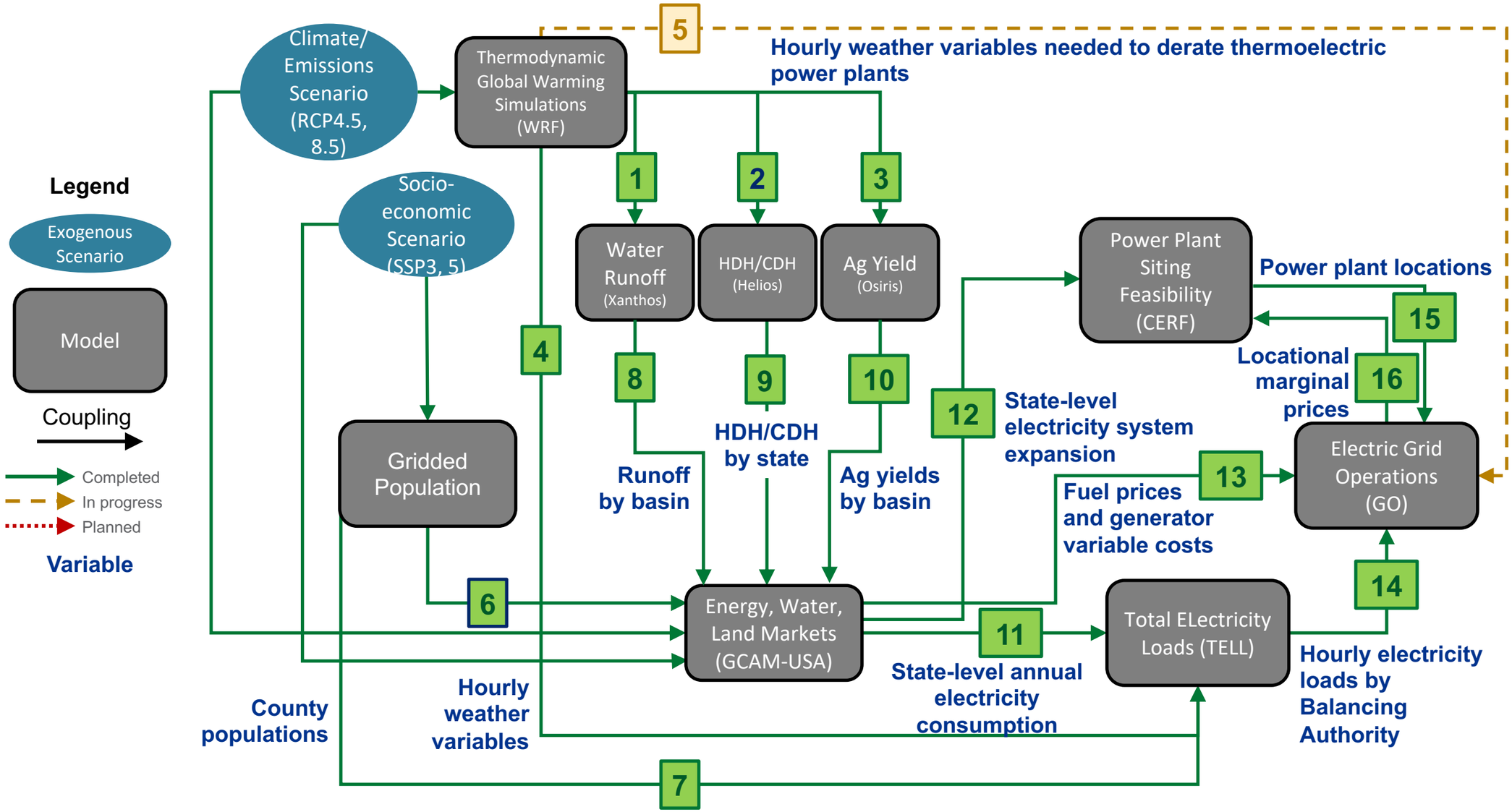
Chapter One

How do we study heat wave impacts on the electric grid?

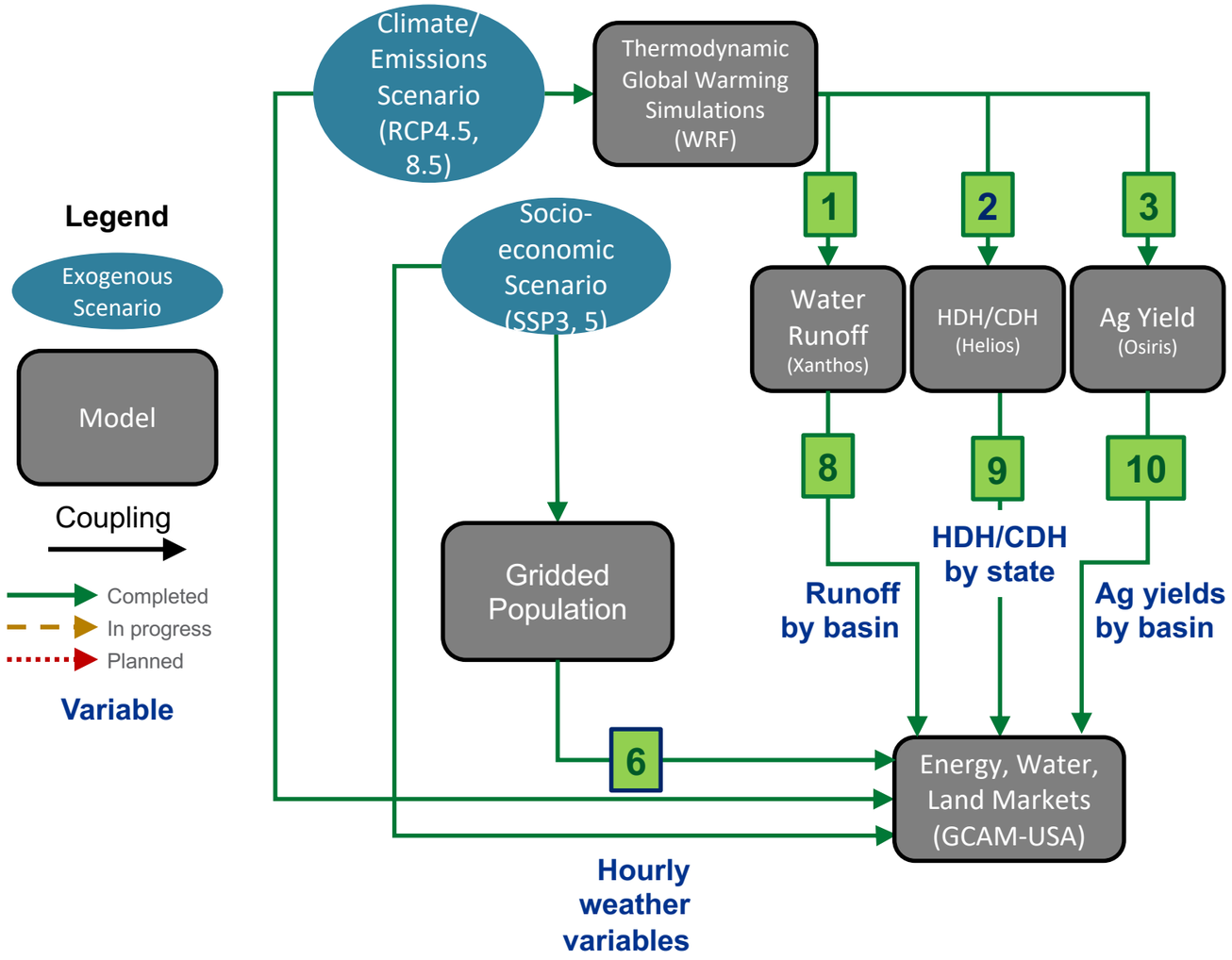
IM3 Experiment Group B Science Question

How will the compound influences of climate change, climate mitigation, heat waves, and socioeconomic change affect the evolution of electricity infrastructure and its ability to meet the projected electricity demands, potentially resulting in electricity grid stress?

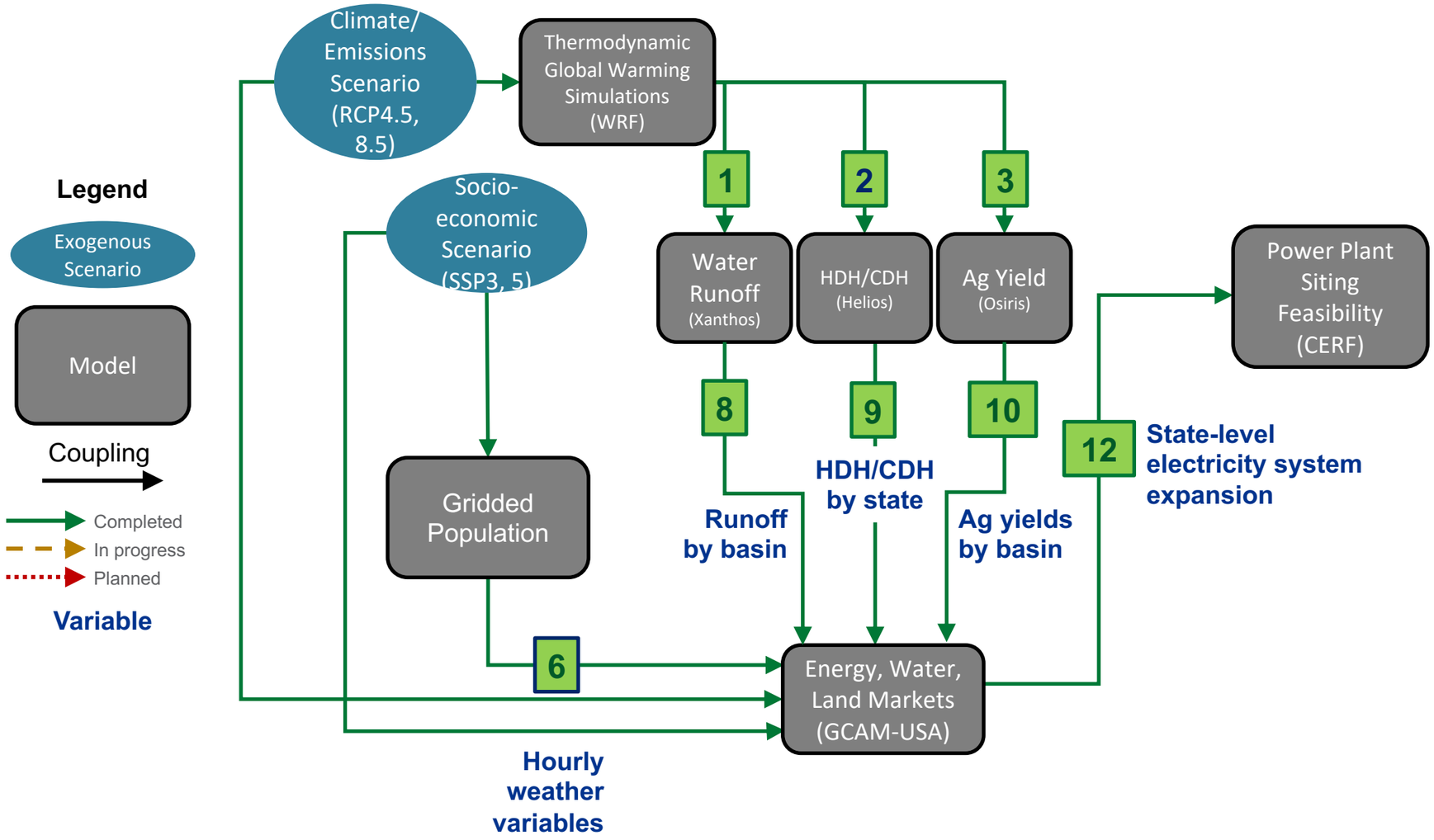
IM3 Experiment Group B Workflow



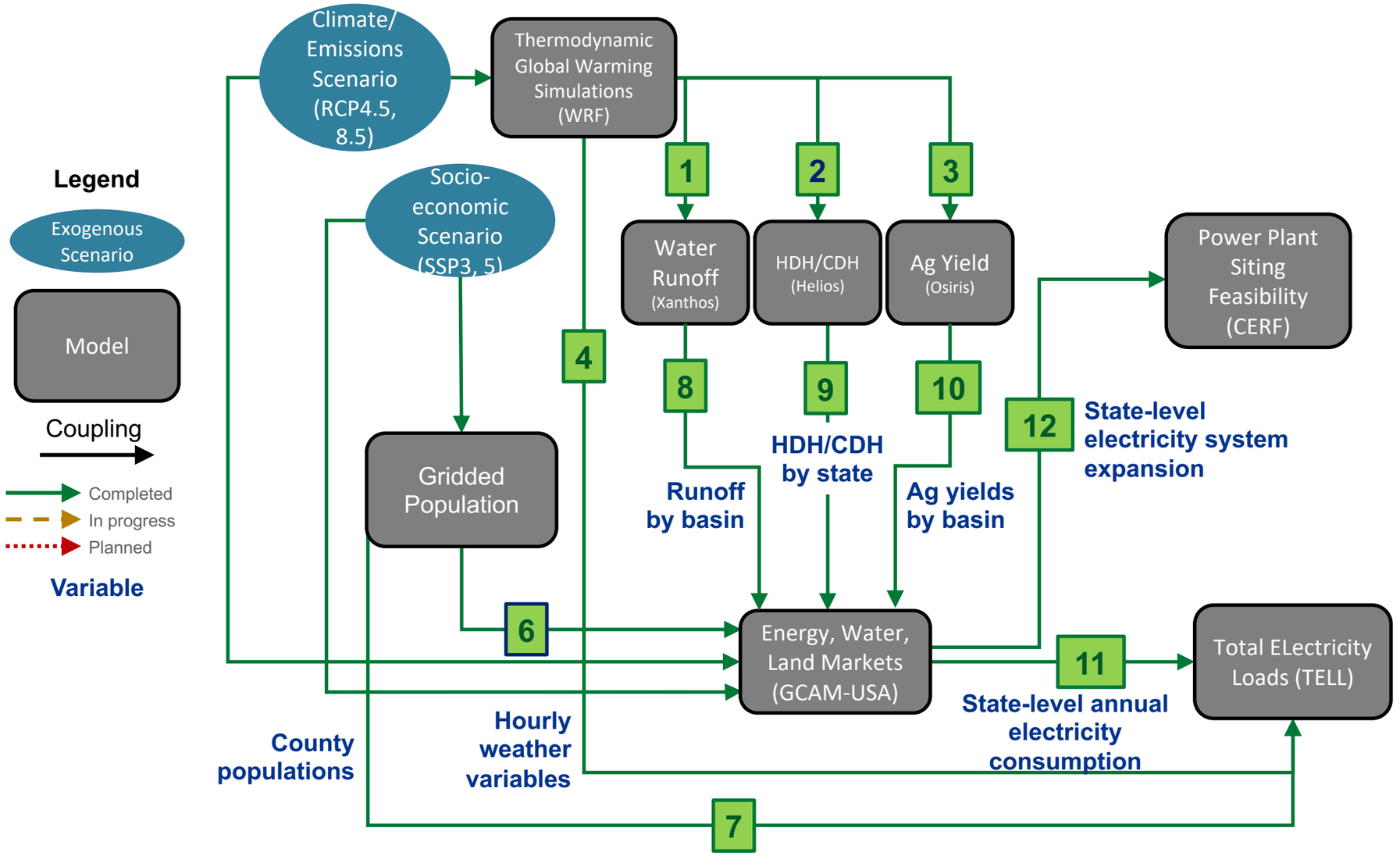
IM3 Experiment Group B Workflow



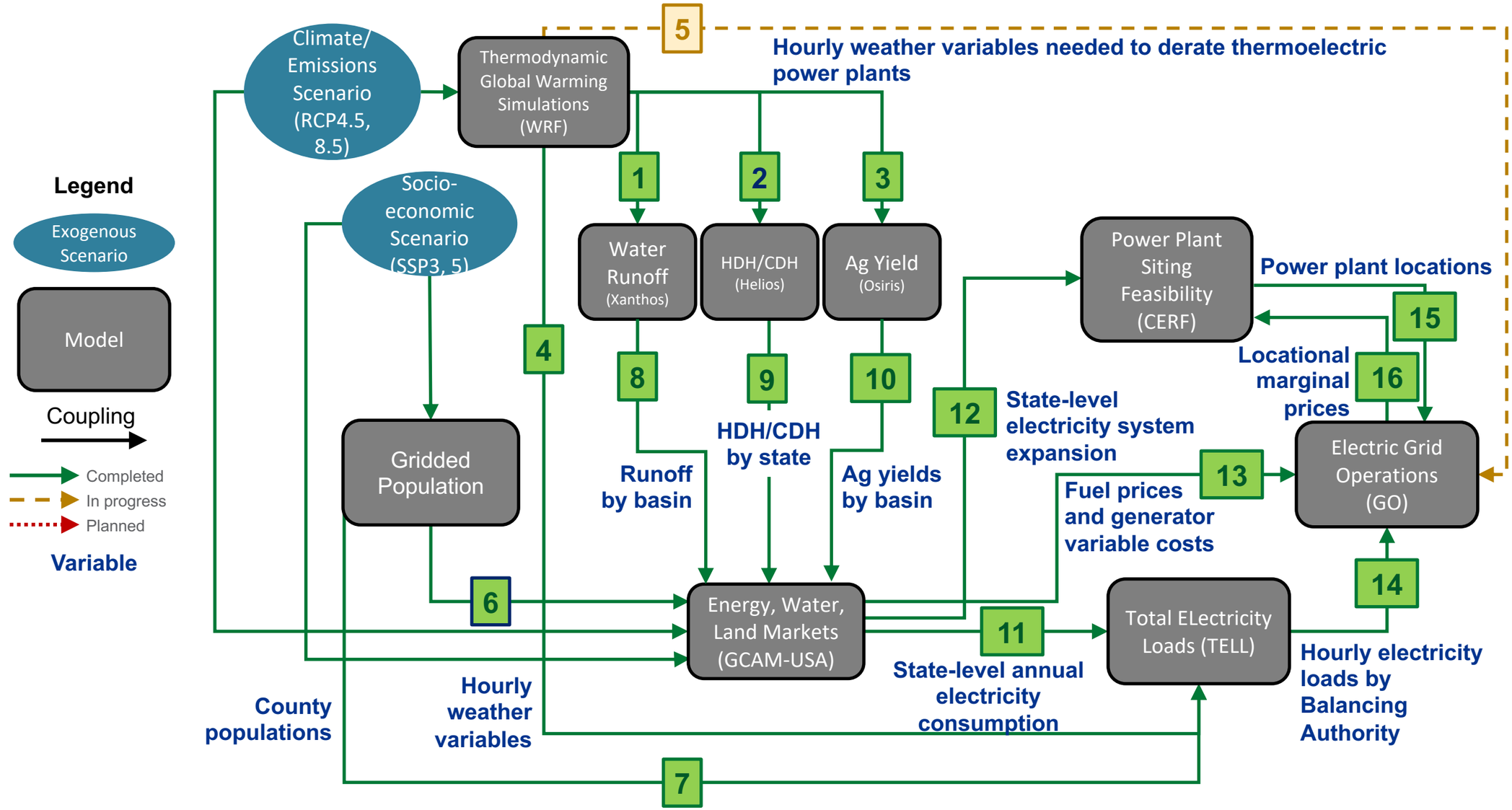
IM3 Experiment Group B Workflow



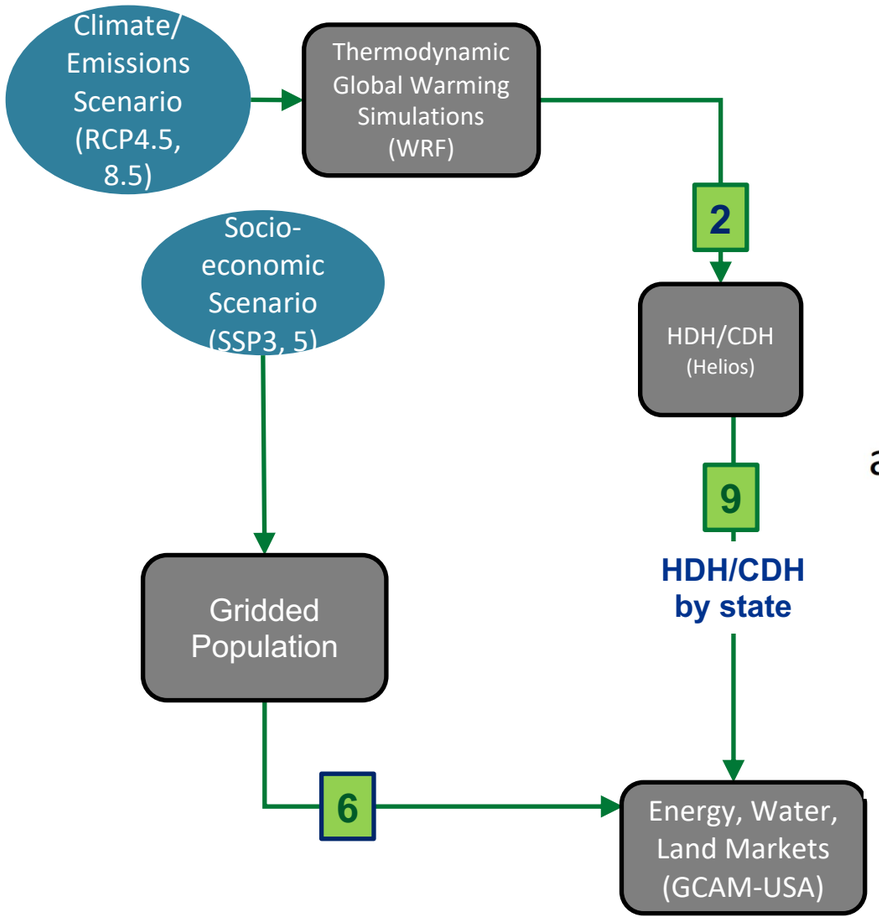
IM3 Experiment Group B Workflow

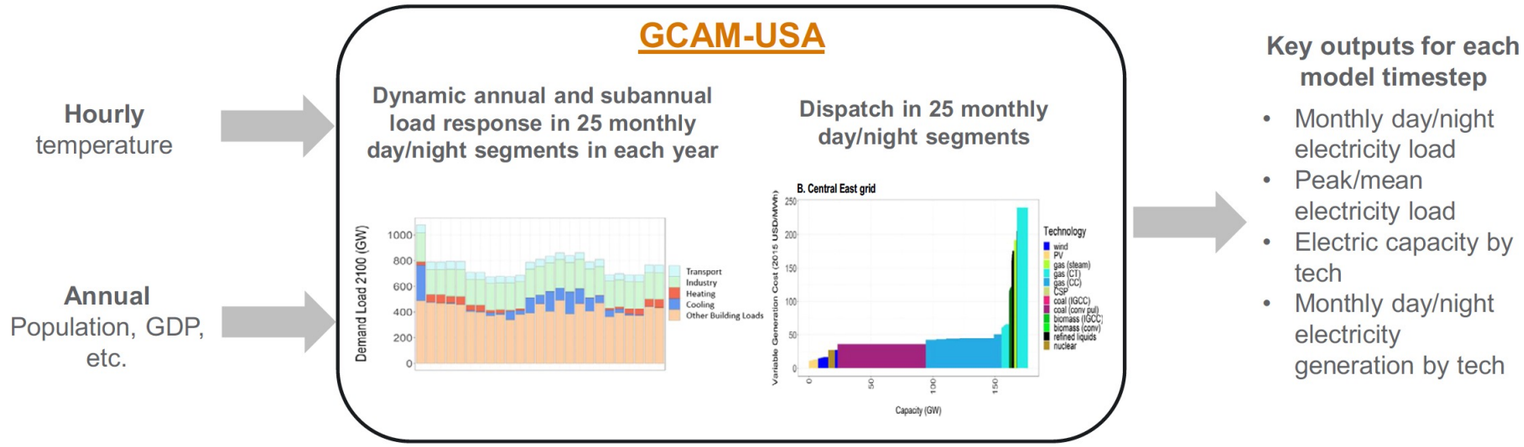


IM3 Experiment Group B Workflow

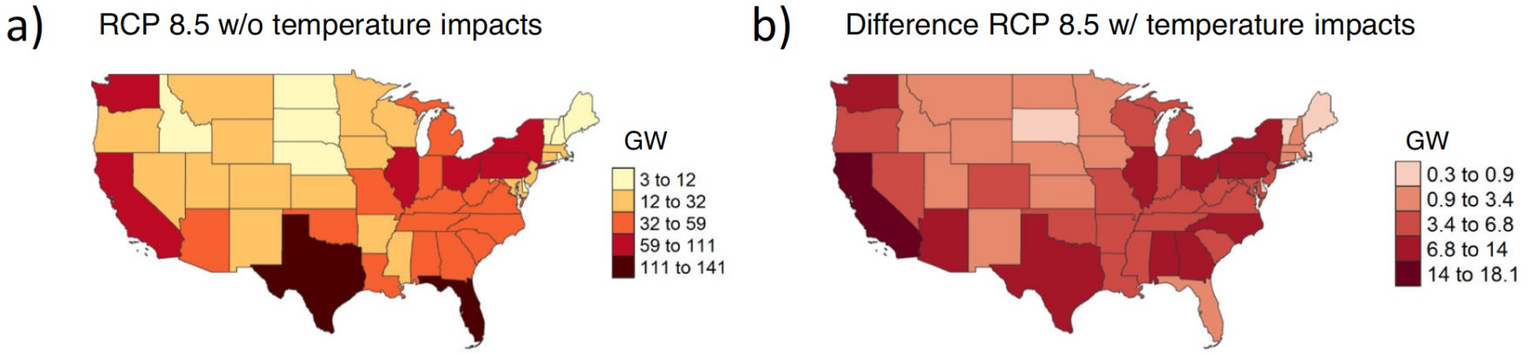


Projecting Annual and Peak Electricity Demand Using GCAM-USA





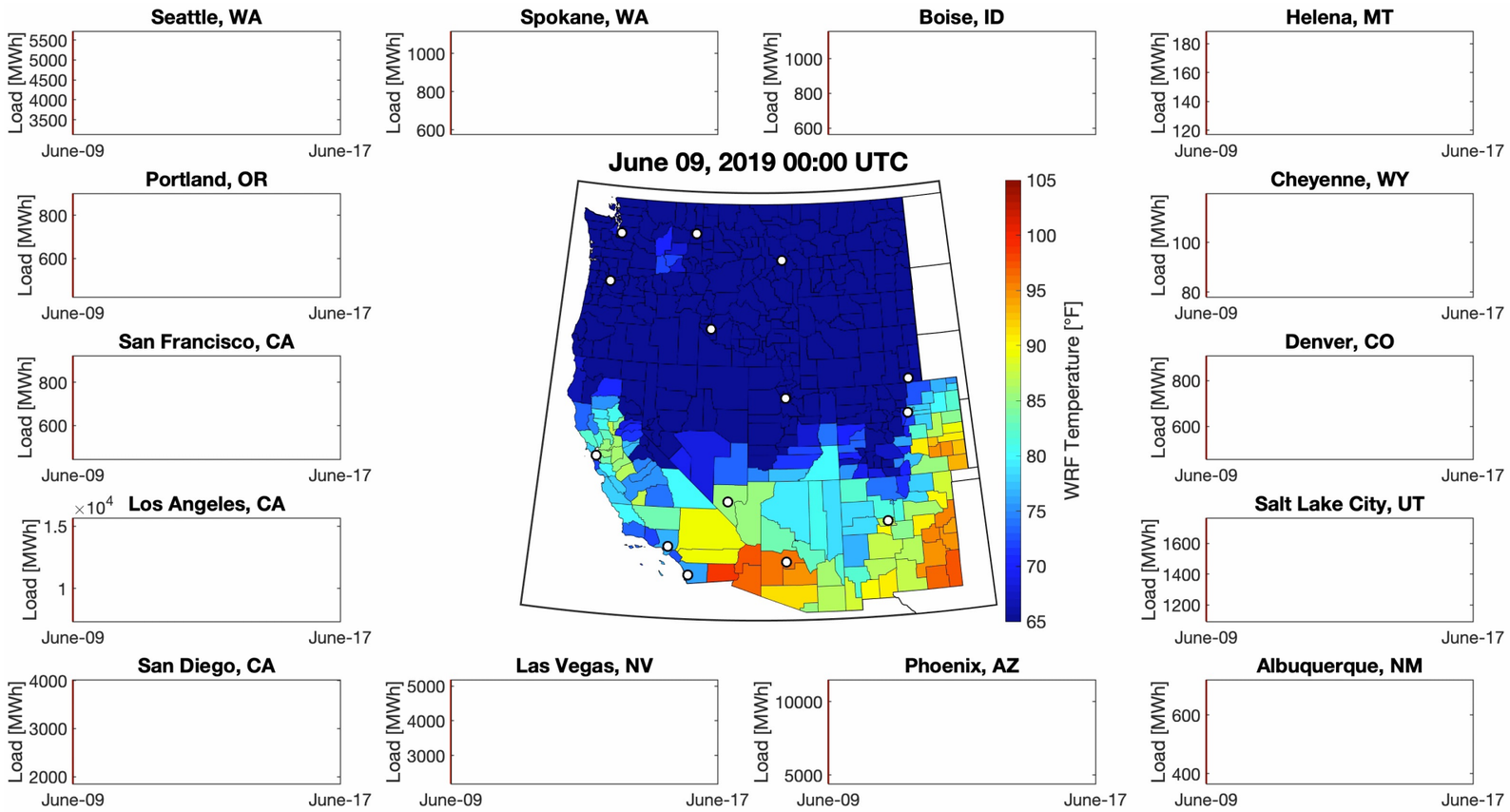
Installed Capacity in 2100 (GW)



Khan, Z., G. Iyer, P. Patel, K. Son, M. Hejazi, C. Burleyson, and M. Wise, 2021: Impacts of long-term temperature change and variability on electricity investments. *Nature Communications*, 12, 1643, https://doi.org/10.1038/s41467-021-21785-1.

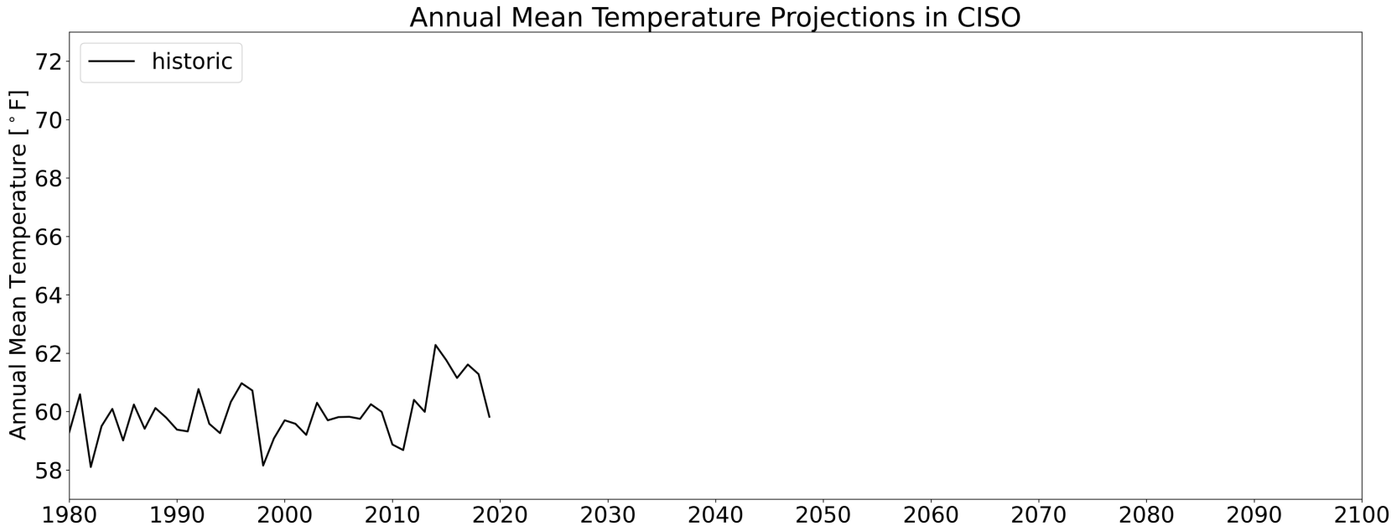
Simulating Hourly Loads Using the Total ELectricity Loads (TELL) Model

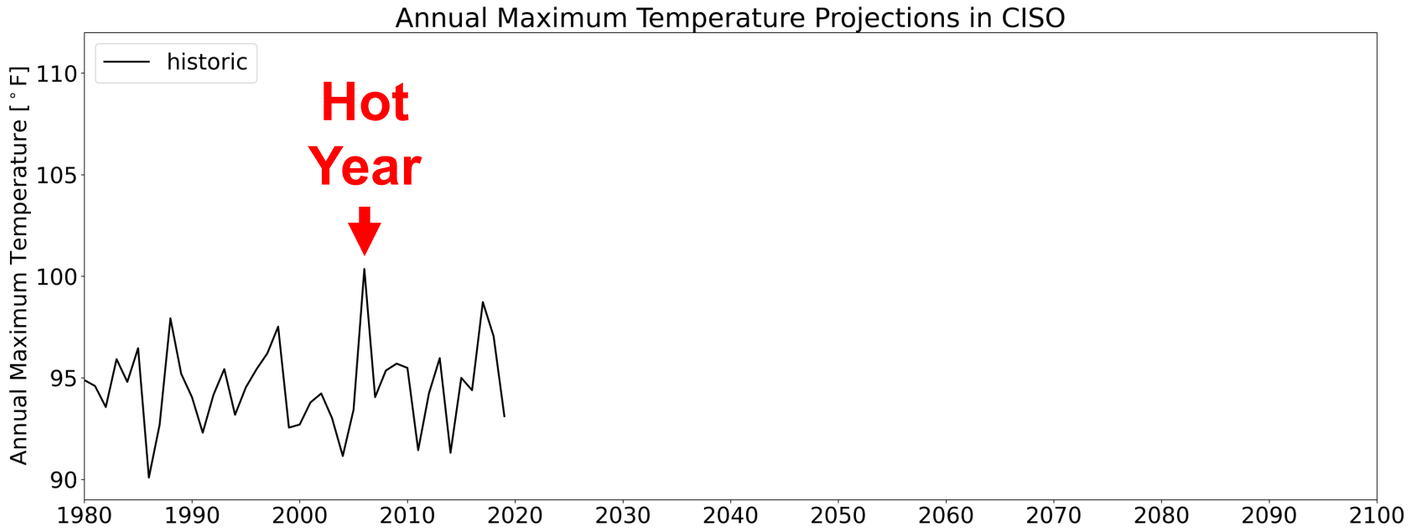
- TELL projects the evolution of hourly electricity demand in response to changes in weather and climate
- Based on a series of machine learning models trained on historical loads and meteorology
- Output is projections of hourly electricity demand at the county-, state-, and BA-scale that are conceptually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



McGrath, C., C. Burleyson, Z. Khan, A. Rahman, T. Thurber, C. Vernon, N. Voisin, and J. 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

Thermodynamic Global Warming Simulations

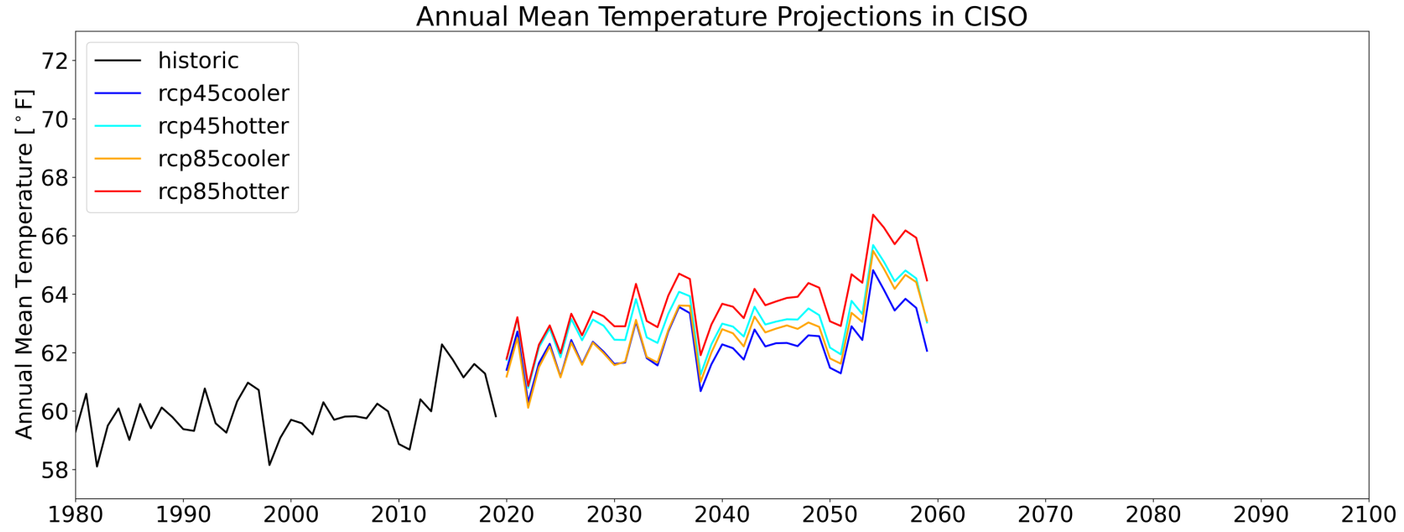


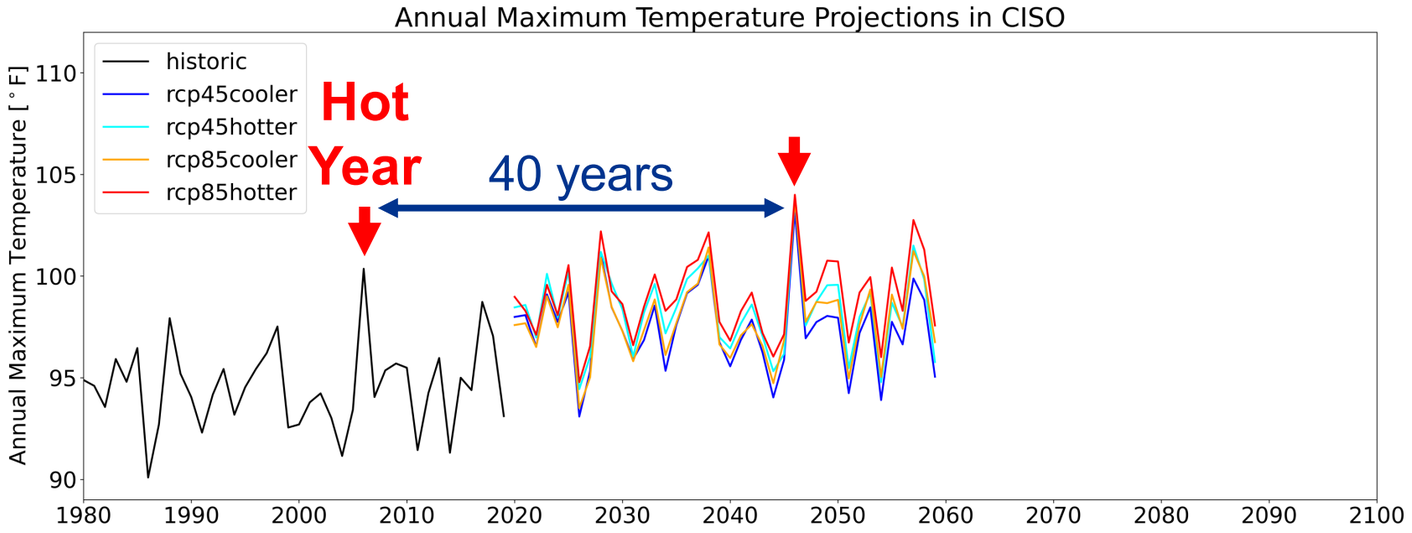


- Historic data reproduces observed sequence of past events (1980–2019)
- Sequence is repeated twice in the future (2020–2059 and 2060–2099) with additional warming gradually applied
- 1/8 deg (~12 km) resolution, U.S., hourly
- 25 hourly and 250+ three-hourly variables
- Actively leveraged in a half-dozen DOE Office of Electricity projects examining extreme weather impacts on the electric grid

TGW simulations were a joint effort between the IM3 and HyperFACETS projects. Data is publicly available: https://tgw-data.msdlive.org/.

Thermodynamic Global Warming Simulations





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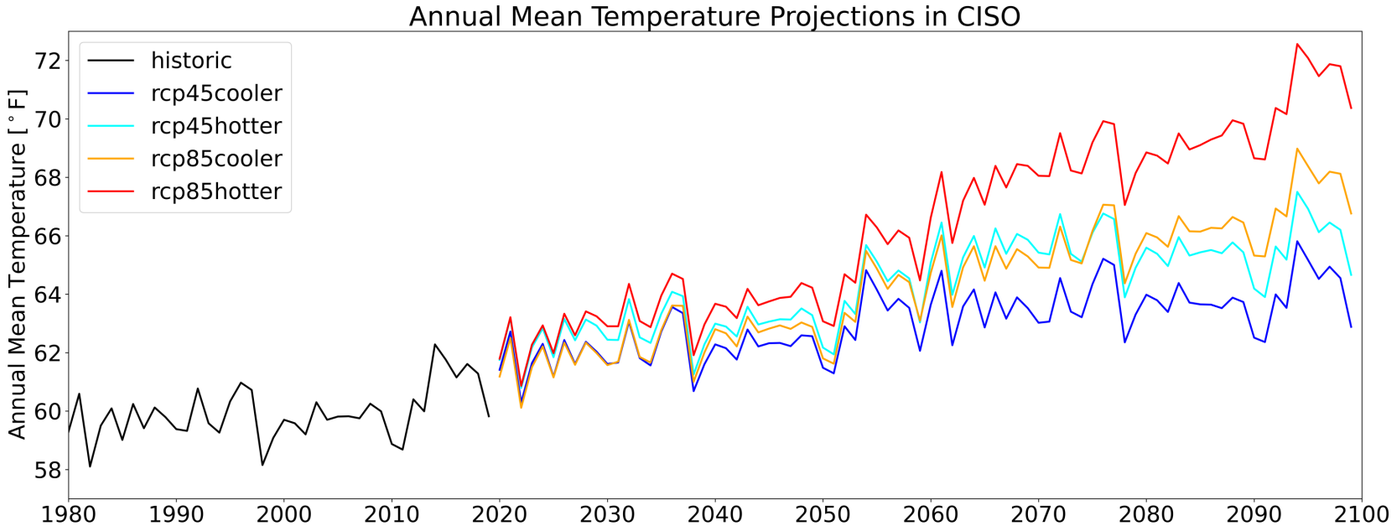
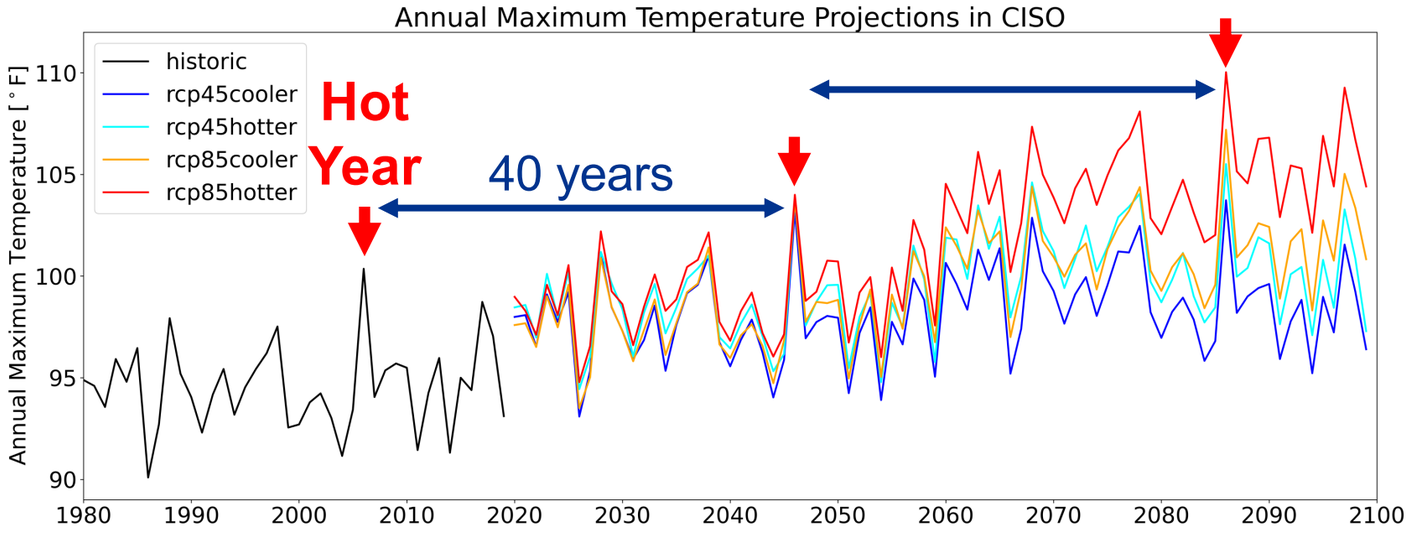
Thermodynamic Global Warming Simulations





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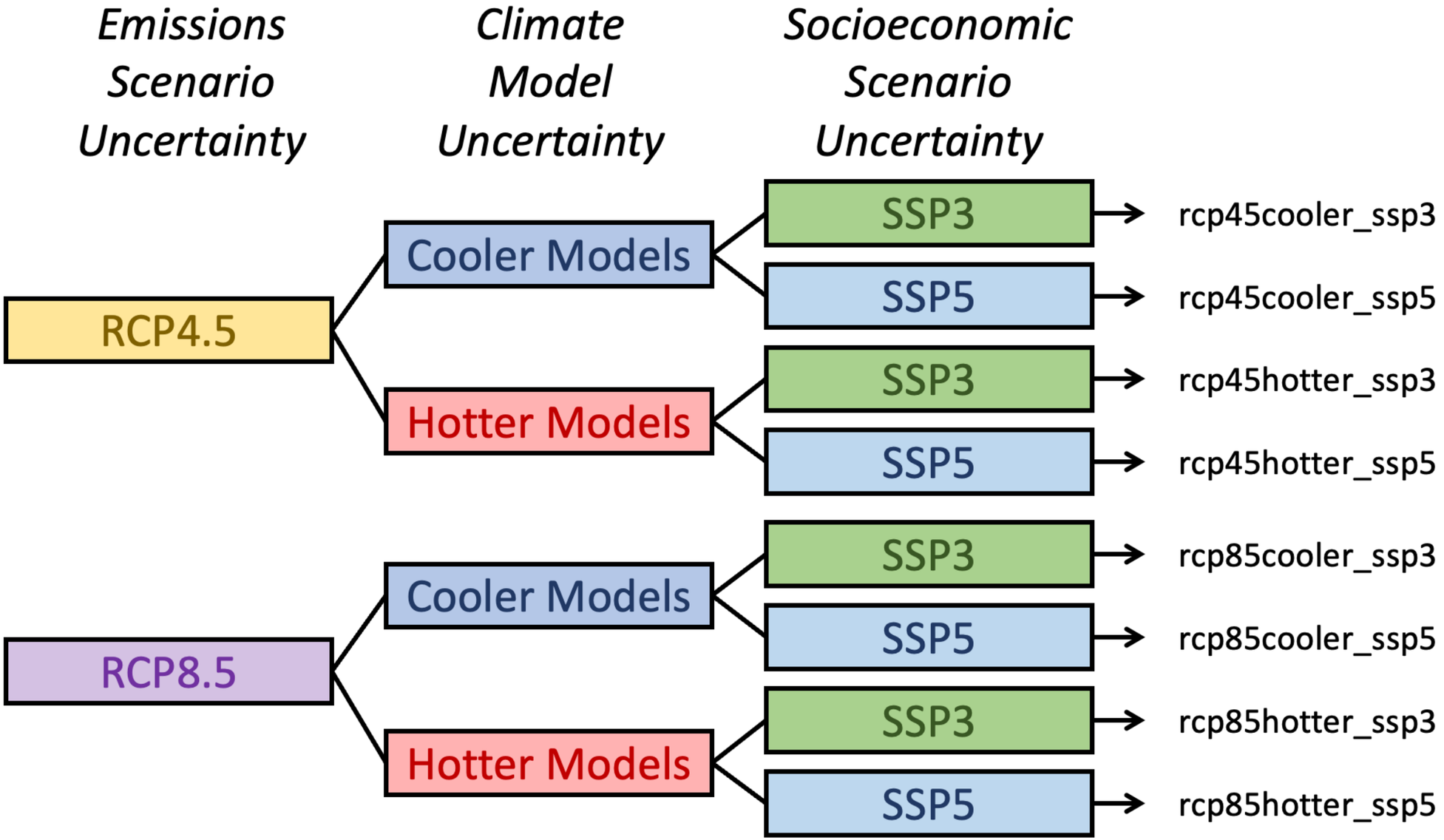
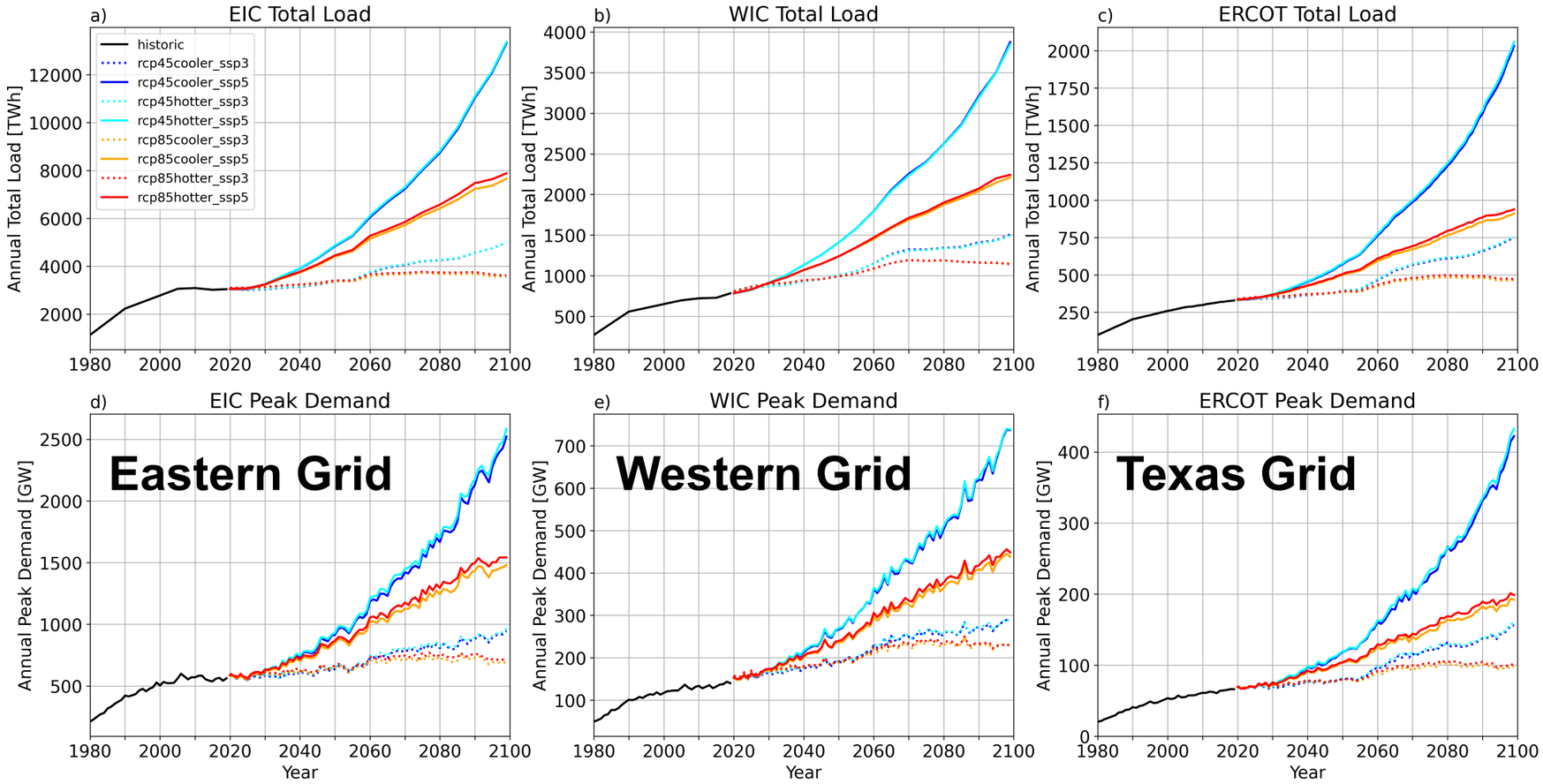
Joint Climate and Socioeconomic Scenarios



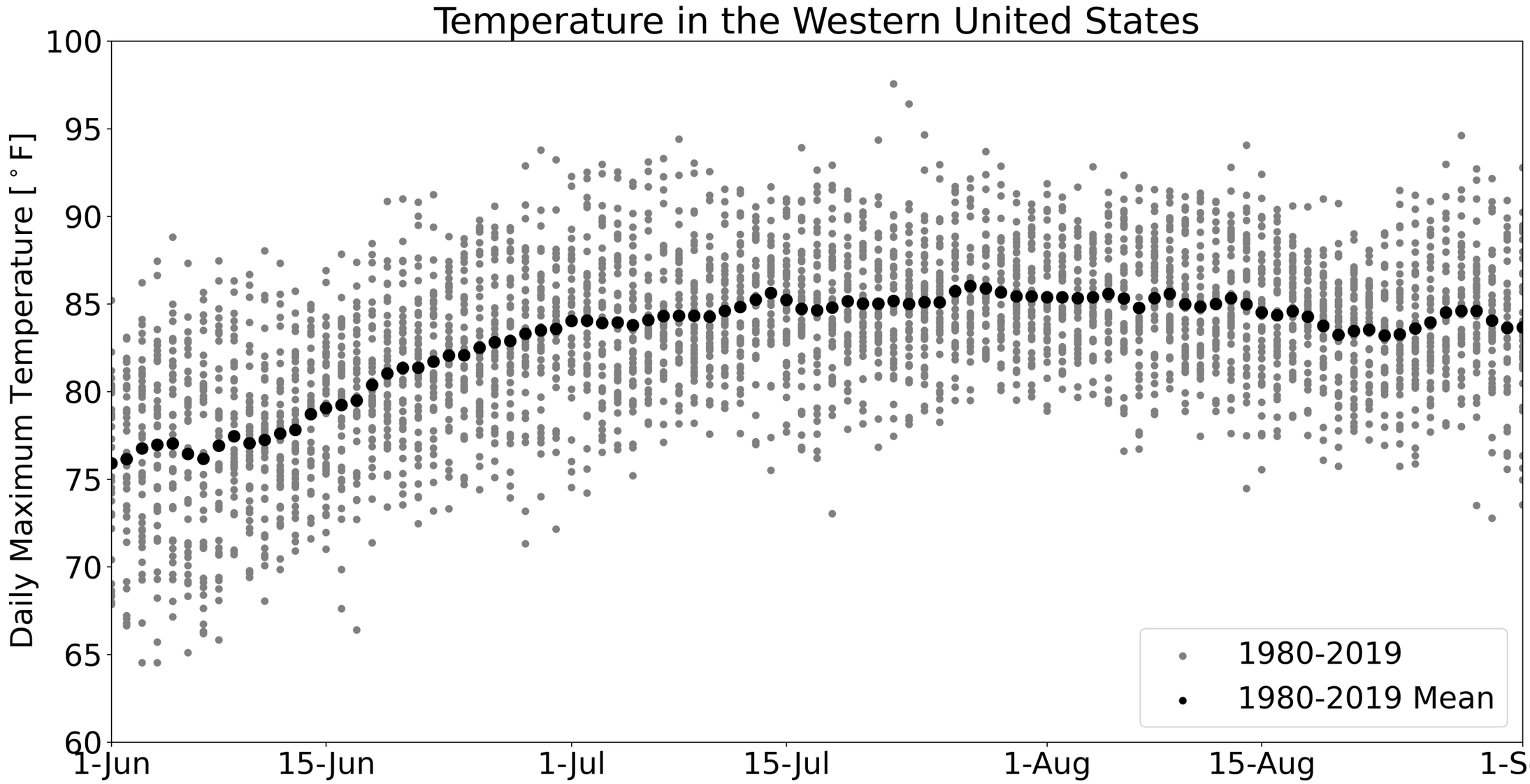
Projections of Electricity Demand



Burleyson, C., Z. Khan, M. Kulshresta, N. Voisin, and J. Rice, 2024: When do different scenarios of projected electricity demand start to meaningfully diverge? In revision in *Applied Energy*.

- More people = more demand
- Less carbon = more demand
- Socioeconomics matter almost immediately
- Climate scenario matters after 20-25 years
- Climate model matters after 50+ years

Finding Heat Wave Events



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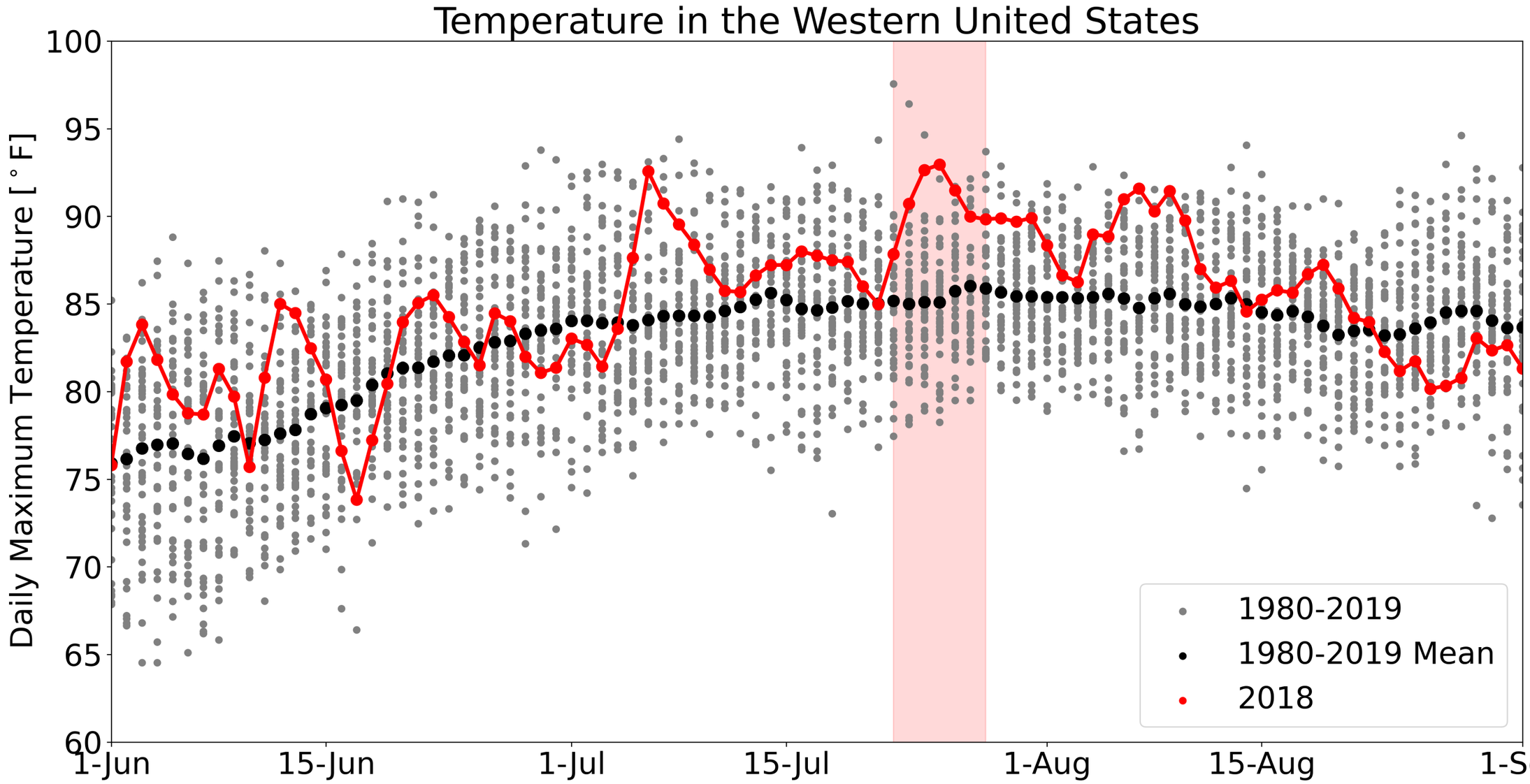
Finding Heat Wave Events



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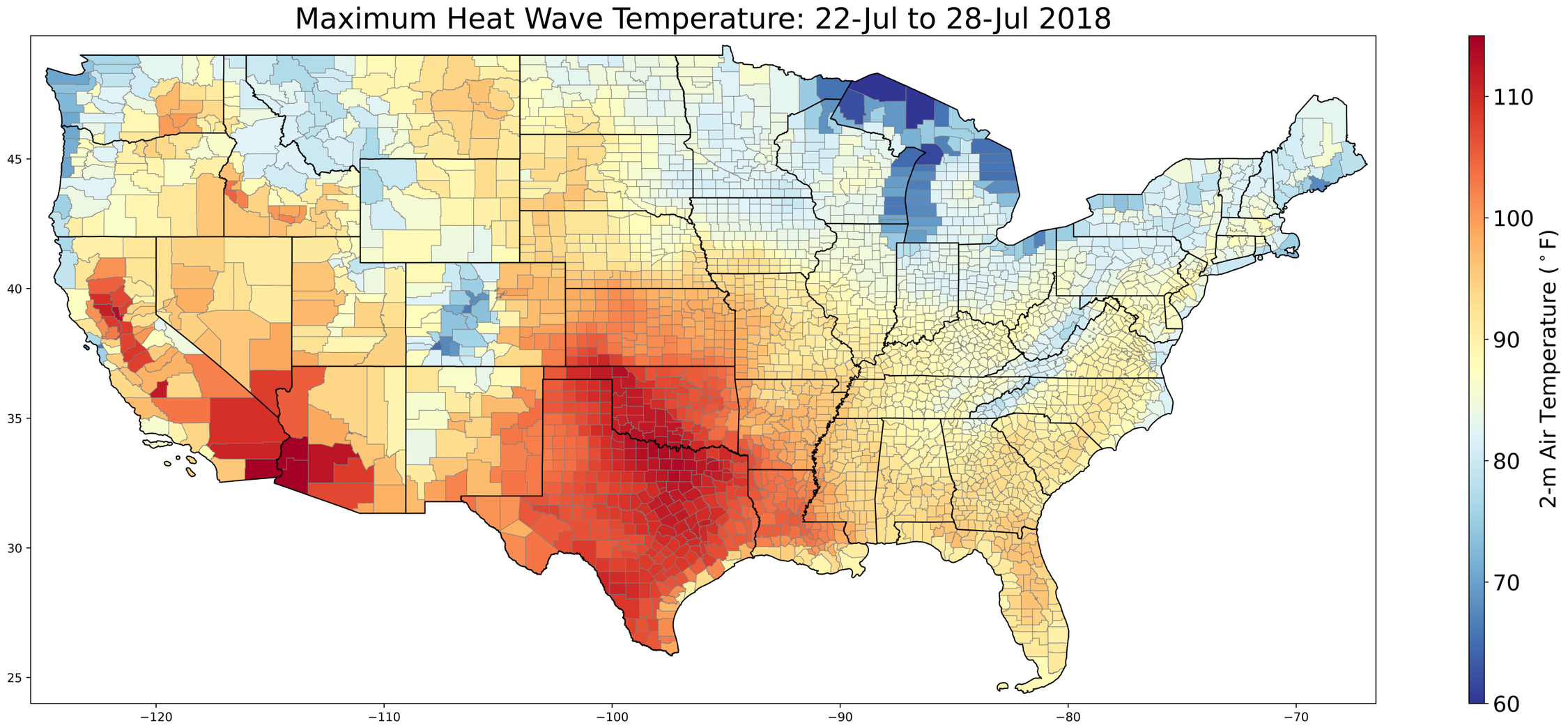
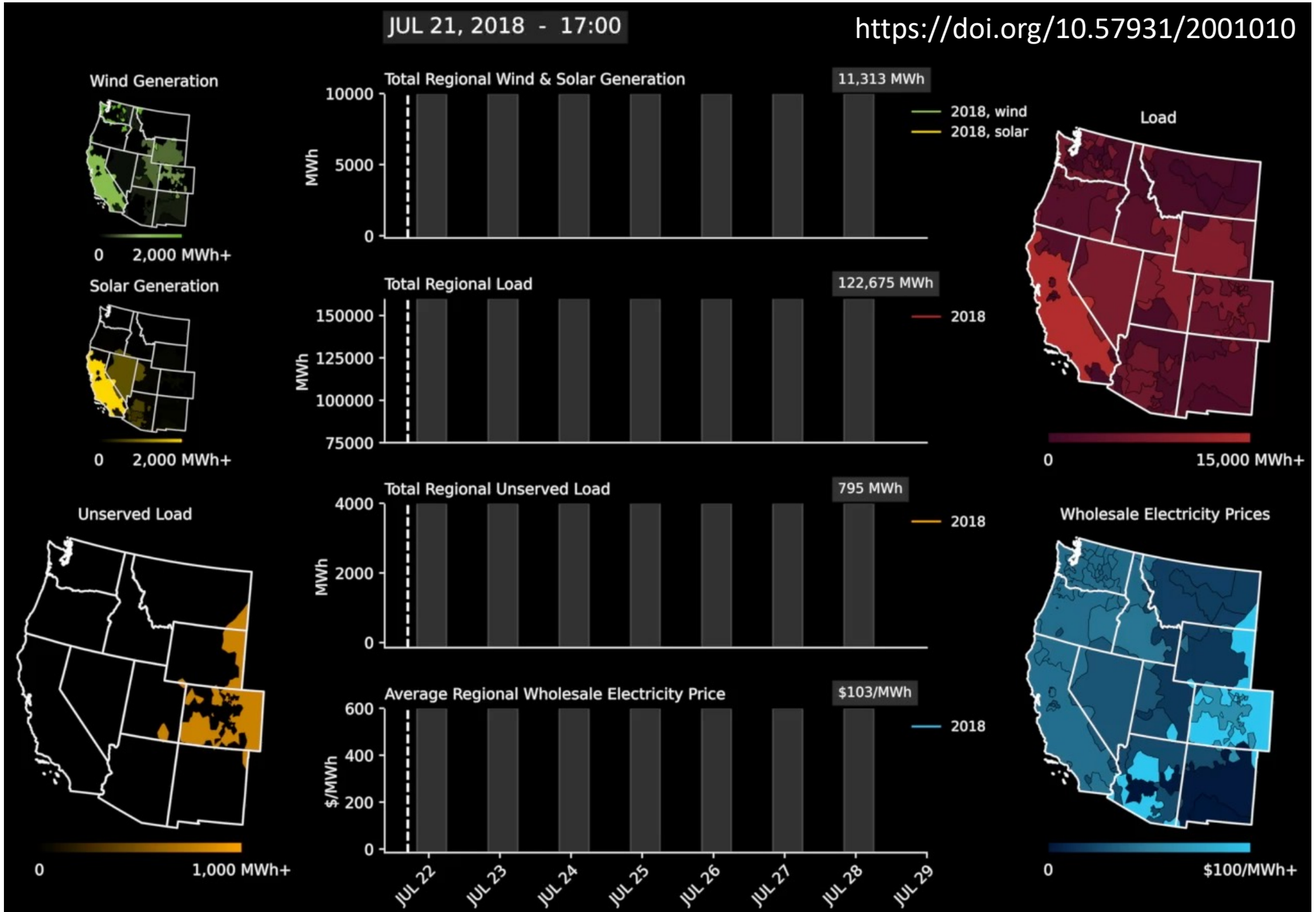
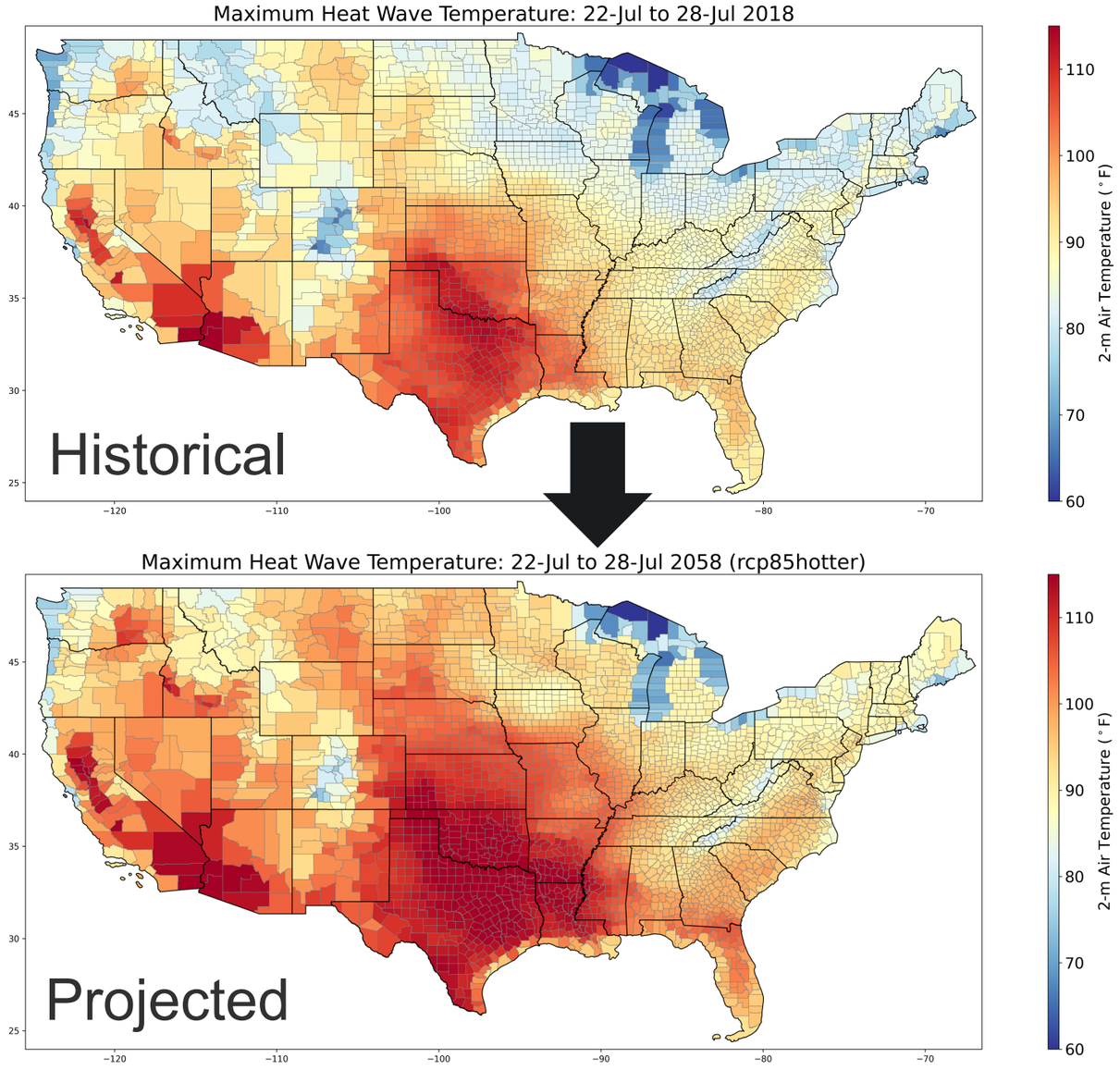
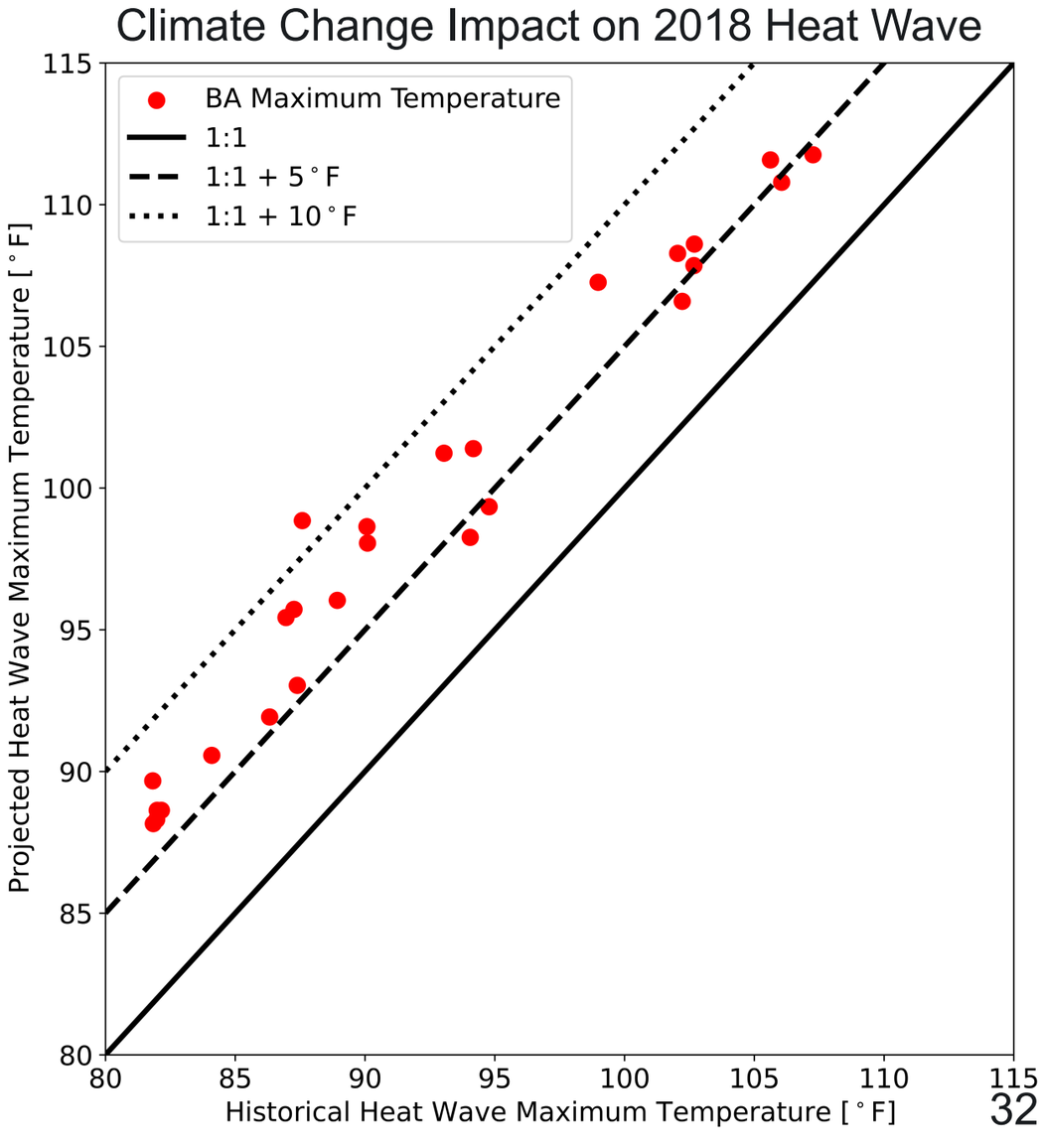


Exploring Historical Heat Wave Grid Stress

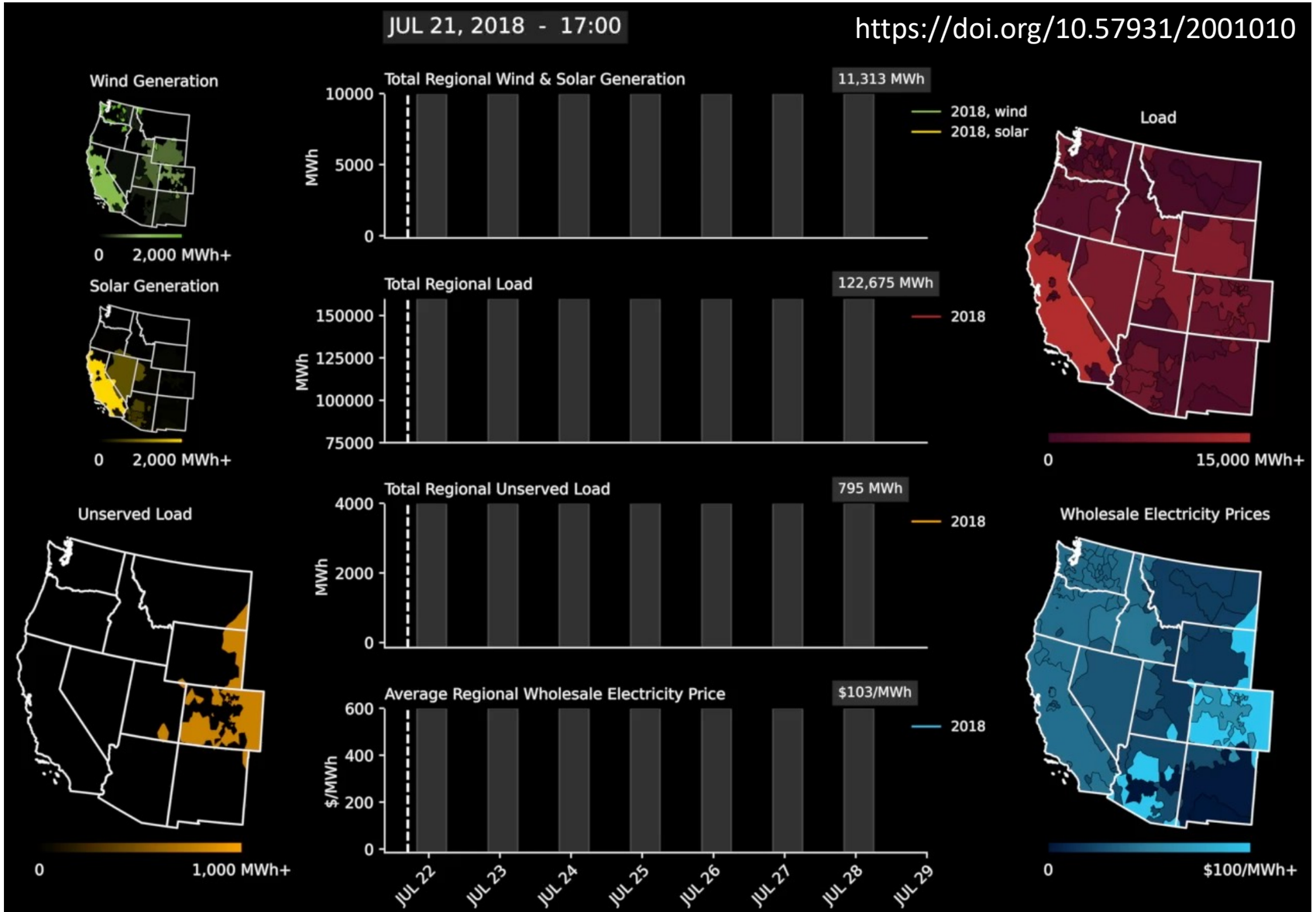


Exploring Future Heat Wave Grid Stress



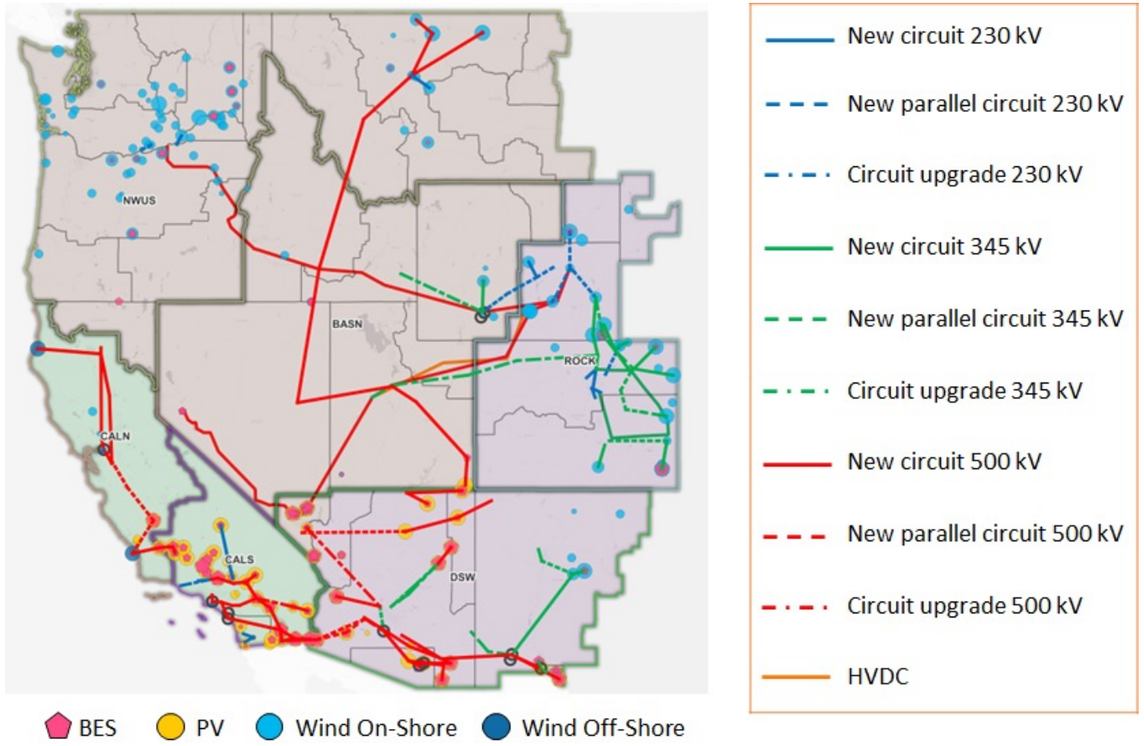


Exploring Future Heat Wave Grid Stress



Stress Tests for Understanding Resilience of System Projections

Projects like the National Transmission Planning Study (NTPS) are using our load model and the TGW historical and future meteorology to test the resilience of their projected system to extreme weather events.



National Transmission Planning Study: Stress Analysis

March 2024

Konstantinos Oikonomou, Kyle Wilson, Mark Weimar, Abhishek Somani, Casey D. Burleyson, Cameron W. Bracken, Fernando Bereta dos Reis, Nathalie Voisin
Pacific Northwest National Laboratory

B&R Code: TF0000000-05300-3123796
DOE Program Manager: Kelly Kozdras, Adria Brooks

U.S. DEPARTMENT OF ENERGY | Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Chapter Two

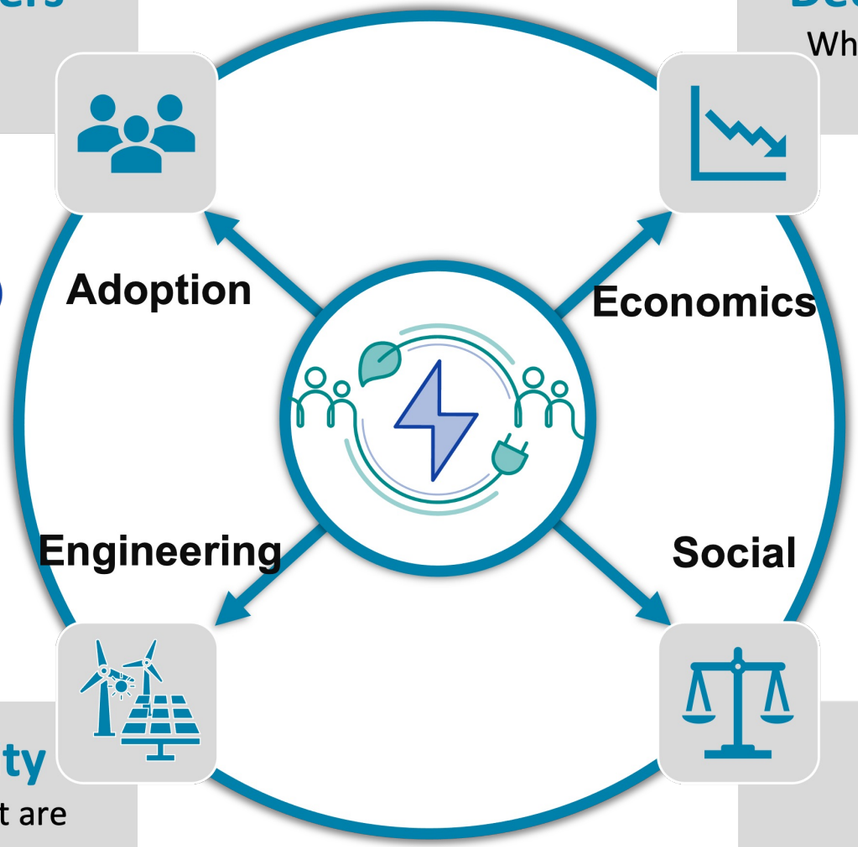
What does all this look like in a decarbonized grid?

PNNL's GODEEEP Project

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

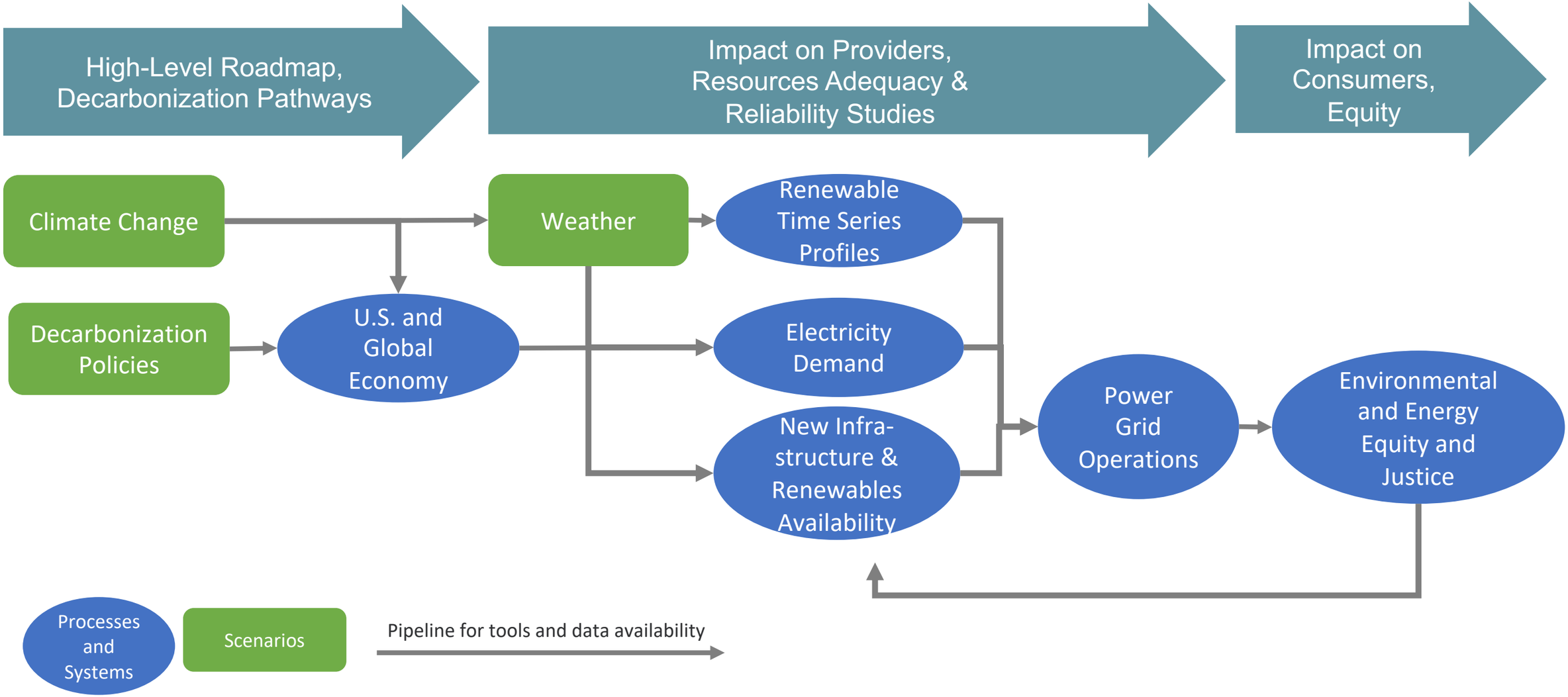
Coordinated research using staff expertise across renowned Climate and Bulk Electric Grid Programs in Fundamental and Applied Research across the Department of Energy's offices

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

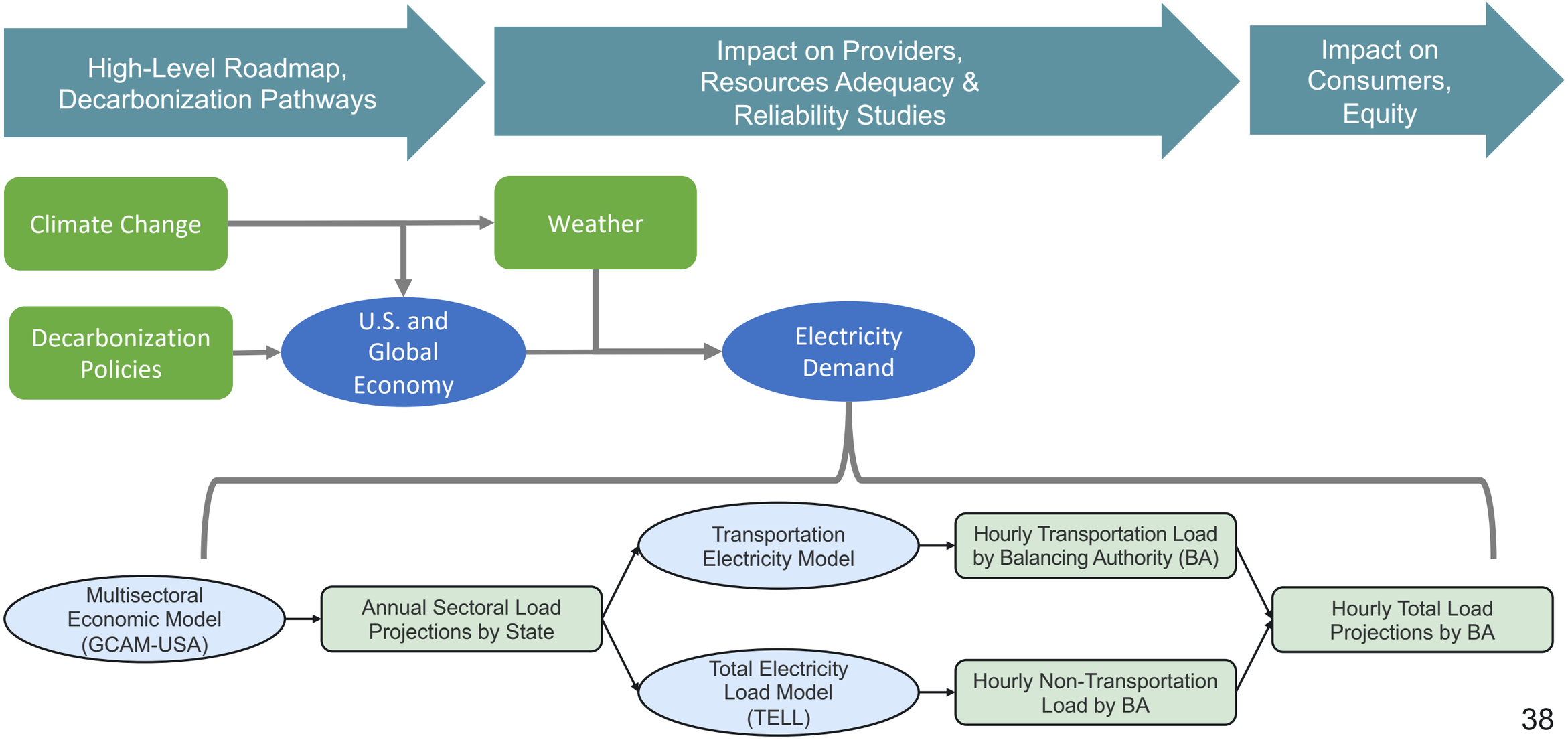
Resilience and Reliability
Infrastructure and operations that are responsive to climate change

Justice and Equity
Environmental and energy equity impacts of decarbonization

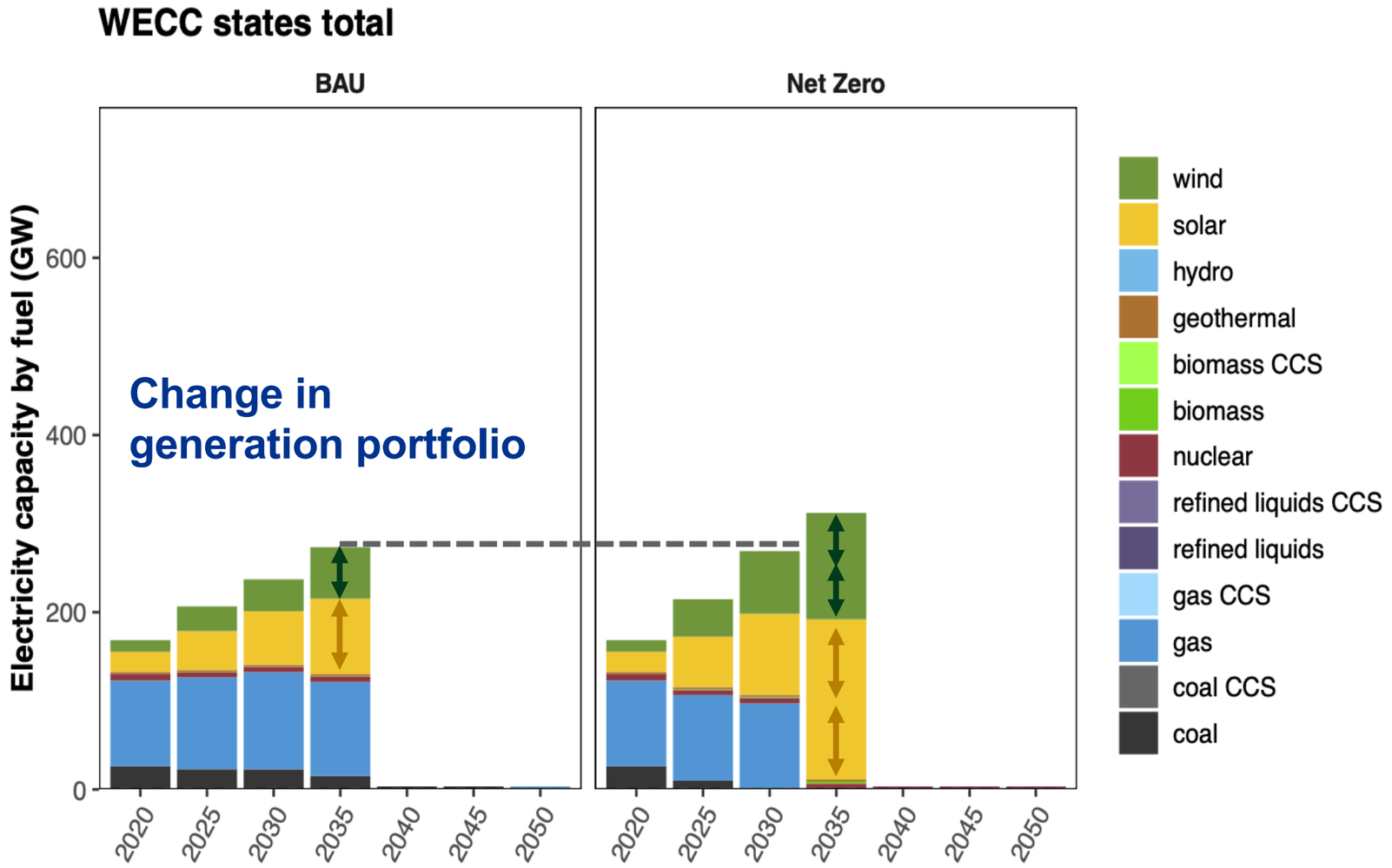
Climate and Decarbonization Impacts on Hourly Load Projections



Climate and Decarbonization Impacts on Hourly Load Projections



Change in Generation Mix Before 2035 - Changes in Demand After 2035



Ou, Yang, & Iyer, Gokul. (2023). GCAM-USA Decarbonization Pathways for GODEEEP (2.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7838872

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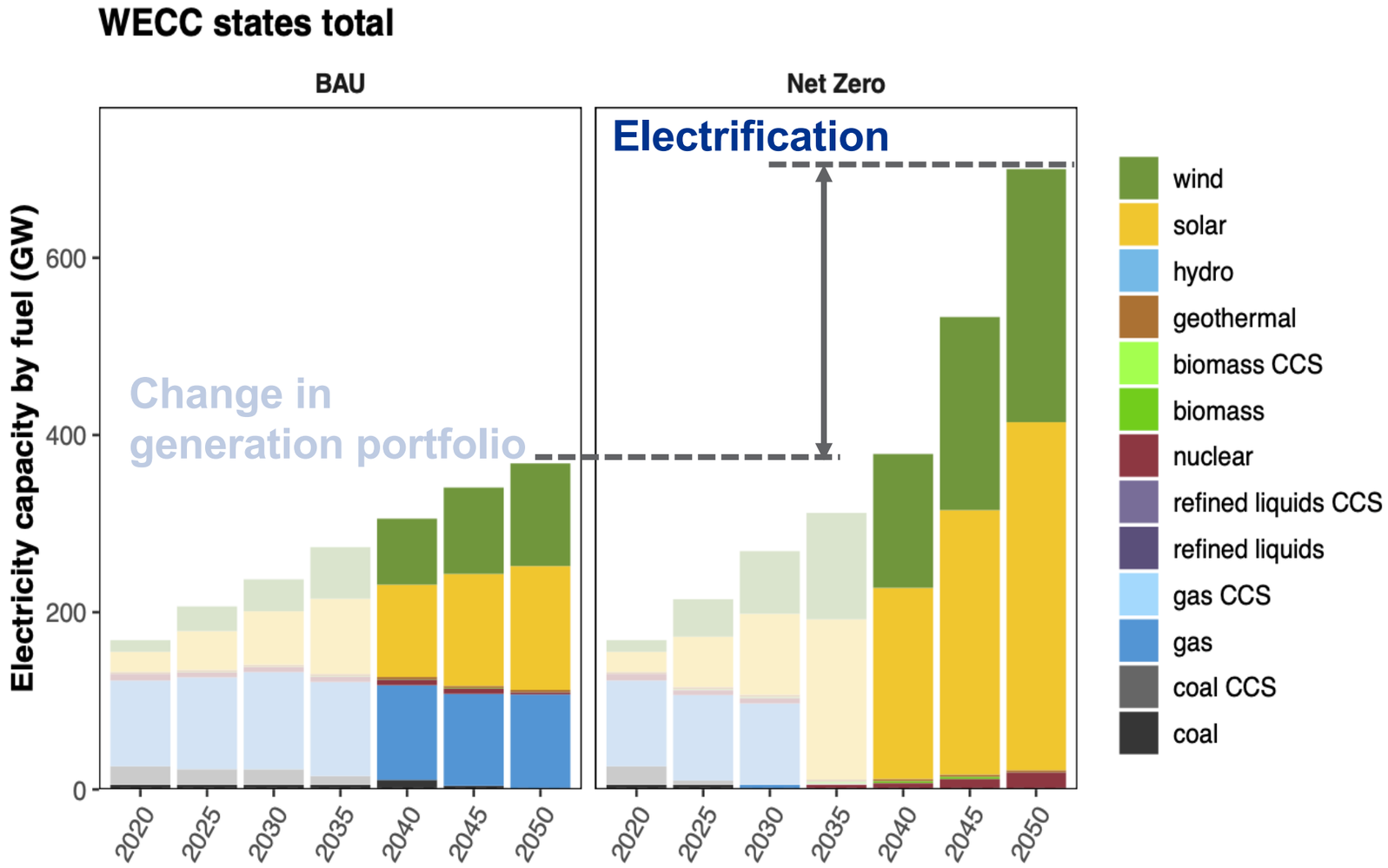

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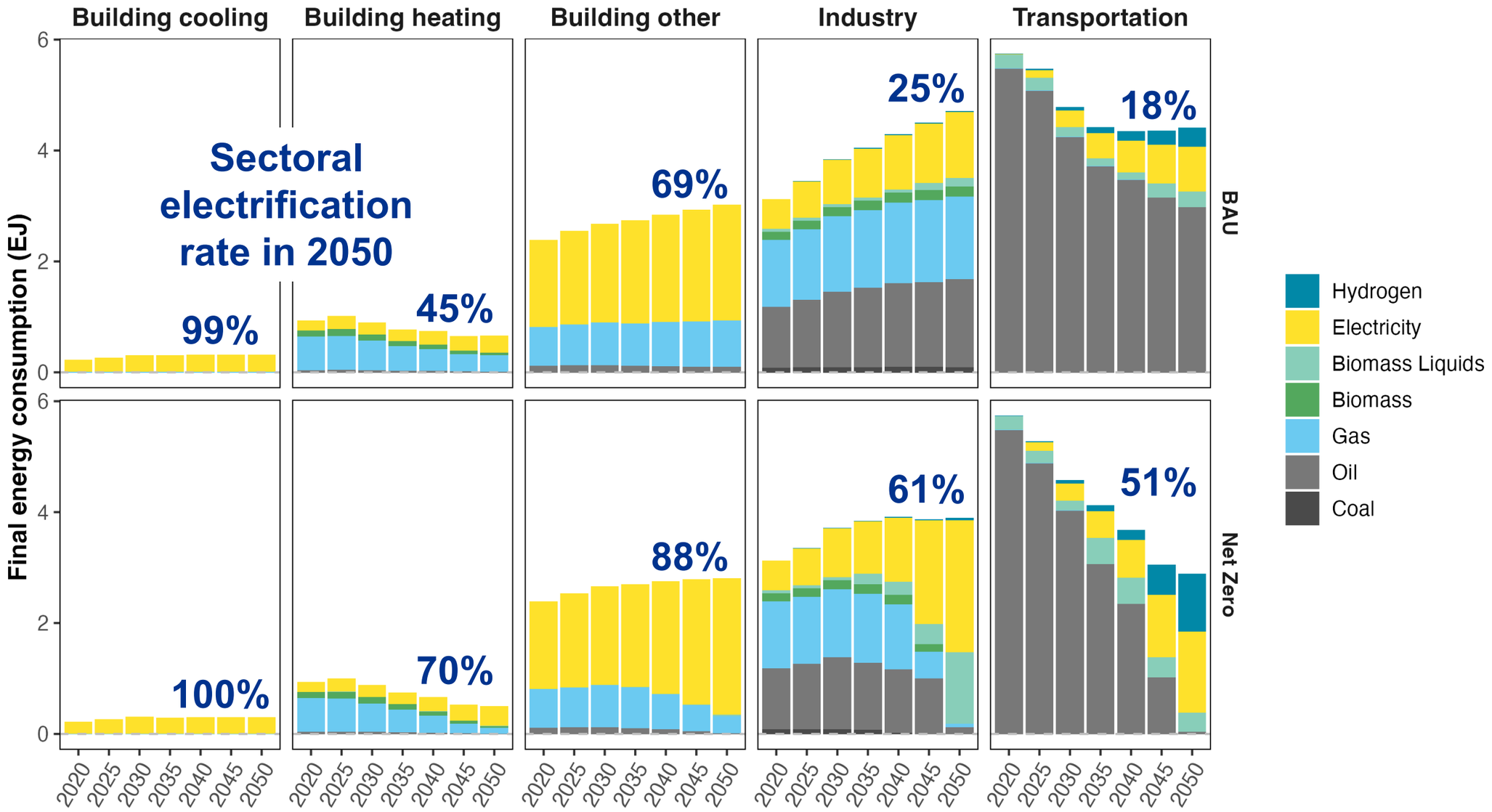
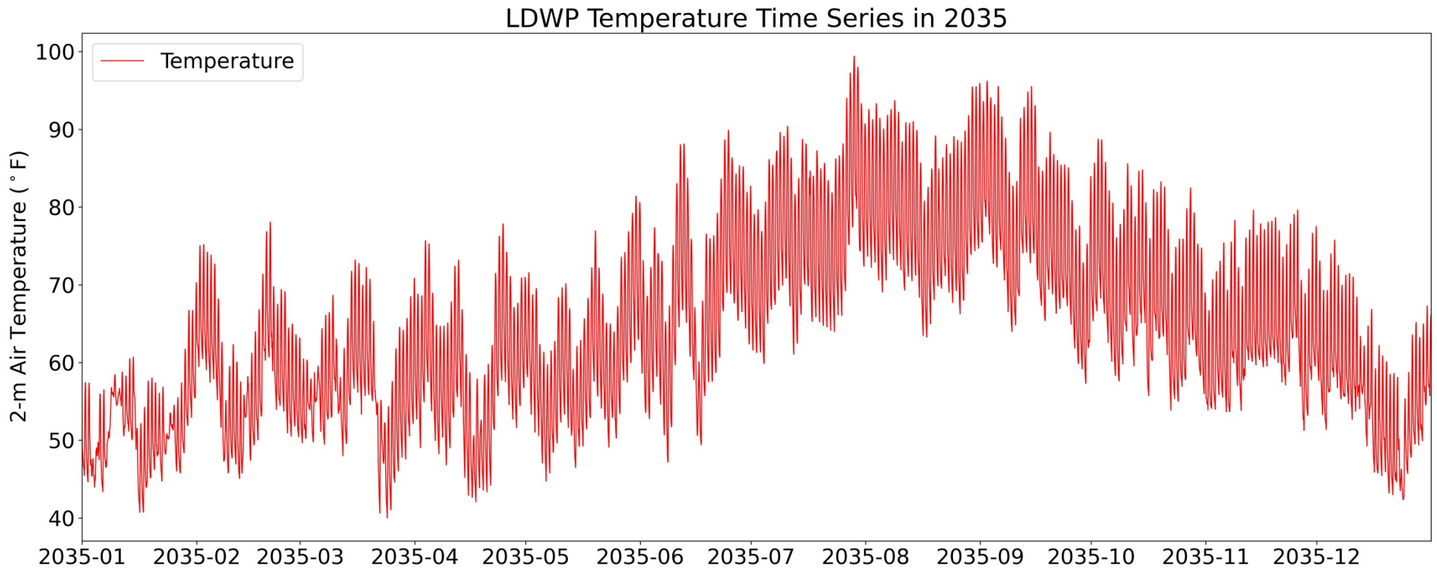
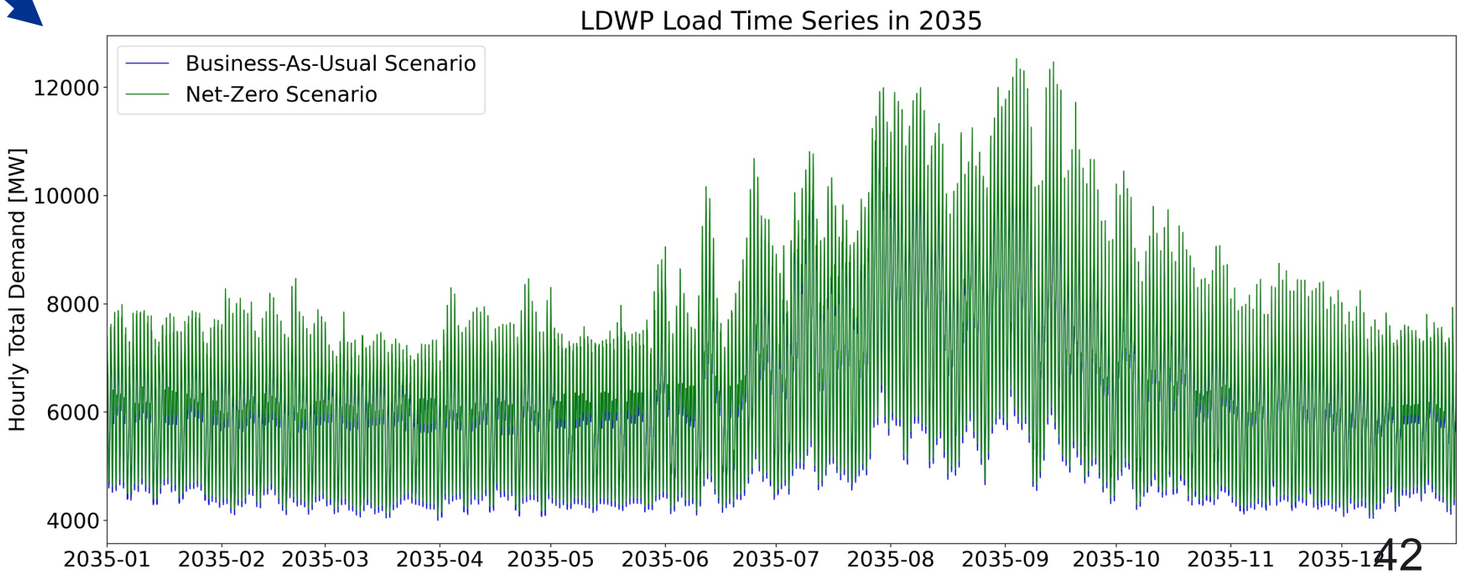
Clean Energy Transition Across Demand Sectors



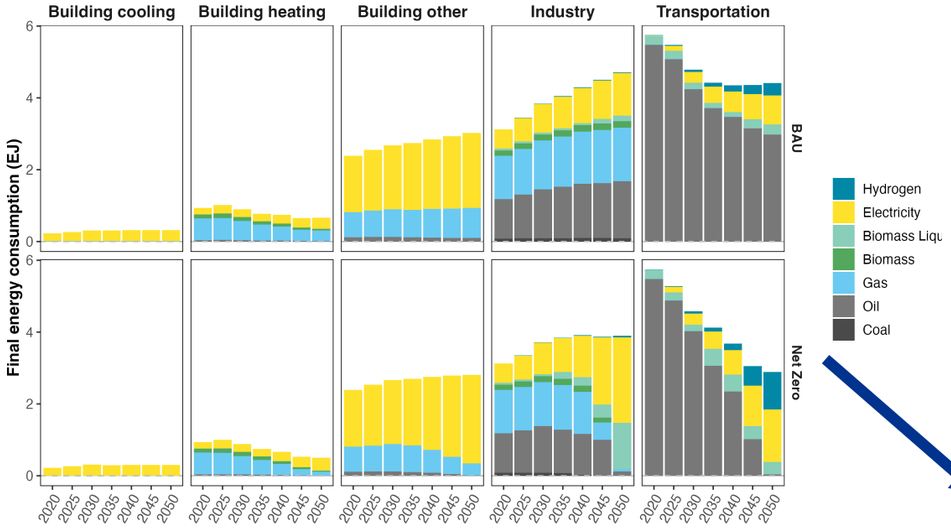
Result Snapshot: Hourly Load Time Series

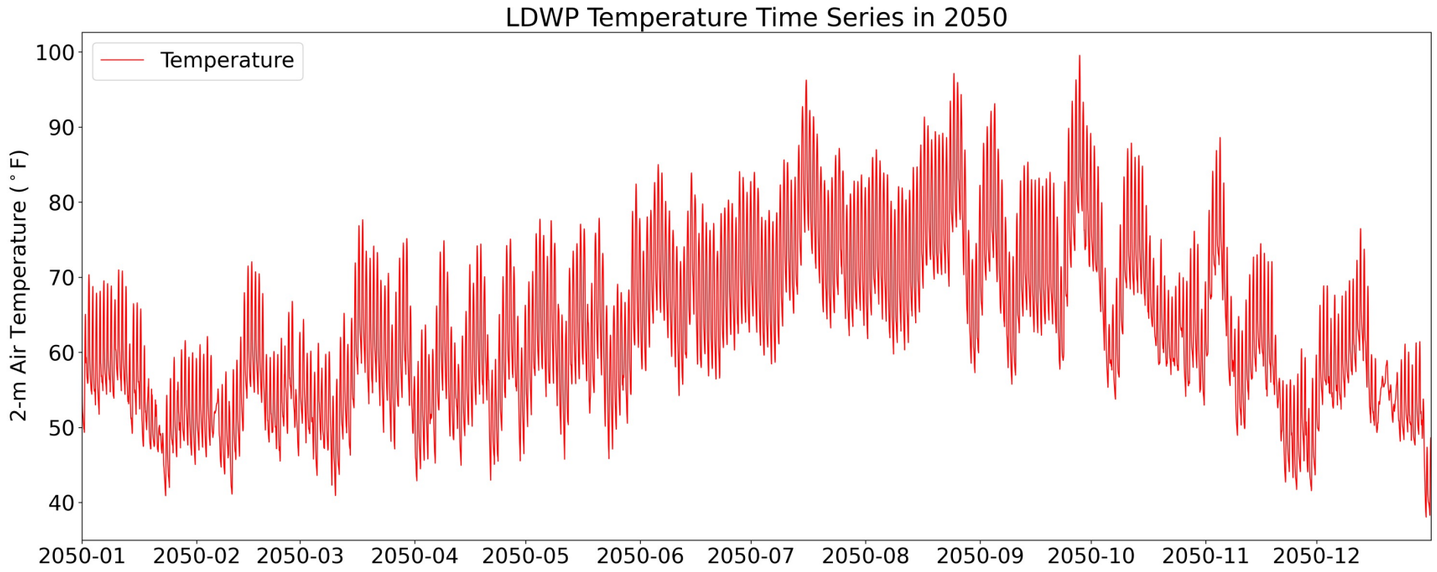


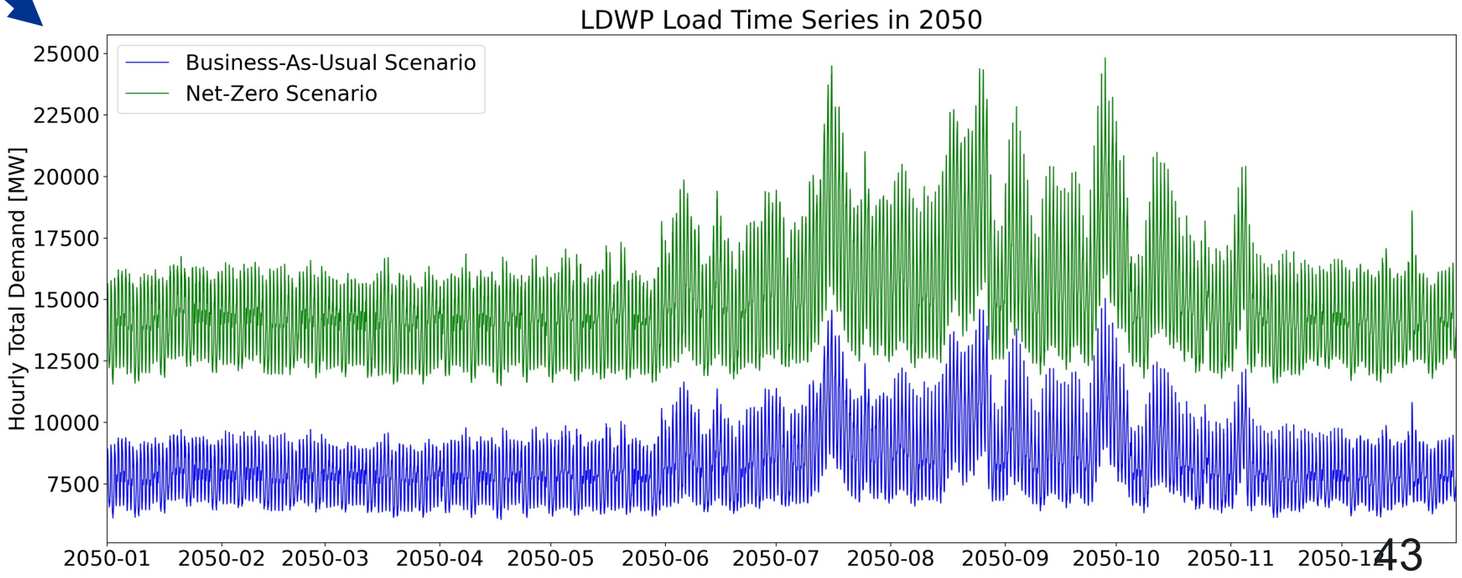


Acharya, S., C. Burleyson, et al., 2024: Weather sensitive high spatio-temporal resolution transportation electric load profiles for multiple decarbonization pathways. *2024 IEEE Power & Energy Society IGST Conference*, 1-5, doi:10.1109/ISGT59692.2024.10454229.
***Winner of the "Best Paper" award**

Result Snapshot: Hourly Load Time Series







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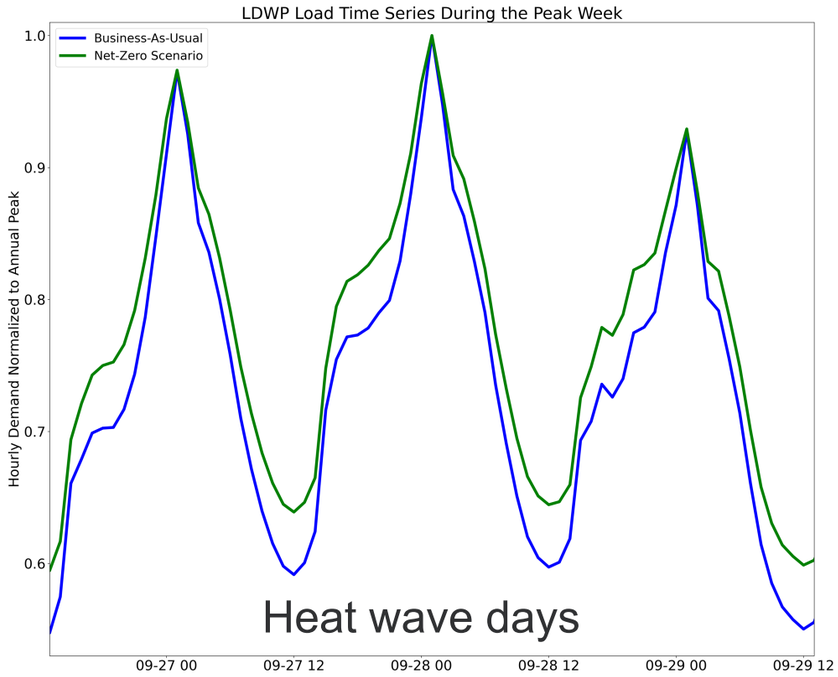
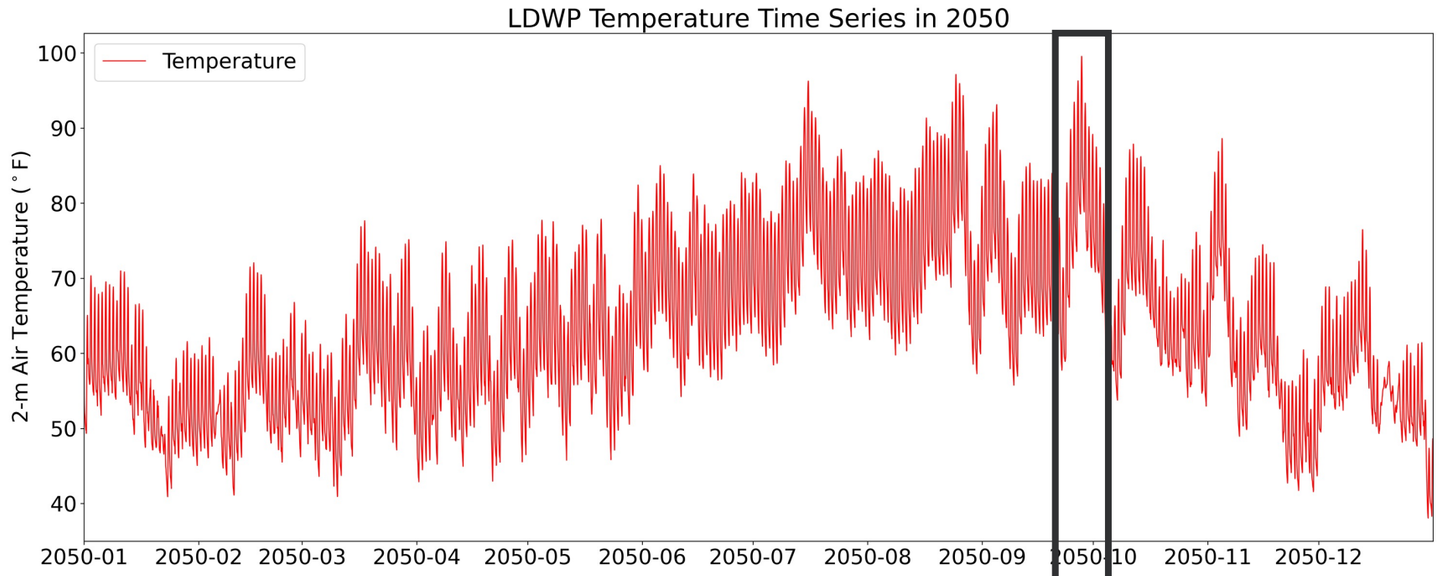
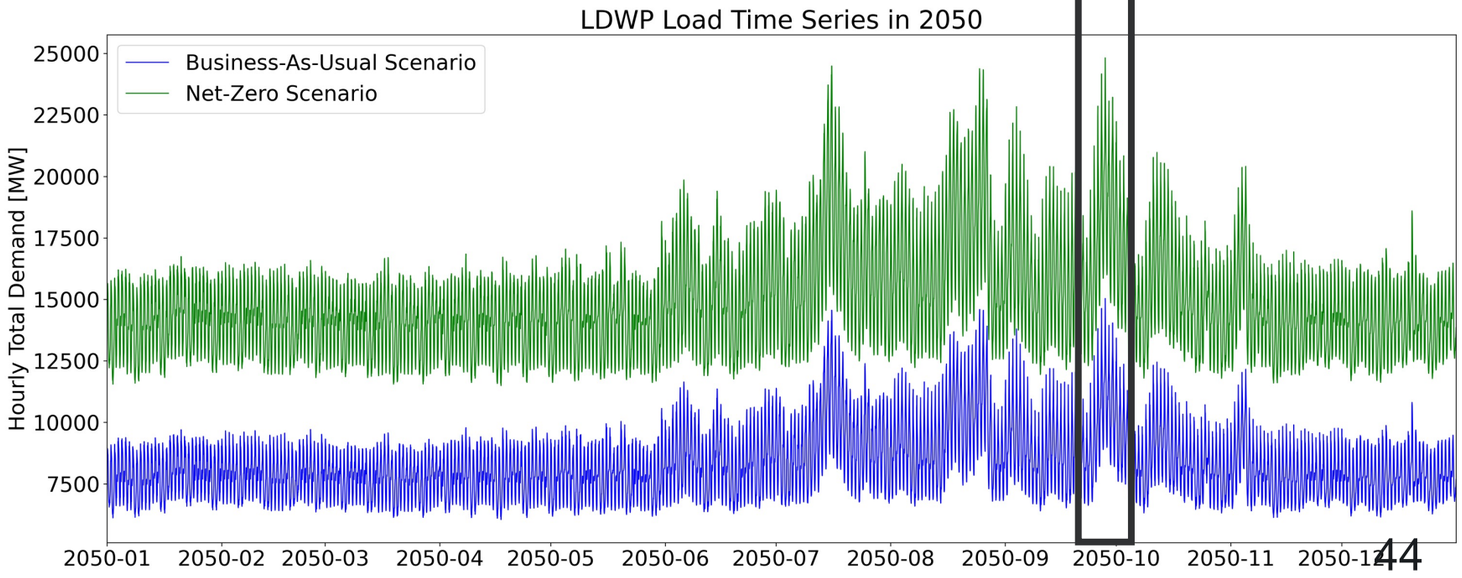
Result Snapshot: Hourly Load Time Series



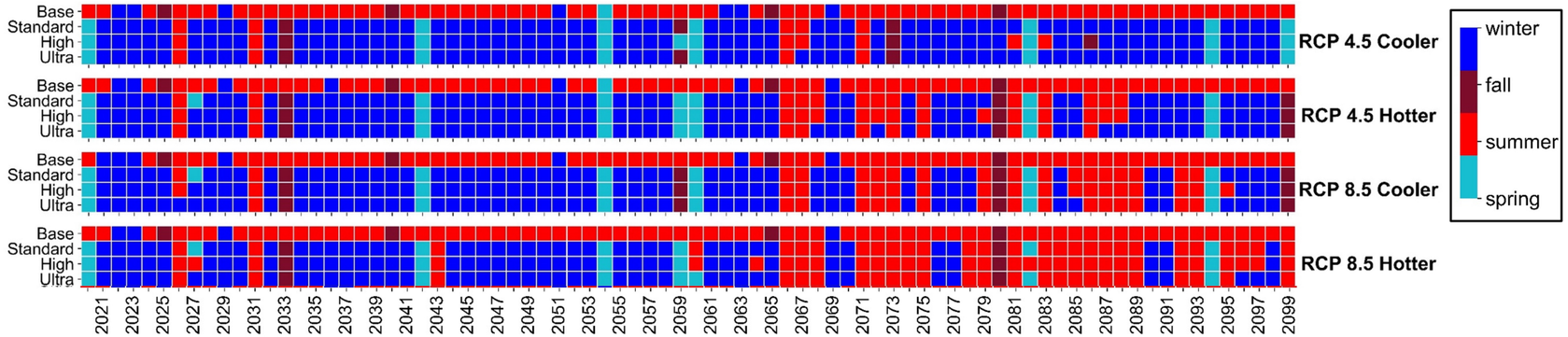




Acharya, S., C. Burleyson, et al., 2024: Weather sensitive high spatio-temporal resolution transportation electric load profiles for multiple decarbonization pathways. *2024 IEEE Power & Energy Society IGST Conference*, 1-5, doi:10.1109/ISGT59692.2024.10454229.

***Winner of the "Best Paper" award**

Not All Adaptations Are Good Adaptations



- Widespread electric heat pump adoption and climate change in Texas will increase uncertainty in seasonal peaking patterns and grid reliability.
- Future peaking behavior depends on the frequency and occurrence of extreme cold events and heat waves as well as the type of heat pumps widely adopted.

Ssembatya, H., J. Kern, K. Oikonomou, N. Voisin, C. Burleyson, and K. Akdemir, 2024: The dual impacts of space heating electrification and climate change drive uncertainties in peak load behavior and future grid reliability. In revision in *Earth's Future* – April 2024.

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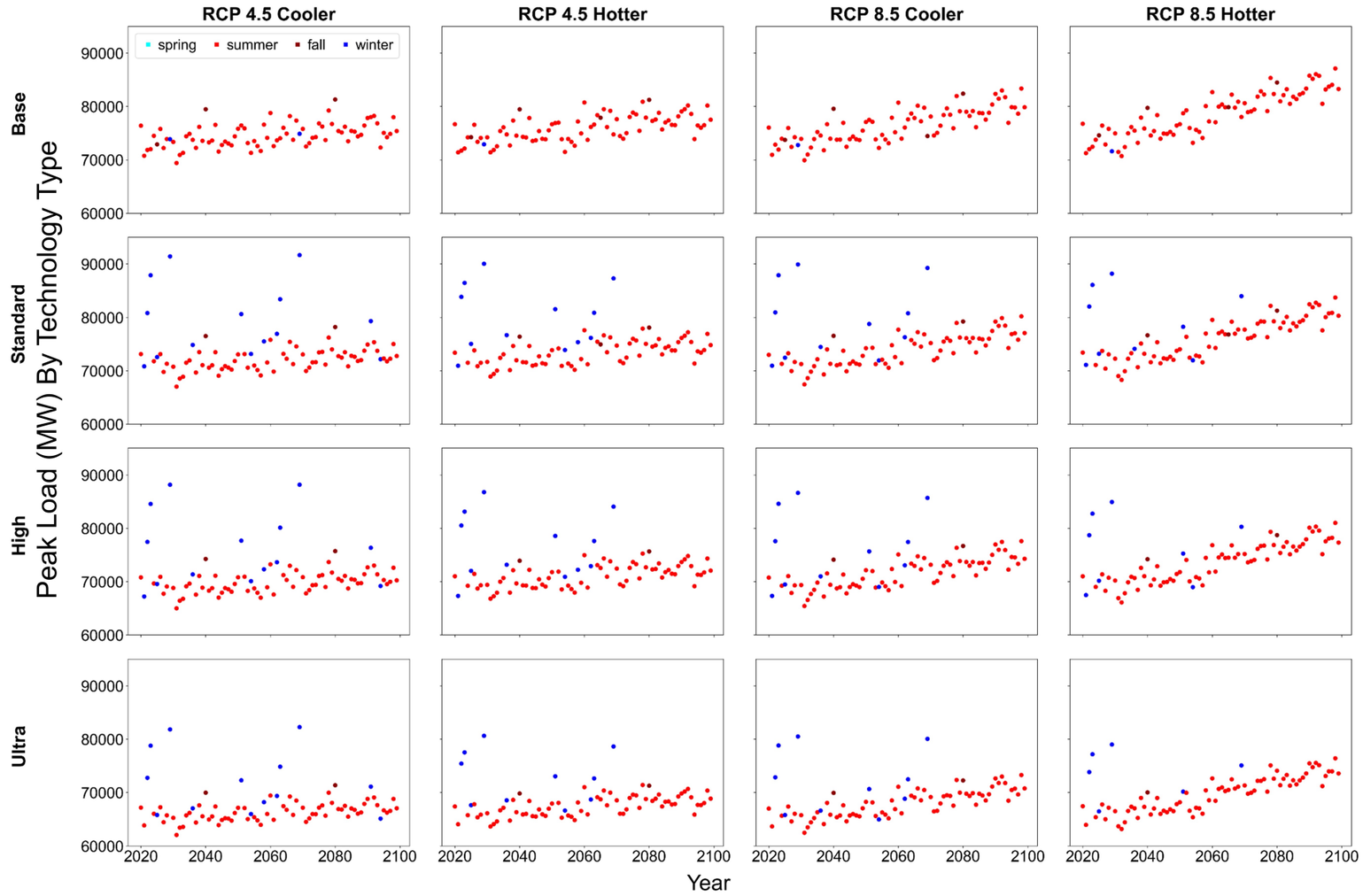

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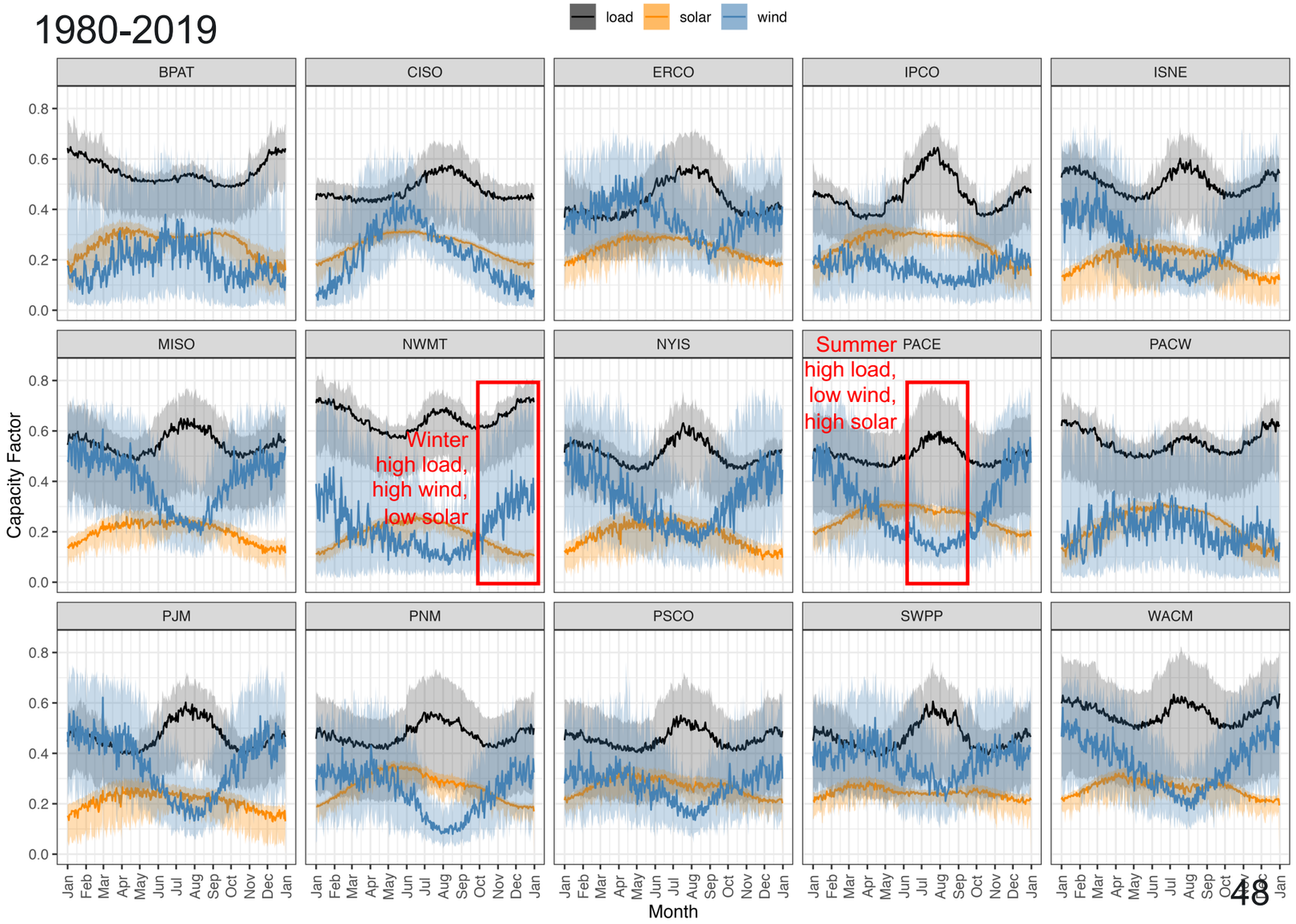
Chapter Three

How do heat waves impact electricity supply?

Wind, Solar, and Load Cycles Vary Depending on the Region and Season

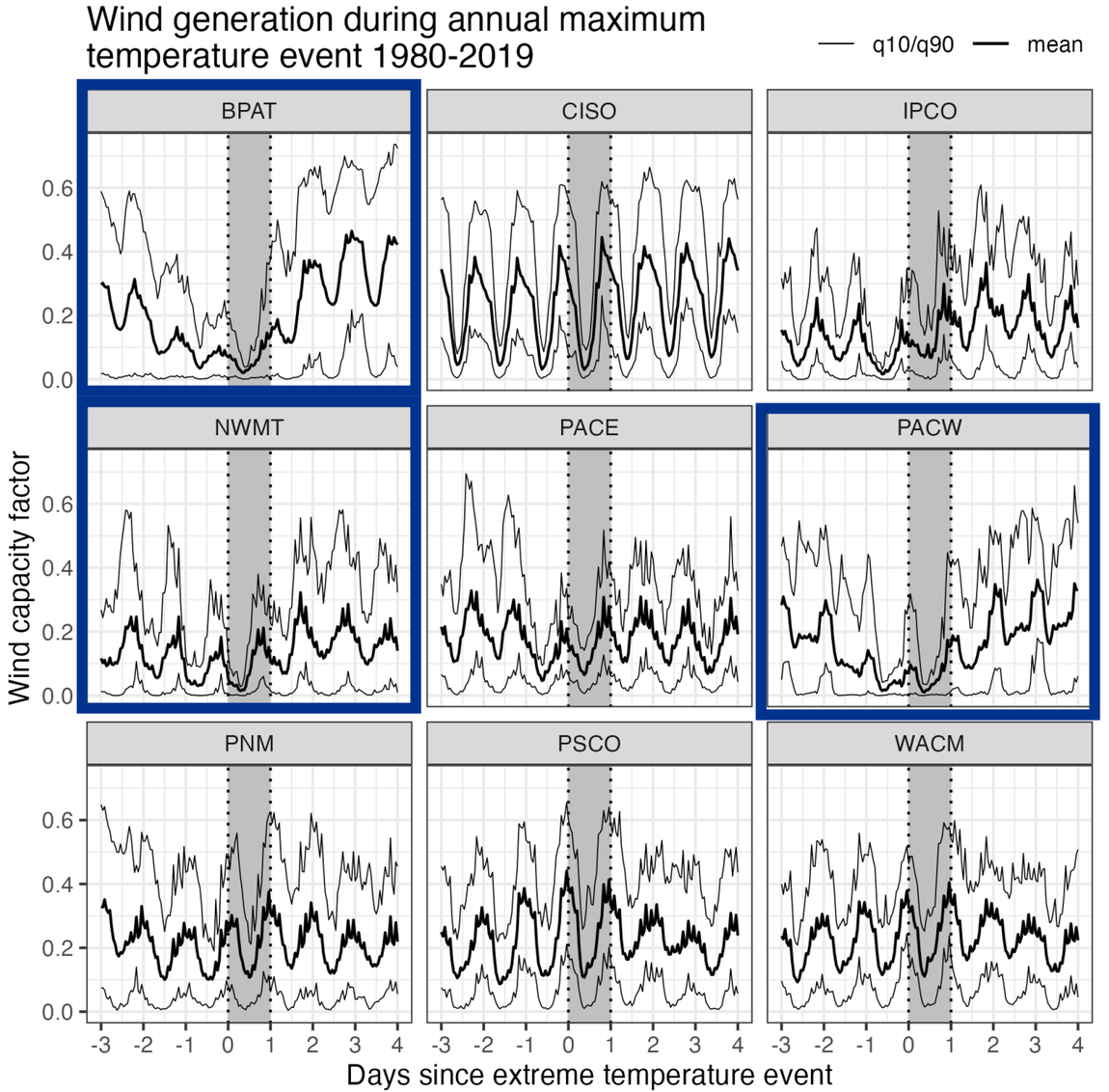
At the seasonal time scale, there is often complementarity between wind and solar generation potential during seasons of high loads.



Bracken, C., N. Voisin, C. Burleyson, A. Campbell, Z. Hou, and D. Broman, 2023: Standardized benchmark of historical compound wind and solar energy droughts across the continental United States. *Renewable Energy*, 220, doi:10.1016/j.renene.2023.119550.

Load and Wind Can Move in Opposite Directions During Heat Waves

BAs in the Pacific Northwest (e.g., BPAT, PACW, and NWMT) show notable suppression of wind generation during heat waves.



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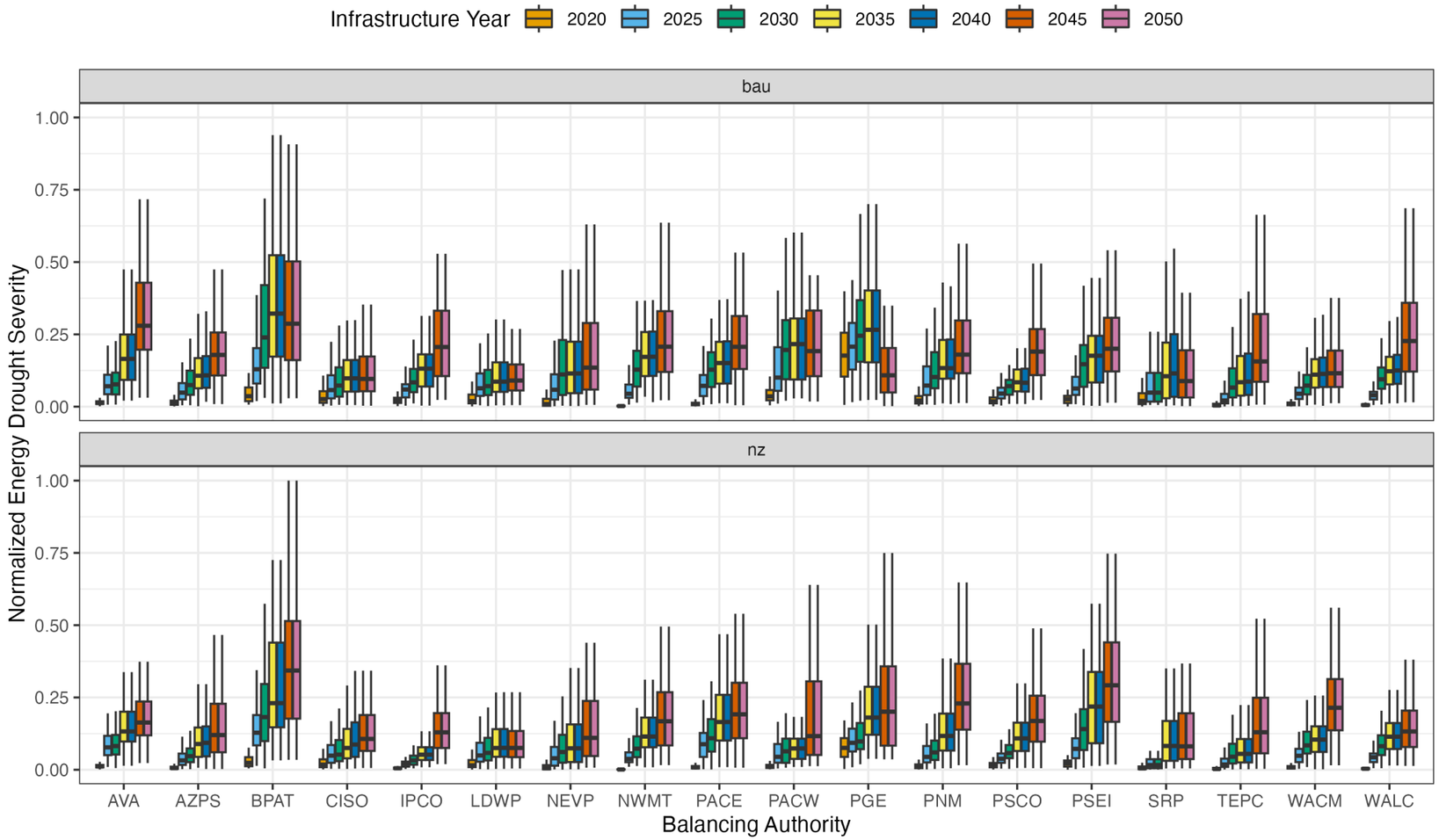
Wind and Solar Droughts Matter in a High-Renewables System

Most energy droughts are short, but some can last up to 3-5 days.

Bracken, C., N. Voisin, C. Burleyson, A. Campbell, Z. Hou, and D. Broman, 2023: Standardized benchmark of historical compound wind and solar energy droughts across the continental United States. *Renewable Energy*, 220, doi:10.1016/j.renene.2023.119550.

The Importance of Wind and Solar Droughts Will Increase in the Future

The relative severity of energy droughts is expected to increase due to increased capacity of renewables.



Bracken, C., et al., 2024: Future energy droughts. In preparation for *Renewable Energy*.

Chapter Four

How do we get information to the decision makers in time and in a useful format?

Getting the Word Out

Publish

- Anderson, O., and Coauthors, 2024: Improved decarbonization planning through climate resiliency modeling. Submitted to *Applied Energy*.
- Oikonomou, K., and Coauthors, 2024: Energy storage planning for enhanced resilience of power systems under extreme events. In preparation for *Applied Energy*.

Present

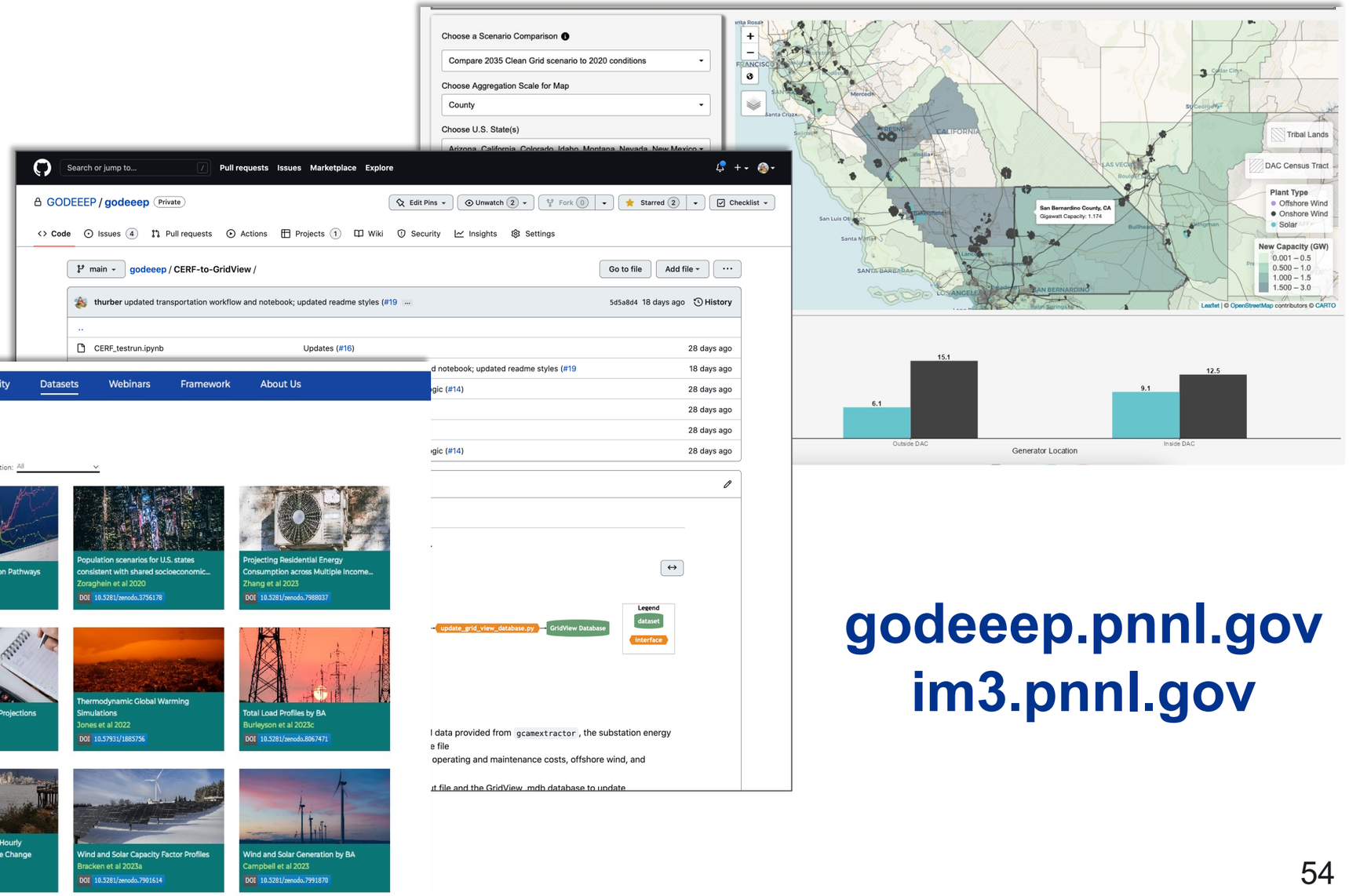
- Western Electricity Coordinating Council (WECC) Reliability Assessment Committee
- Pacific Northwest Utilities Conference Committee (PNUCC) Load Forecasting Workshop
- Electricity Systems Integration Group (ESIG) Technical Workshop
- Electric Power Research Institute (EPRI) Heat Waves Workshop
- Workshop on FERC Order 896 Transmission Planning Standard
- Invited presentations to Bonneville Power Authority, Salt River Project, Western Power Pool, Colorado Energy Office, Minnesota Energy Office

Serve

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

Sharing Data and Models

Open-source, vetted datasets and models are available in multiple formats in support of targeted questions by industry.



godeeep.pnnl.gov
im3.pnnl.gov

Advancing the Science of Stress Testing

- Testing using historical load-wind-solar-hydro data for a limited number of specific historical events
- Testing using data for a wide range of historical events
- Testing using data based on forcing from a single climate dataset
- Testing using data based on forcing from multiple climate datasets


EVERYTHING
EVERYWHERE
ALL AT ONCE

Acknowledgements

People

- Samrat Acharya, Kerem Akdemir, Cameron Bracken, Dan Broman, Allison Campbell, Malini Ghosal, Jason Hou, Jordan Kern, Zarrar Khan, Misha Kulshresta, Gokul Iyer, Casey McGrath, Kendall Mongird, Aowabin Rahman, Jennie Rice, Abhishek Somani, Henry Ssembatya, Travis Thurber, Kostas Oikonomou, Yang Ou, Chris Vernon, Nathalie Voisin

Projects

- Integrated Multisector Multiscale Modeling (IM3)
- Grid Operations, Decarbonization, Environmental and Energy Equity Platform (GODEEEP)
- National Transmission Planning Study (NTPS)
- North American Energy Resilience Model (NAERM)
- North American Electric Reliability Corporation (NERC)
- West Coast Offshore Wind Transmission Study (WOW-TS)

Key Messages and Results

- To assess the resilience and reliability of the bulk power system, it is critical to evaluate system performance with coincident load-wind-solar-hydro conditions and across a wide range of historical and projected weather conditions.
- The conditions that stressed the system in the past will not be the ones that stress the system in the future. It is important to consider isolated, compounding, and sequential extreme events.
- PNNL innovations:
  - Open-source spatially- and temporally-coincident load, wind, and solar data
  - Capture consistent and realistic impacts on electricity supply and demand for use in stress testing projected infrastructure
  - Quantitative characterization of wind and solar droughts
- Come join us!