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ON CLIMATE- AND EQUITY-INFORMED RESILIENT GRID PLANNING

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DEEP DIVE ONE: Decarbonization and Climate Impacts on Hourly Electricity Load Projections

Hosted by: Stephanie Waldhoff
Expert Panelists: Casey Burleyson, Malini Ghosal, Yang Ou
June 26, 2023



PNNL

Grid Resilience @ PNNL – GODEEEP Webinar Series

Decarbonization and Climate Impacts on Hourly Electricity Load Projections

Casey Burleyson, Malini Ghosal, Yang Ou,

and the GODEEEP team

June 26, 2023

Pacific Northwest NATIONAL LABORATORY

GODEEEP Grid Operations, Decarbonization, Environmental and Energy Equity Platform @PNNL

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

https://godeeep.pnl.gov/

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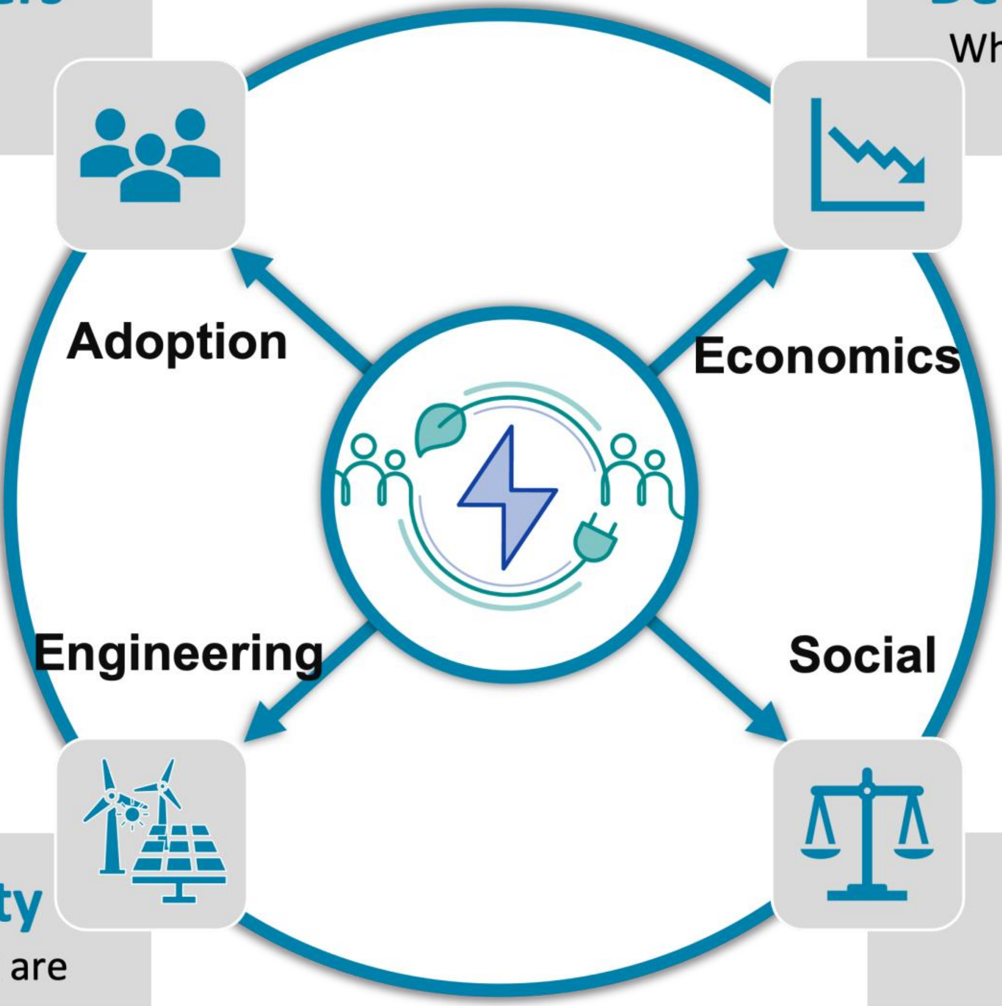
GODEEEP Grid Operations, Decarbonization, Environmental and Energy Equity Platform @PNNL

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

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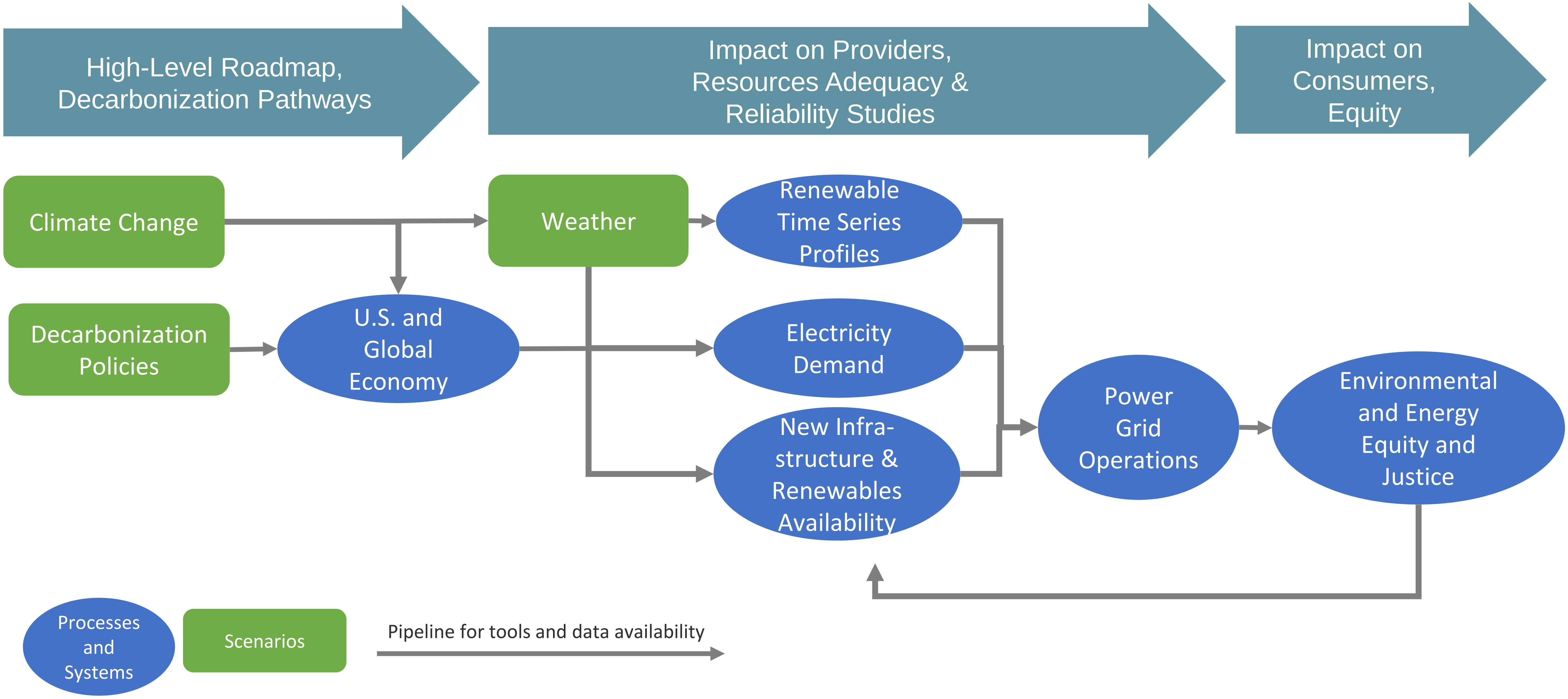
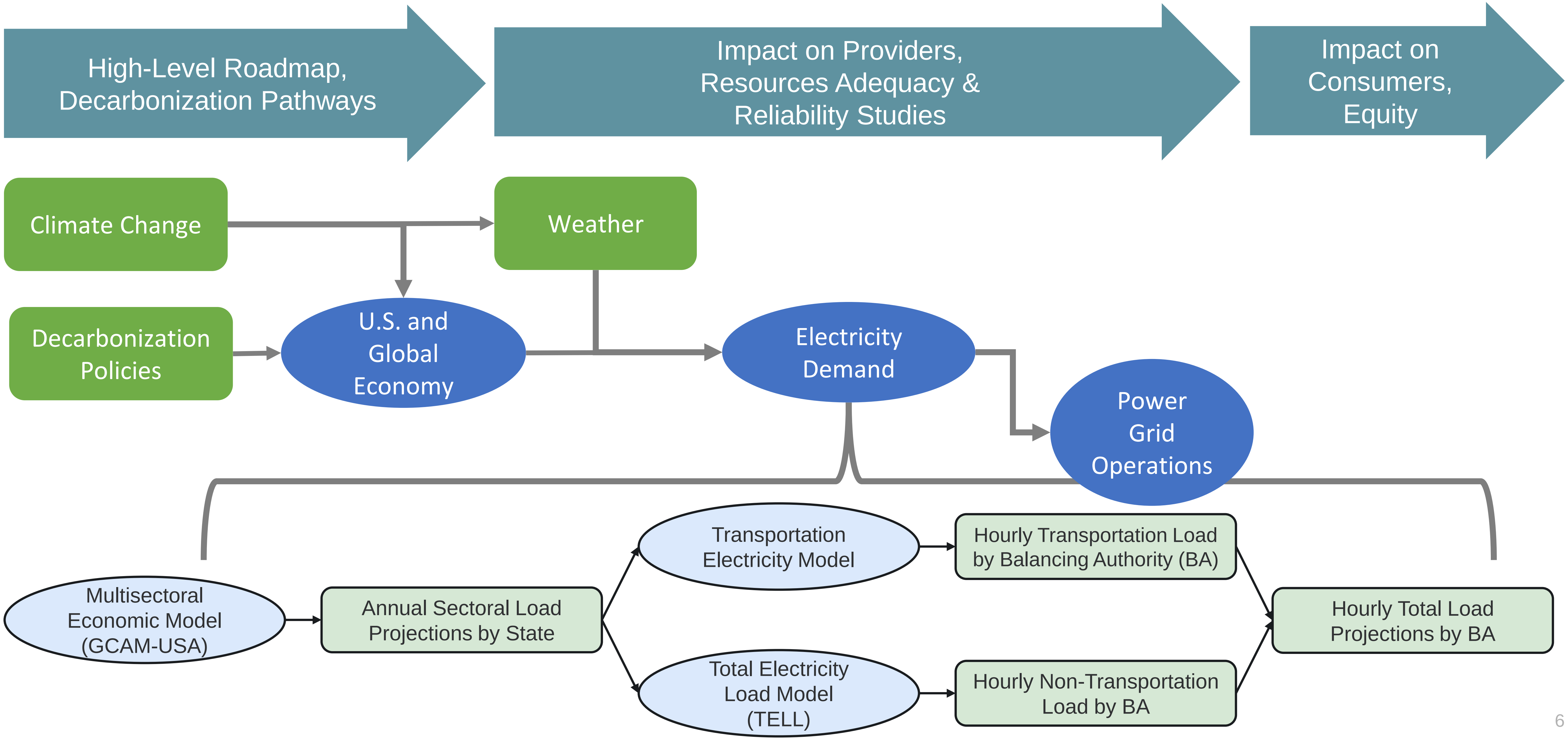
Consistent, open-source, end-to-end framework with intermediate datasets and tools for flexible customization

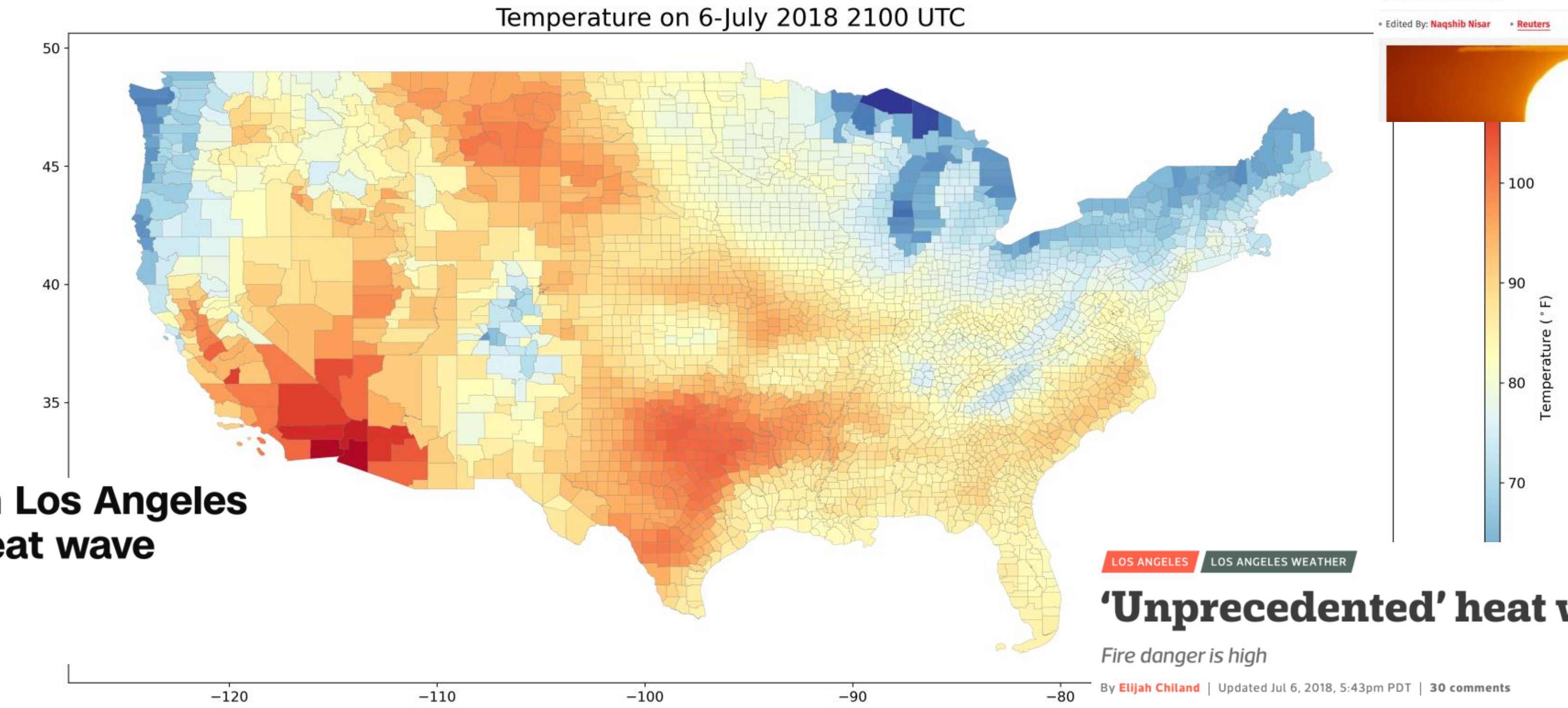


Climate and decarbonization impacts on hourly load projections



Example use cases

- Projecting hourly electricity supply and demand for system reliability studies
  - Example: Heat wave and cold snap impacts
  - Example: System reliability with high renewables penetration and/or low hydro
  - Example: Assessing climate change impacts on the future grid
- Exploring load profile shifts with electrified transportation and heating (i.e., super duck curves?)
- Creating baseline systems projections that can be used to understand the impact of new transmission corridors



Records Broken as Heat Wave Bakes Southern California

• Edited By: Naqshib Nisar • Reuters • Last Updated: JULY 07, 2018, 12:56 IST

High temperatures will exceed 100 degrees Fahrenheit (37 Celsius) in Los Angeles and San Diego on Saturday, the National Weather Service said in a series of excessive heat warnings and advisories.

Thousands without power in Los Angeles after high demand due to heat wave

By Dakin Andone, CNN
Updated 8:19 PM EDT, Sat July 7, 2018

LOS ANGELES | LOS ANGELES WEATHER

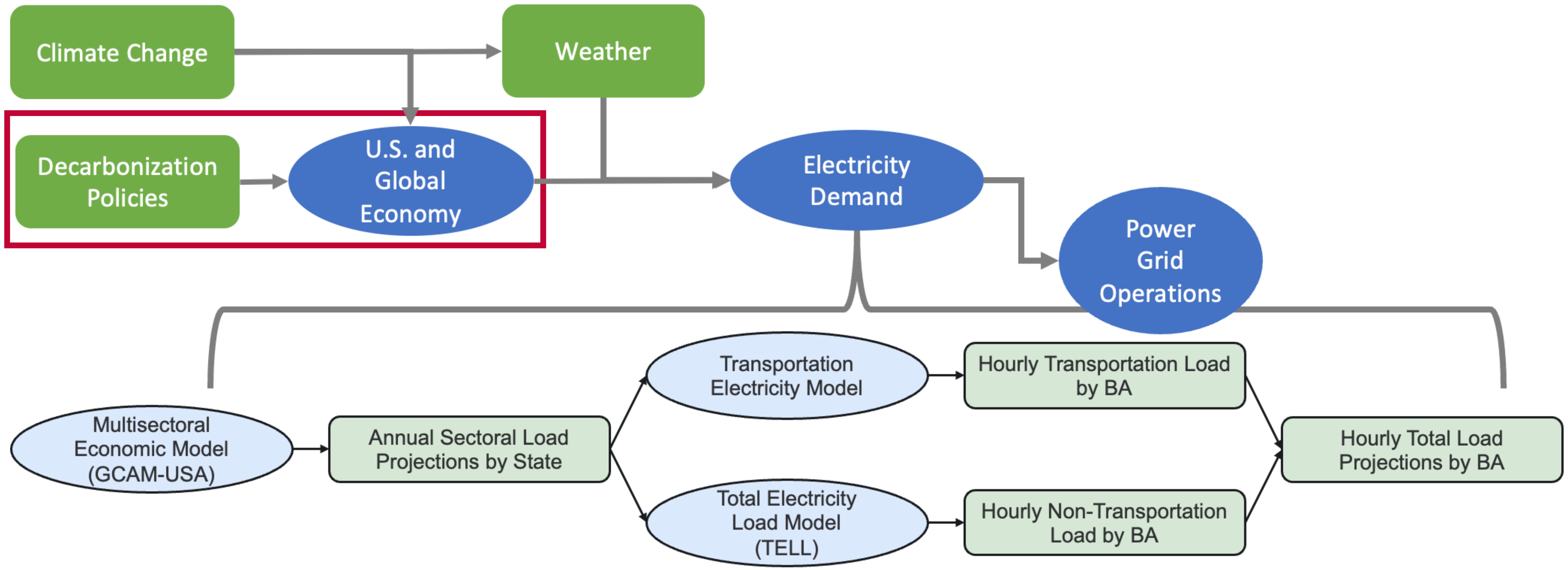
'Unprecedented' heat wave sets new records

Fire danger is high

By Elijah Chiland | Updated Jul 6, 2018, 5:43pm PDT | 30 comments

Global Change Analysis Model with U.S. state-level representation (GCAM-USA)

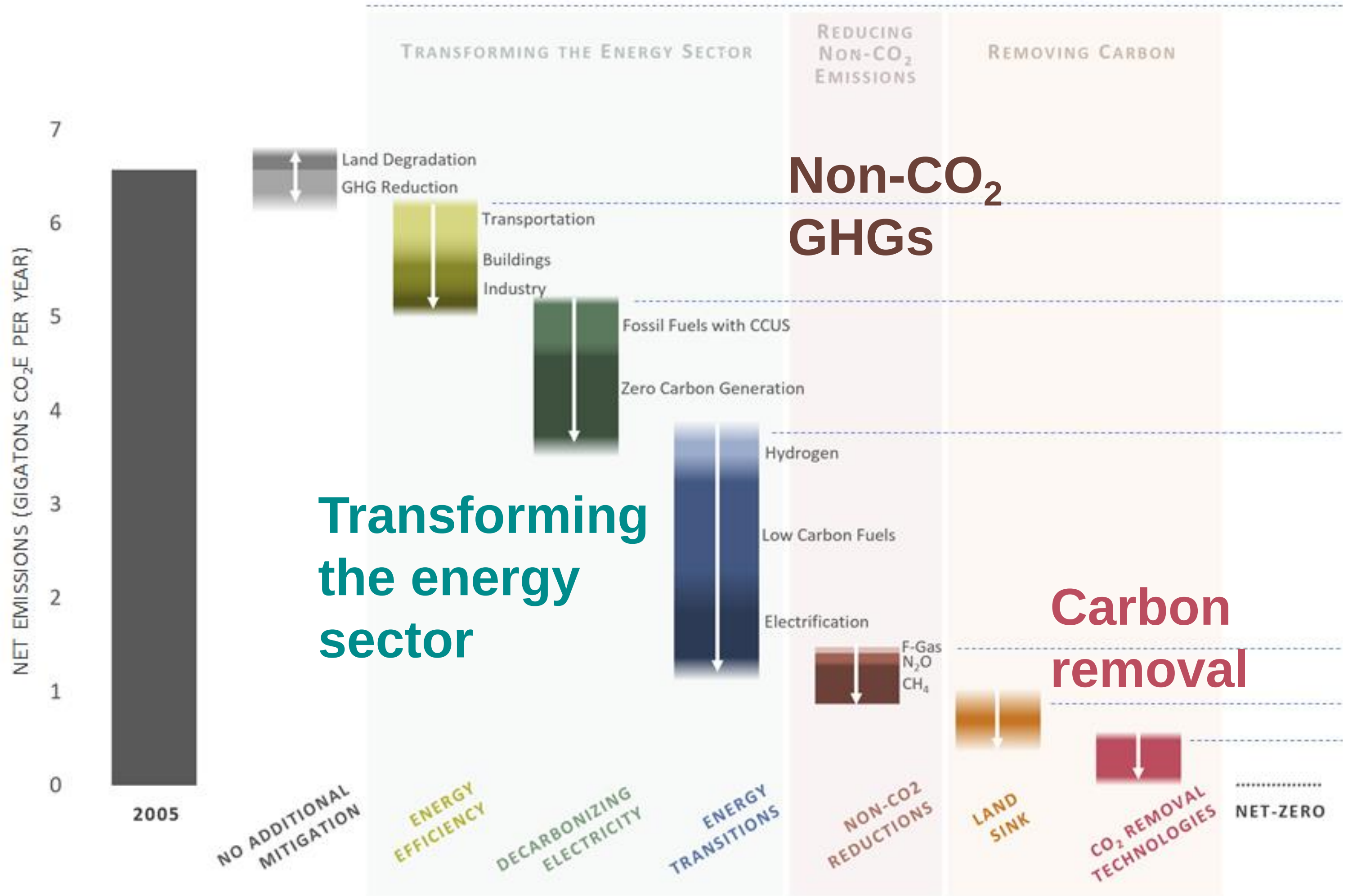
- GCAM-USA provides a “boundary-condition” of the long-term transitions towards net-zero, such as energy demand and fuel mix across sectors and states
- GCAM-USA’s long-term projection will help drive utility-grade grid operations models to translate the large-scale projections into “on the ground” realizations of future grids, with quantifiable measurements of grid operations reliability and resilience



Using GCAM-USA to model economy-wide net-zero greenhouse gas (GHG) pathways

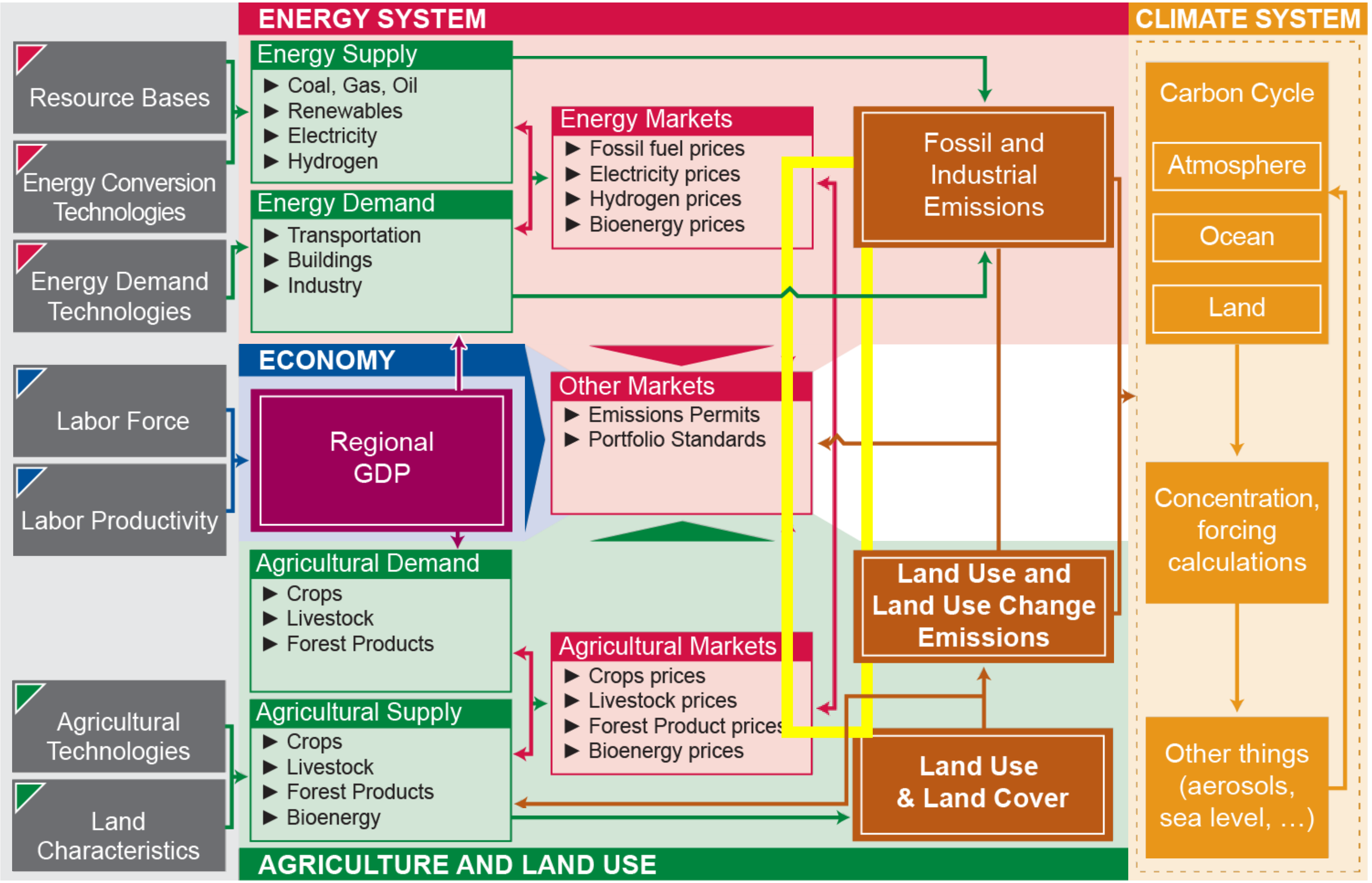
- Achieving net-zero entails **economy-wide** transitions, such as unprecedented electric capacity expansion
- Electricity load is sensitive to many factors (demand, climate, economics, fuel prices, etc.)
- A holistic understanding of electricity generation and demand is important to understand the **co-evolution** of cross-sector dynamics
- GCAM-USA endogenizes cross-sector linkages, such as energy flow, energy prices, food prices, water, and land
- GCAM-USA models a full suite of greenhouse gases (CO_2, methane, F-gases)

Representative Pathway to 2050 Net Zero GHG

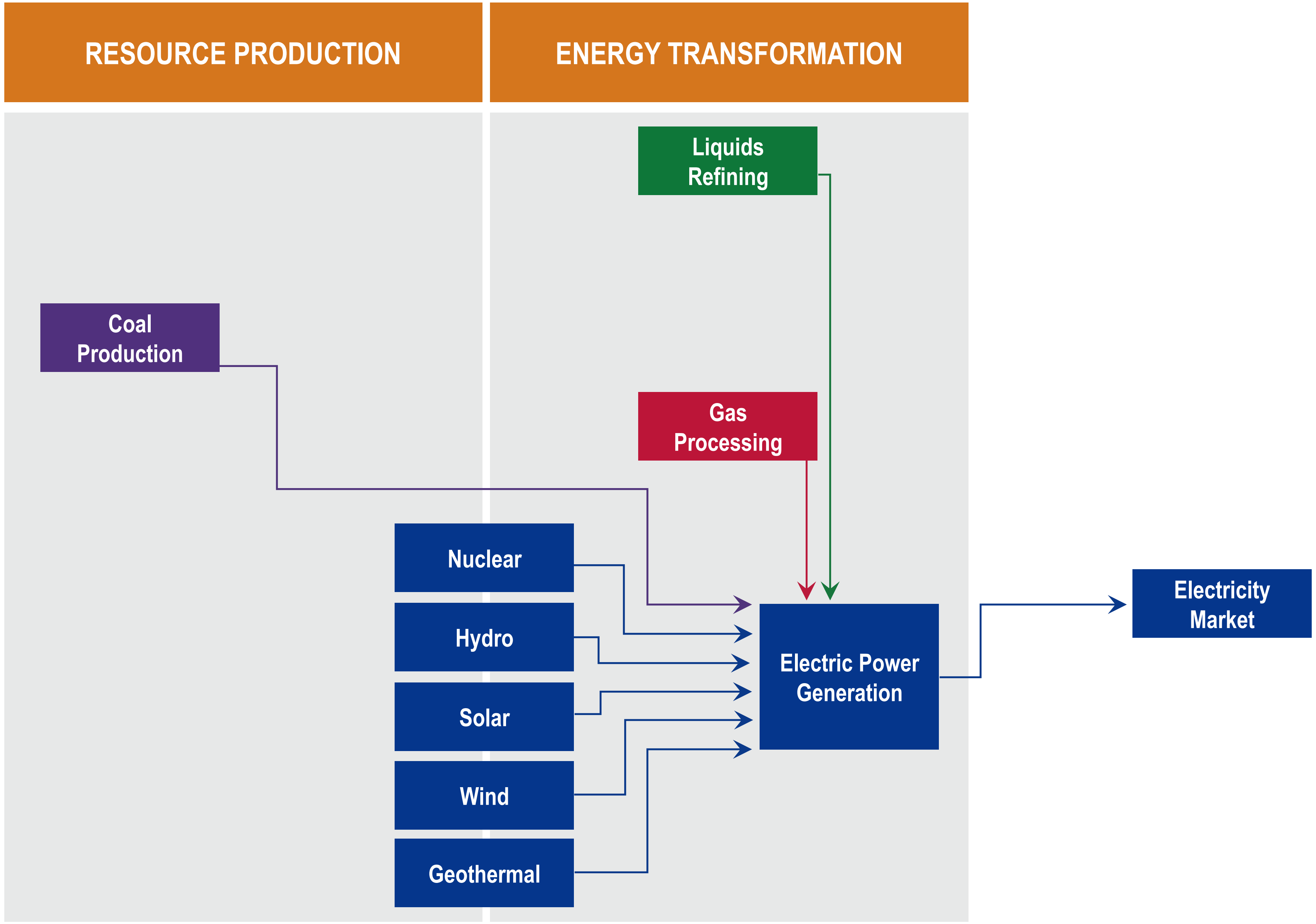


Source: US Long-Term Strategy, 2021

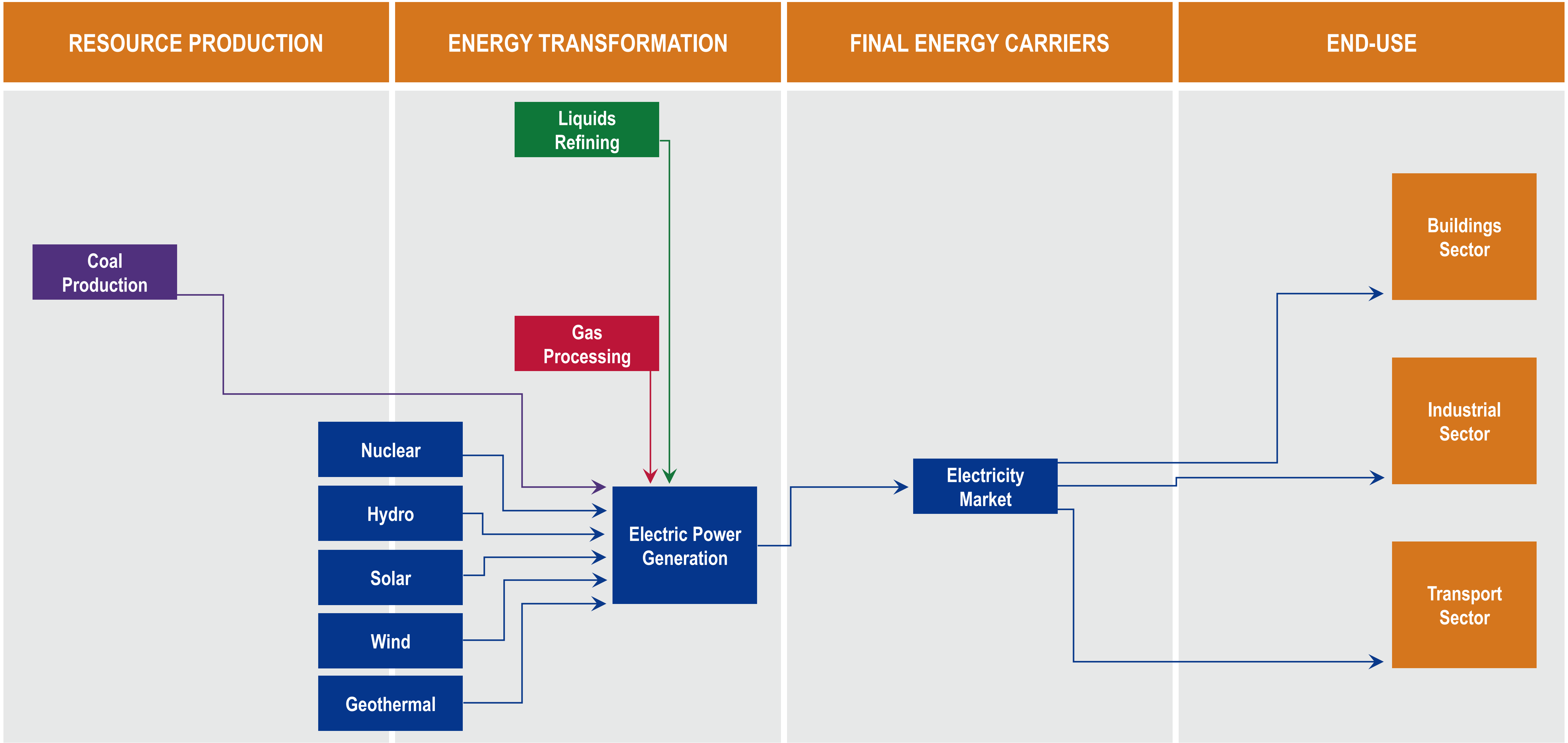
GCAM-USA links economic, energy, land-use, water, and climate systems



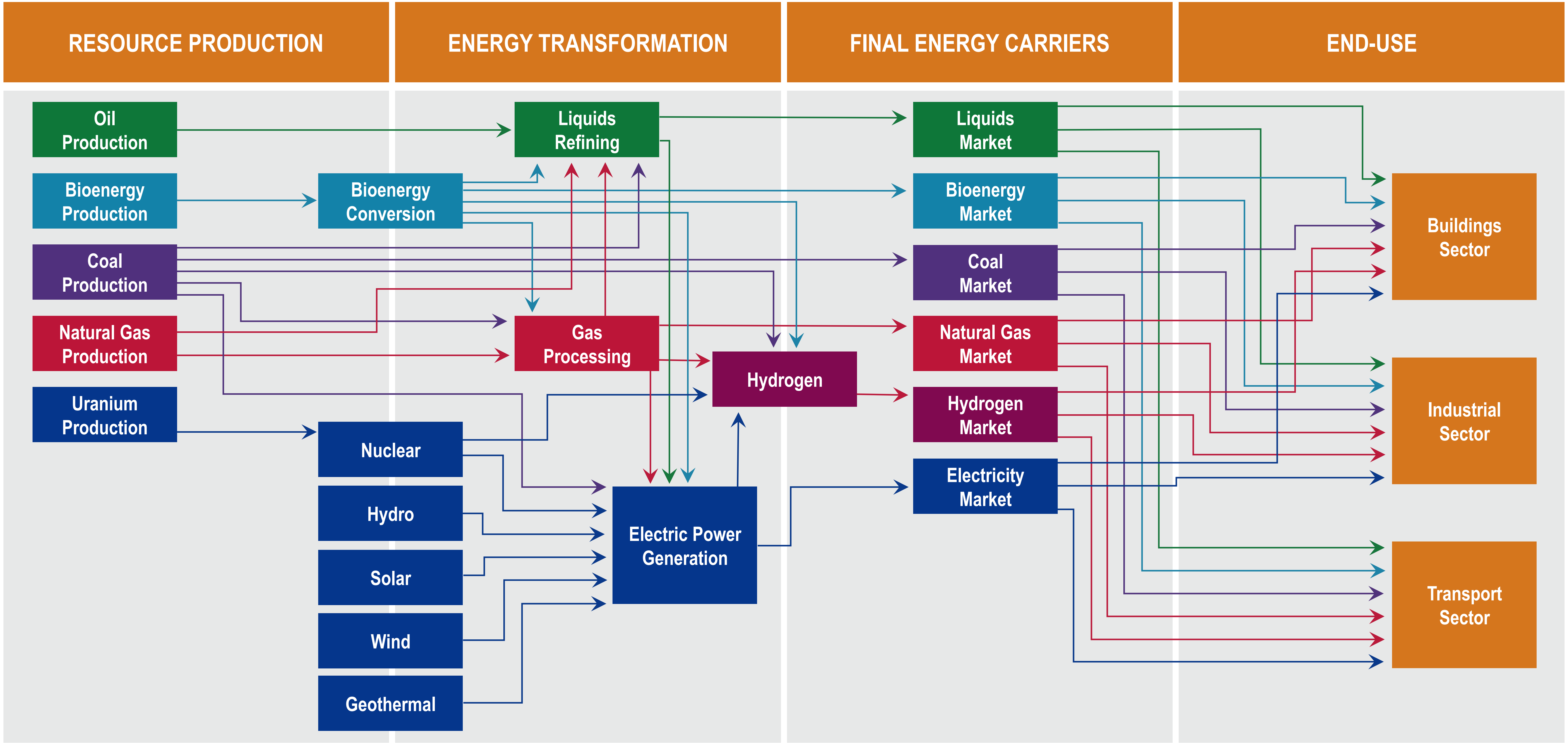
Electricity supply modeling



Electricity supply and demand modeling

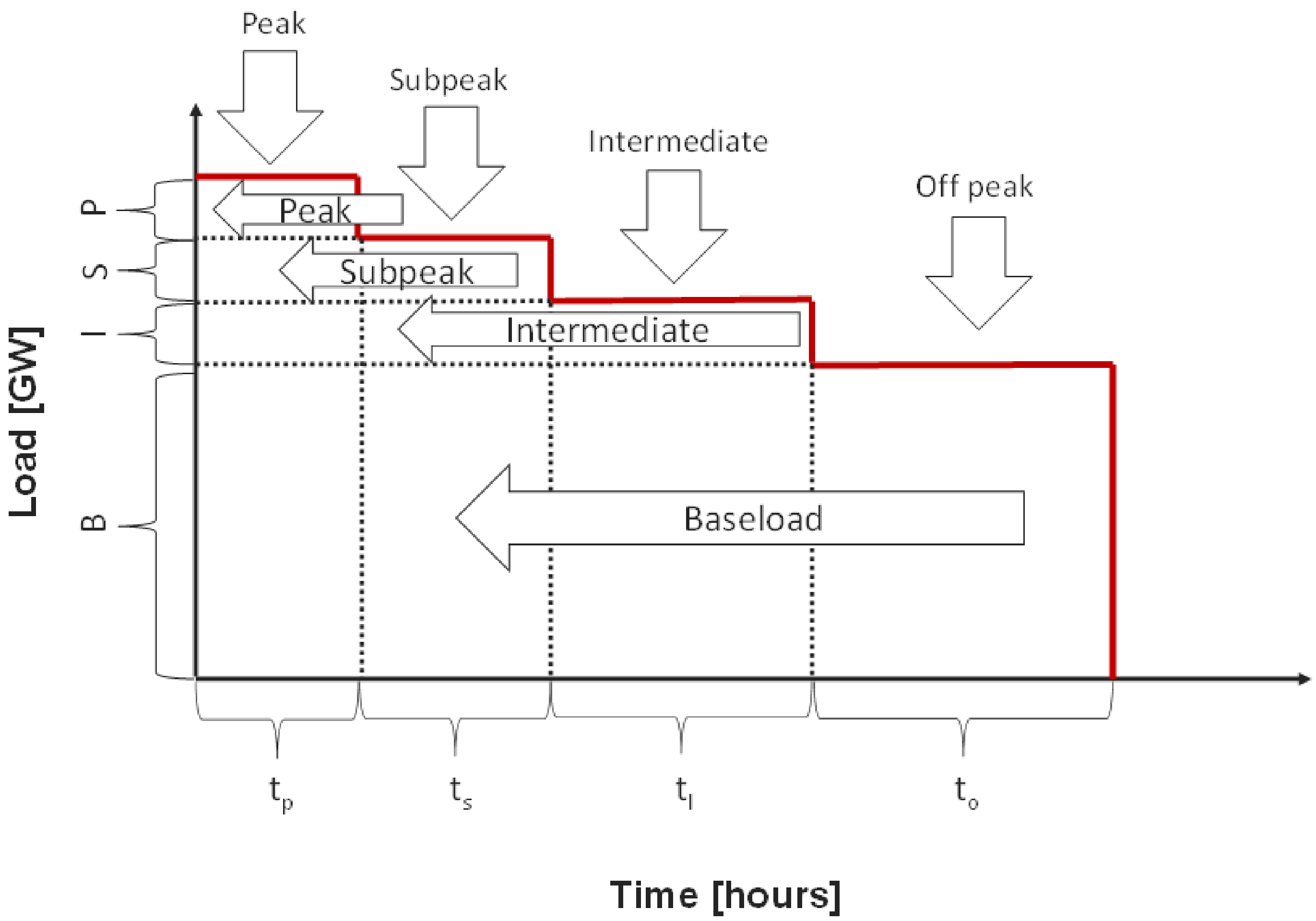


Full energy system representation



GCAM-USA's electricity sector

- Electricity supply broken out into four sectors (load duration curve segments) to capture intra-annual variation of electricity demand

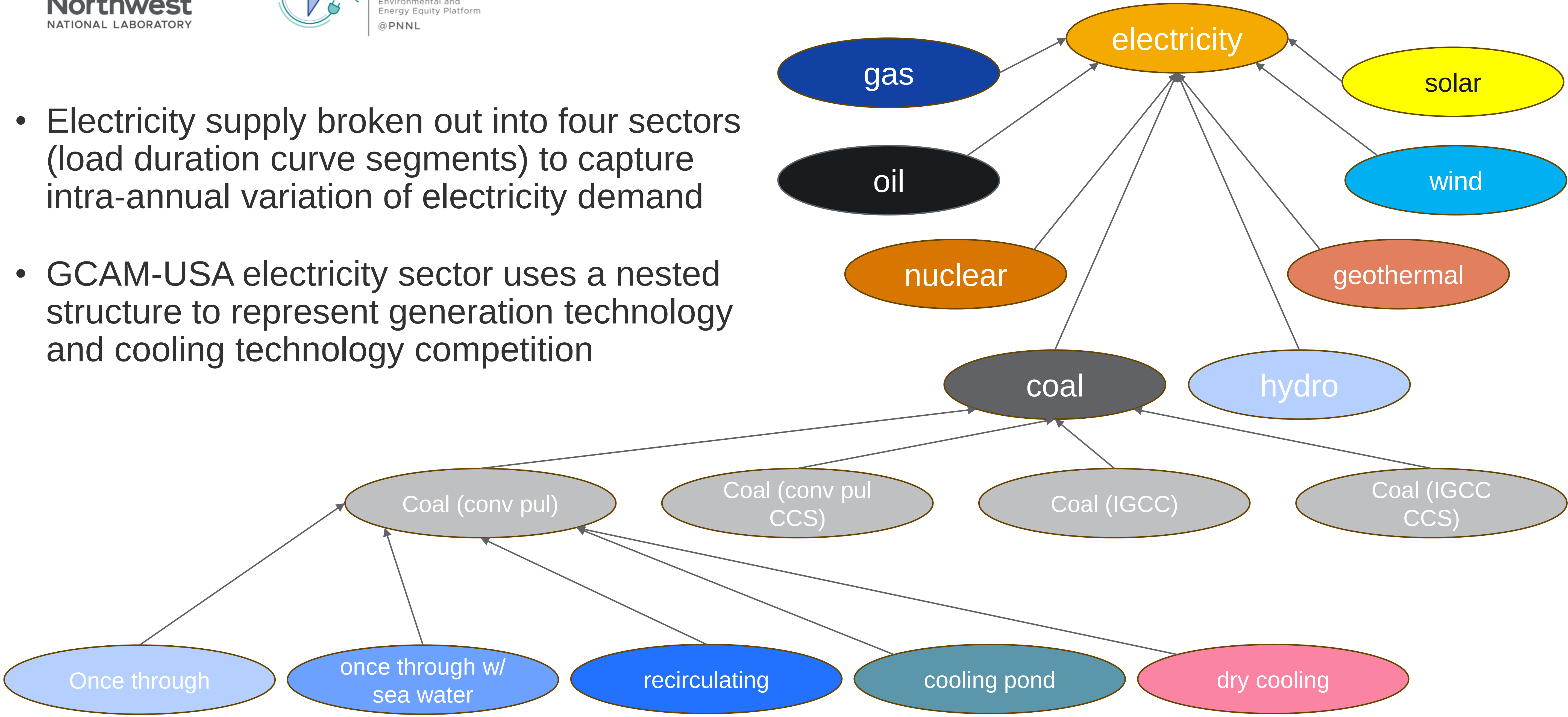


Sub-annual load profiles

GCAM-USA's electricity sector

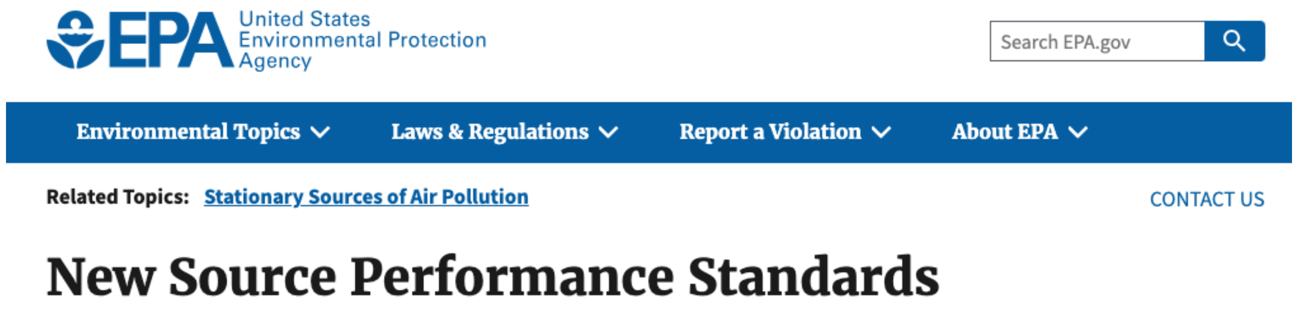
- Electricity supply broken out into four sectors (load duration curve segments) to capture intra-annual variation of electricity demand

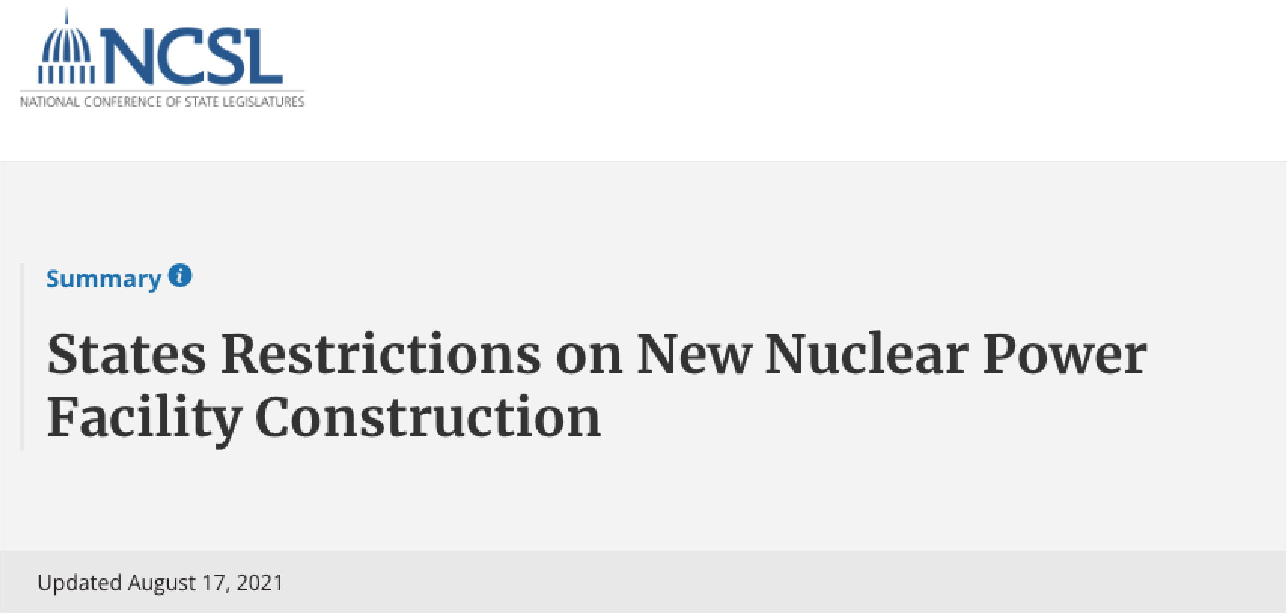
- GCAM-USA electricity sector uses a nested structure to represent generation technology and cooling technology competition



GCAM-USA's electricity sector

- Electricity supply broken out into four sectors (load duration curve segments) to capture intra-annual variation of electricity demand
- GCAM-USA electricity sector uses a nested structure to represent generation technology and cooling technology competition
- Fuel mix
  - No new coal generation without CCS, consistent with Clean Air Act Section 111 (b) New Source Performance Standards
  - State-specific coal and nuclear power retirement pathways based on announced retirements and fleet age-structure





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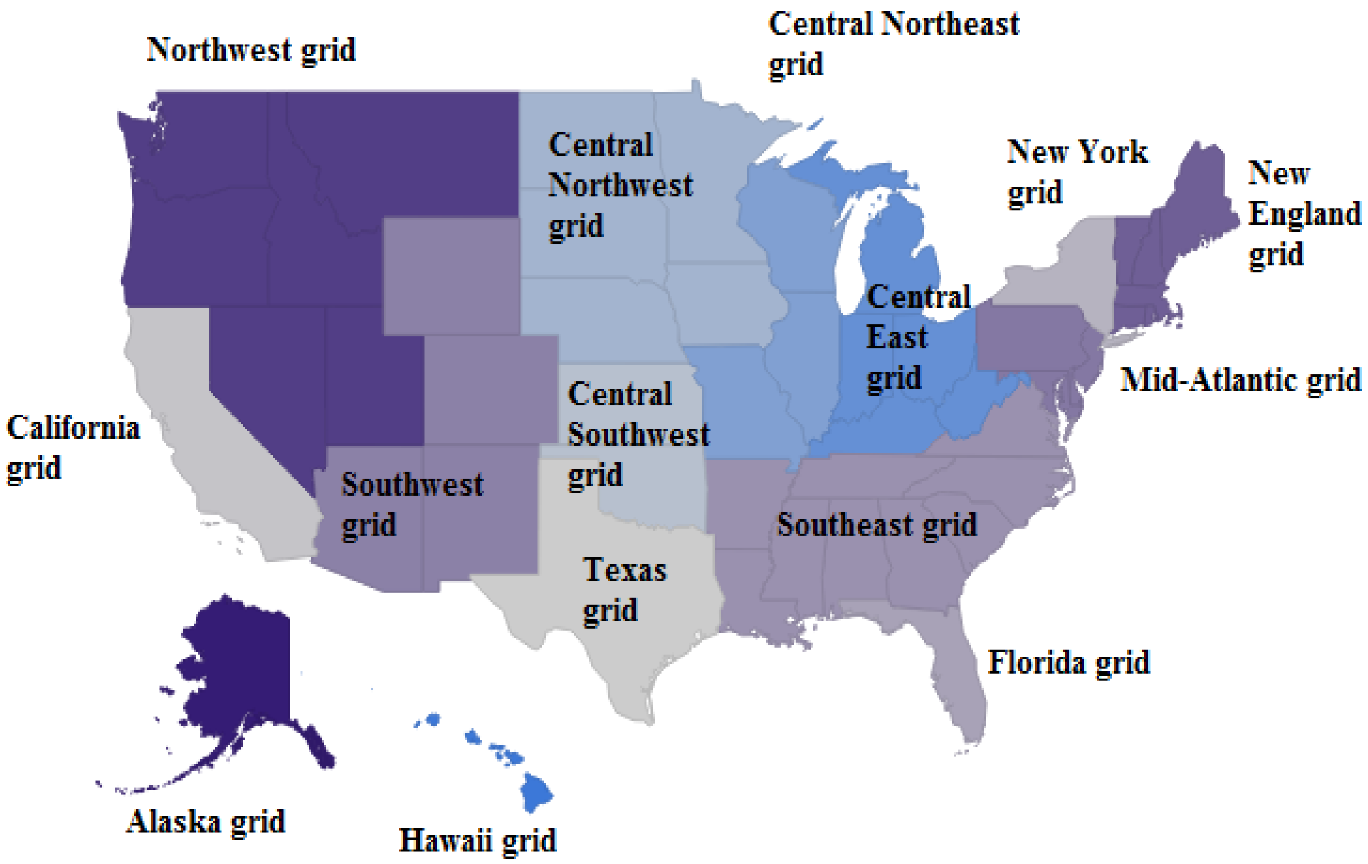
- Electricity trade in fifteen grid (NERC) regions

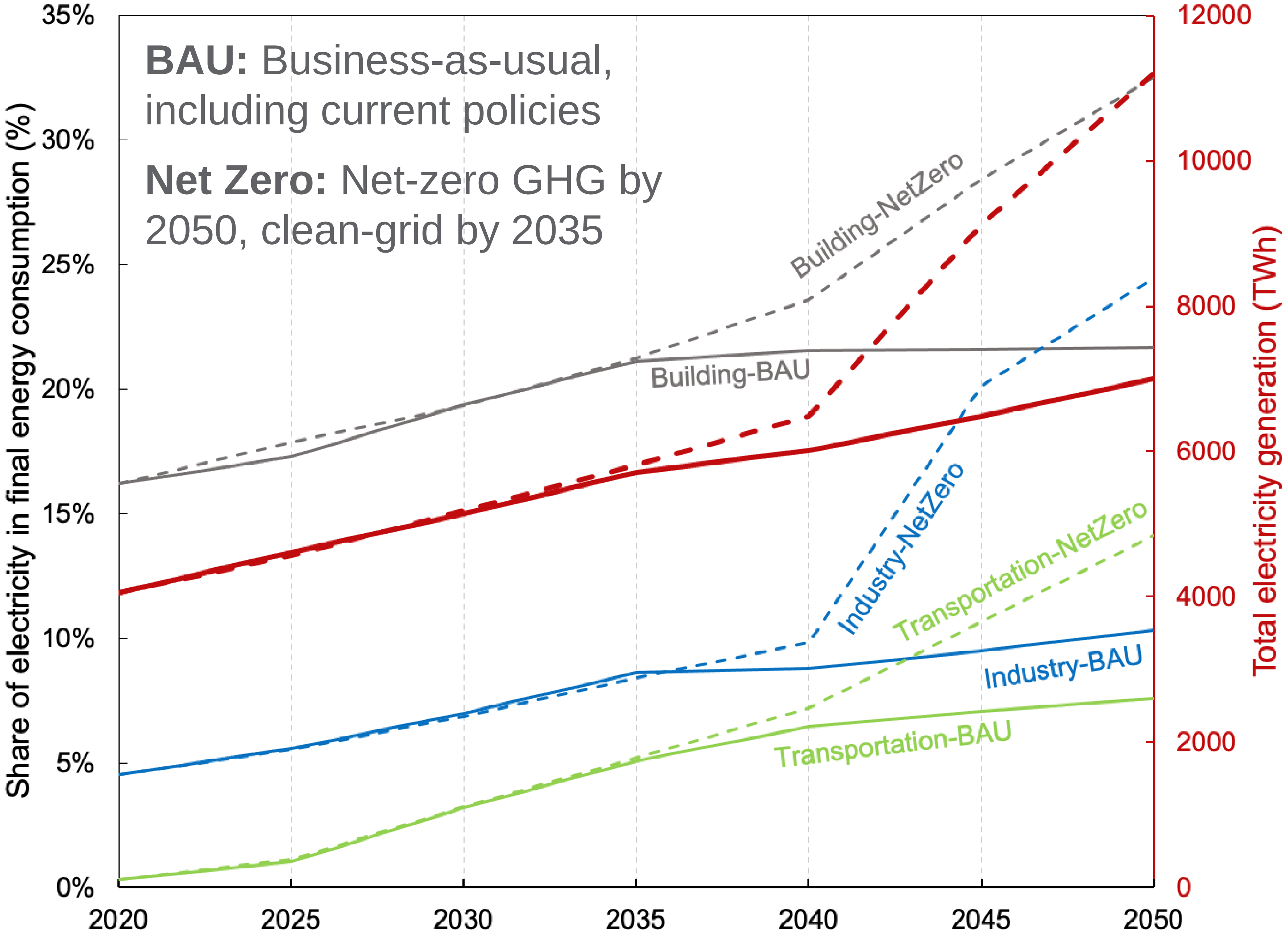


Grid regions are consistent with NERC regions

NERC: North American Electric Reliability Corporation

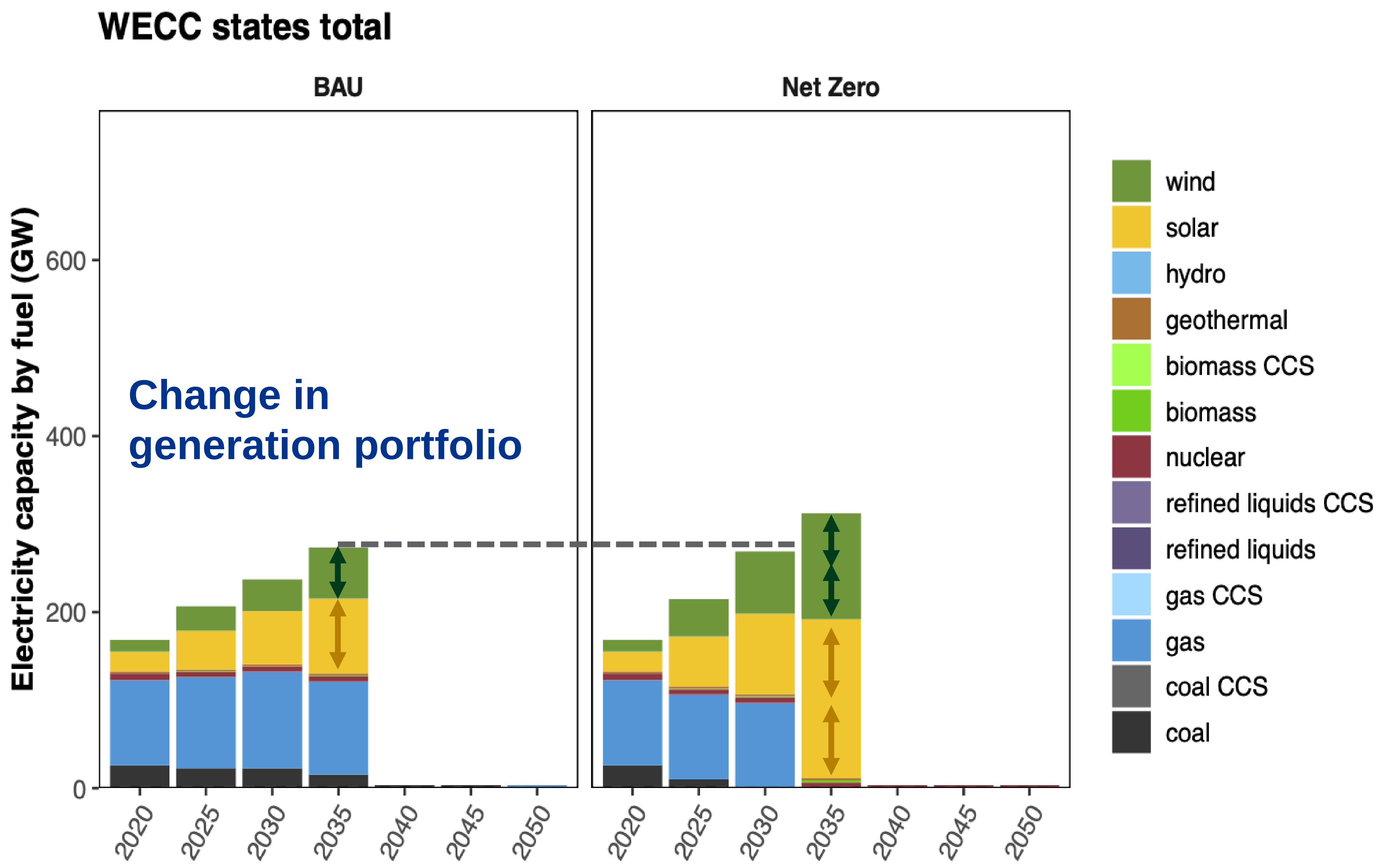
GCAM-USA's projection of the co-evolution of electricity demand and electricity generation

Electricity Demand



Electricity Generation

Current policies are not enough to achieve net-zero emission by 2050



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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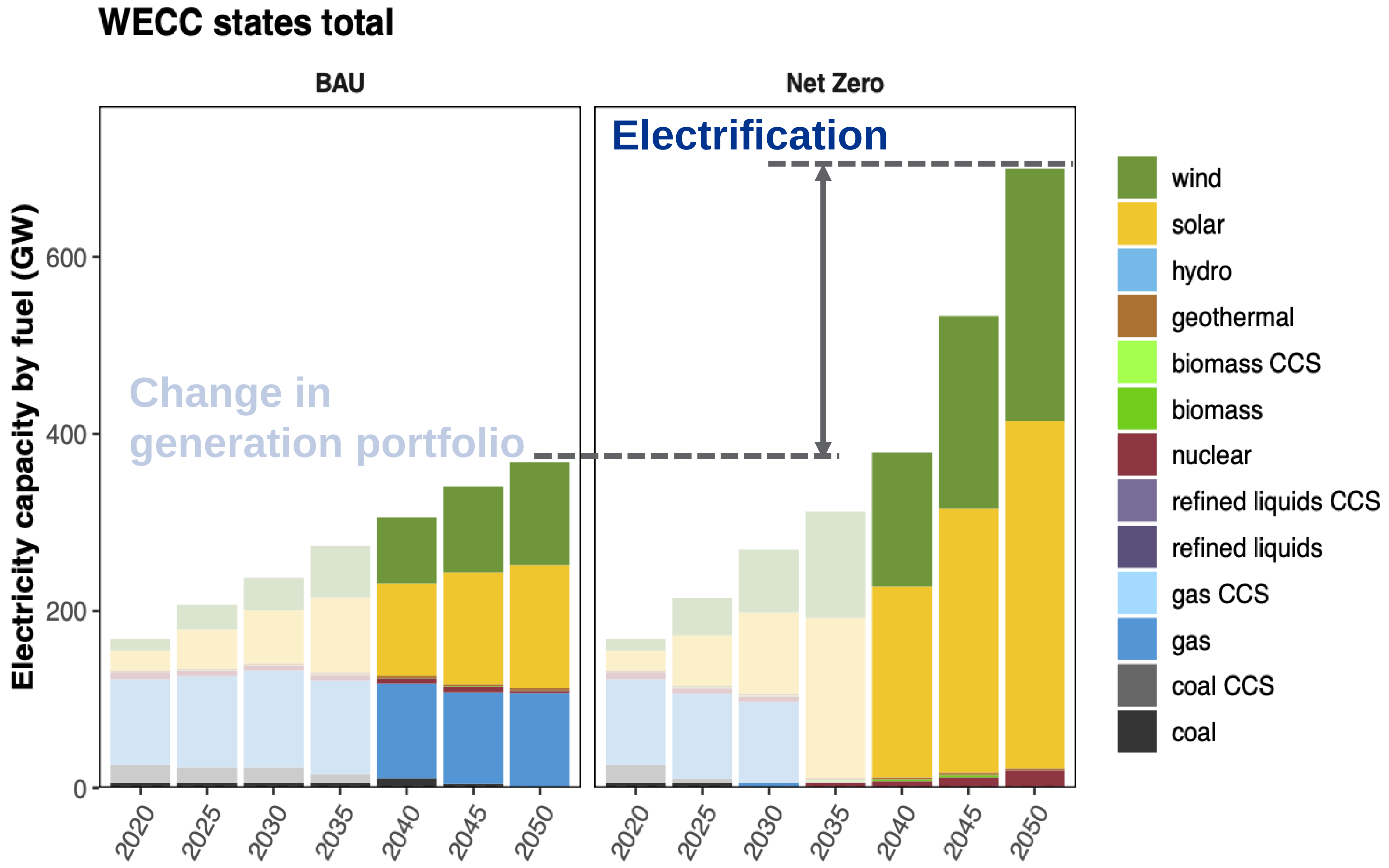

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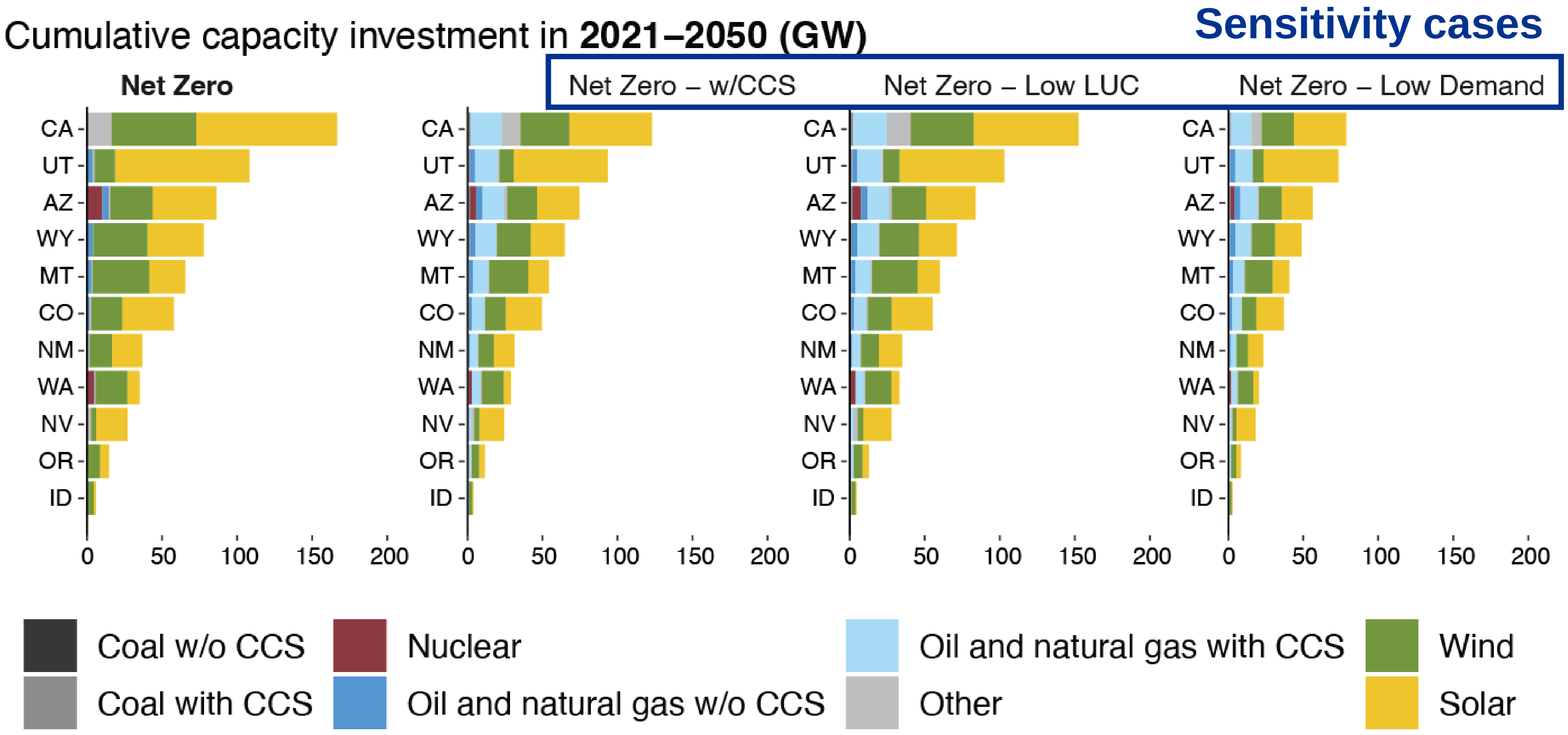
Capacity investment in response to uncertainties in net-zero pathways



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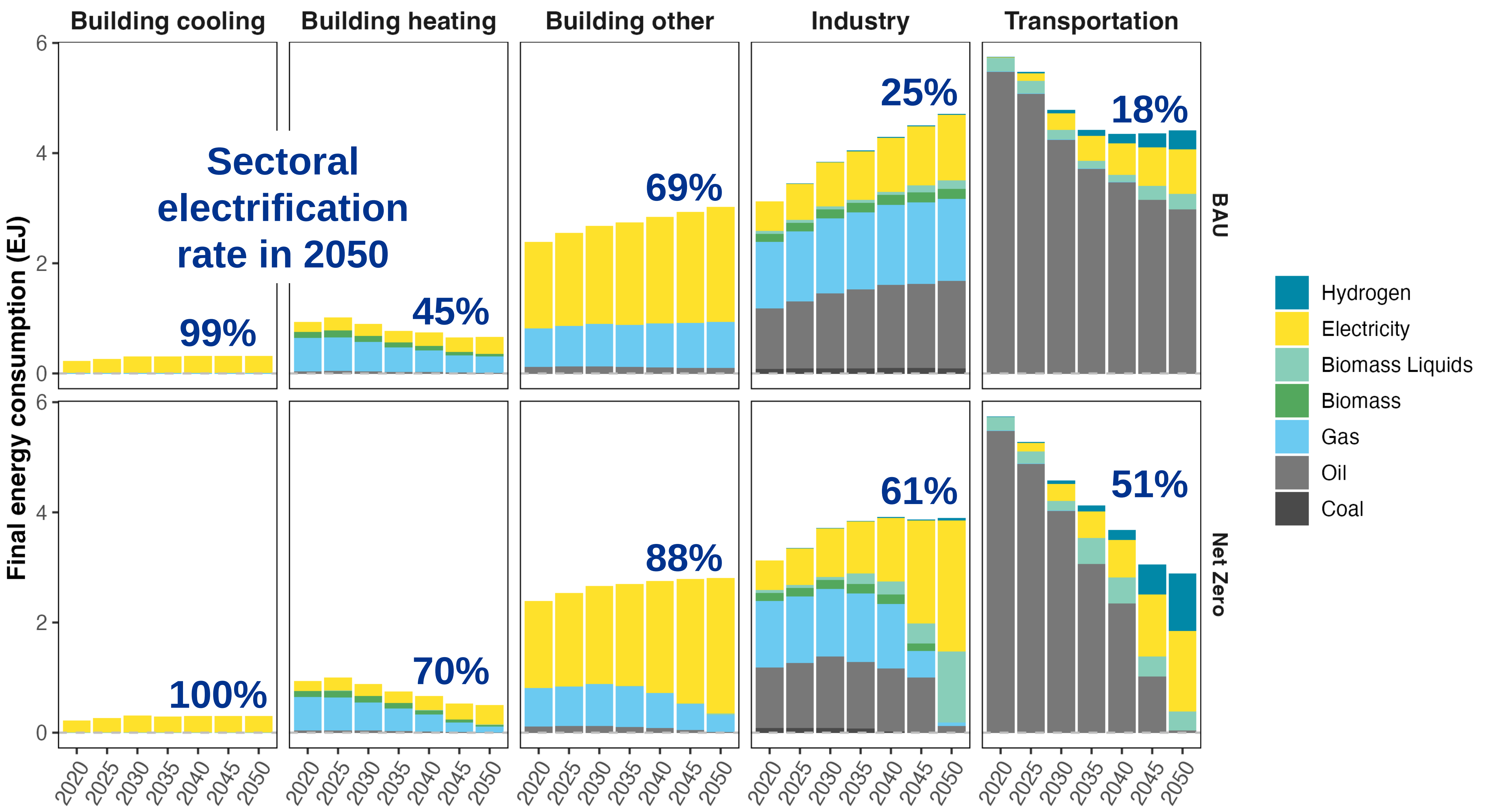
Clean-energy transition across demand sectors



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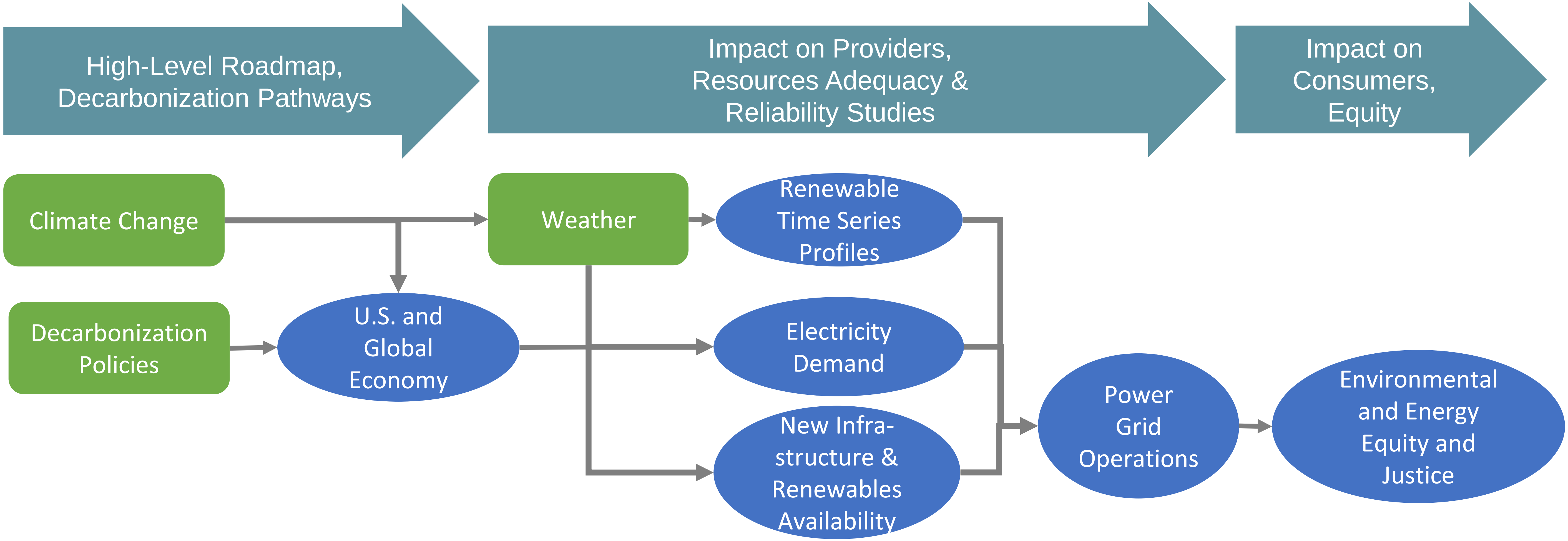
Short Q&A

Bridging the gap from scenarios to power systems models

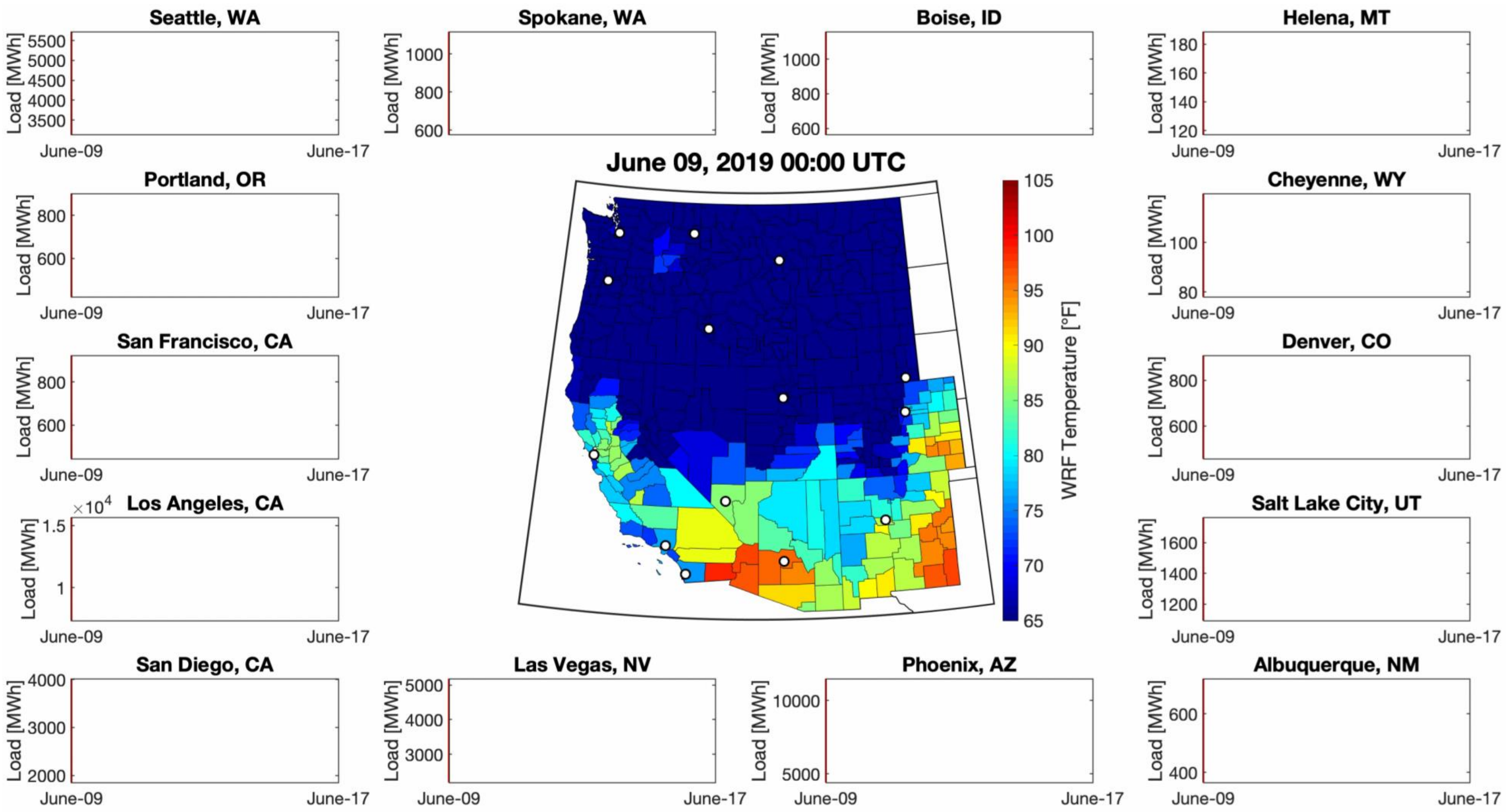


How do we generate future hourly load profiles that are at a spatial resolution adequate for input to a grid operations model, but that also maintain conceptual and quantitative consistency with GCAM-USA's annual state-level results?

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

How TELL works

- Formulate machine learning (ML) models that relate the historical observed meteorology to the hourly time series of total electricity demand for each of the BAs that report their hourly loads in the EIA-930 dataset
- Use the ML models to predict historical or future hourly loads for each BA based on climate projections
- Distribute the hourly loads for each BA to the counties that BA operates in and then aggregate the county-level hourly loads from all BAs into annual state-level loads
- Calculate state-level scaling factors that force the state-level total loads from TELL to match the annual state-level non-transportation loads from GCAM-USA
- Apply the state scaling factors to each county-level time series
- Output yearly time series of total non-transportation loads at the state-, county-, and BA-scale that are conceptually and quantitatively consistent with each other

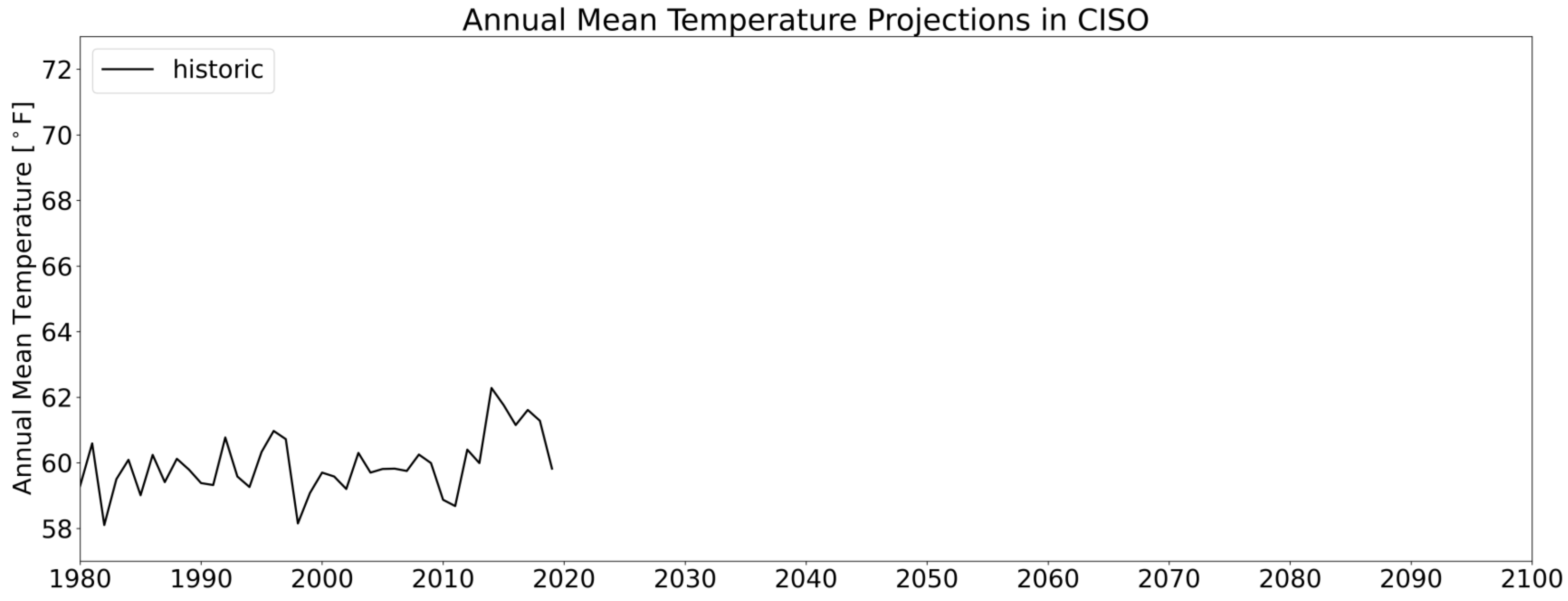
Data for the TELL machine learning models

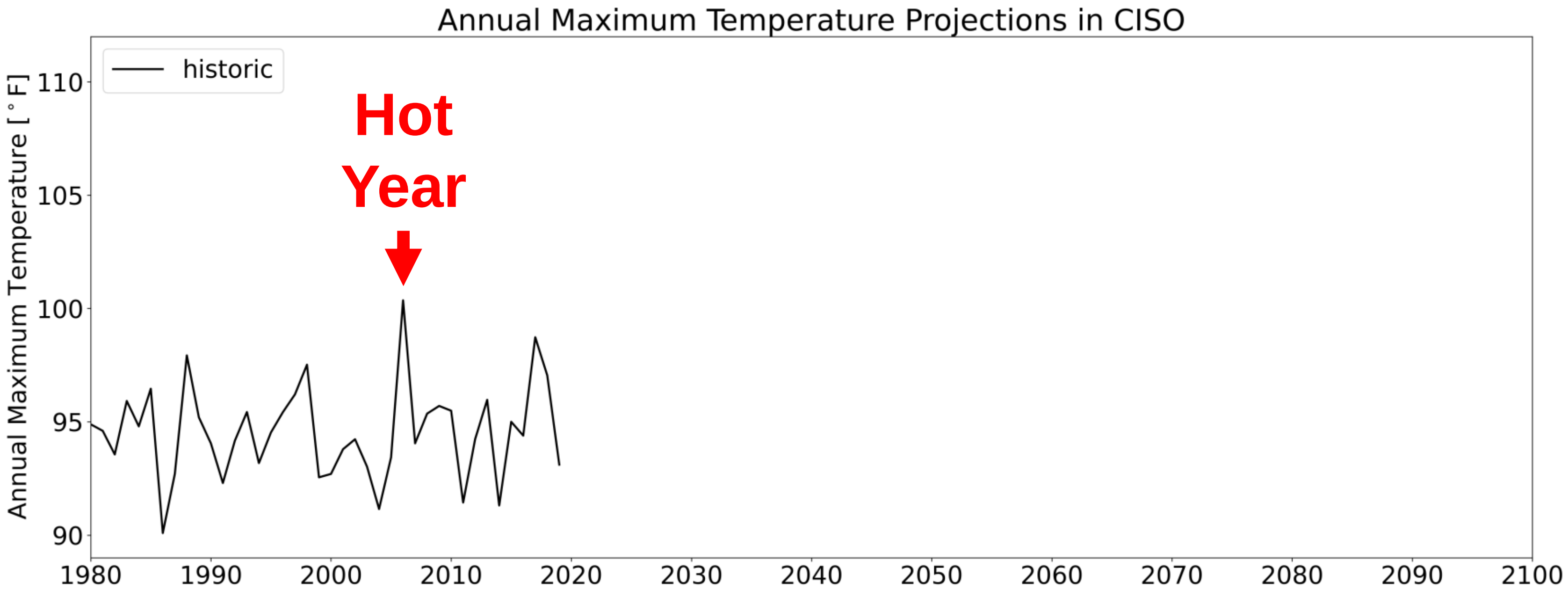
Predictive Variable	Units	Source
Temperature	K	Climate Projections
Specific Humidity	kg kg^{-1}	Climate Projections
Shortwave Radiation	W m^{-2}	Climate Projections
Longwave Radiation	W m^{-2}	Climate Projections
Wind Speed	m s^{-1}	Climate Projections
Day of Week	Weekday/Weekend	N/A
Federal Holiday	Yes/No	N/A
Hour of Day	00-23 UTC	N/A

Target Variable	Units	Source
BA Hourly Demand	MWh	EIA-930

- Model hourly demand for each BA using a multi-layered perceptron (MLP) neural network
- Training: 2016–2018
- Evaluation: 2019
- Each BA trained and evaluated independently
- Hyperparameter tuning is performed using grid search

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

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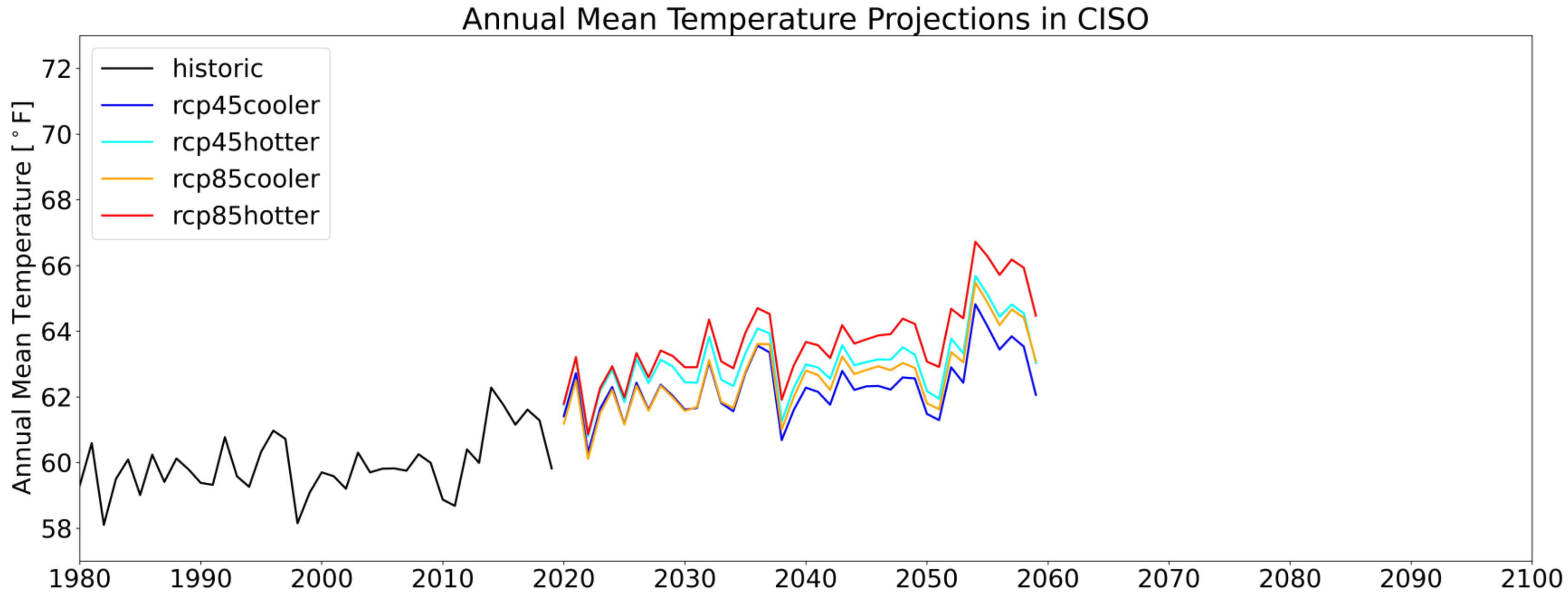

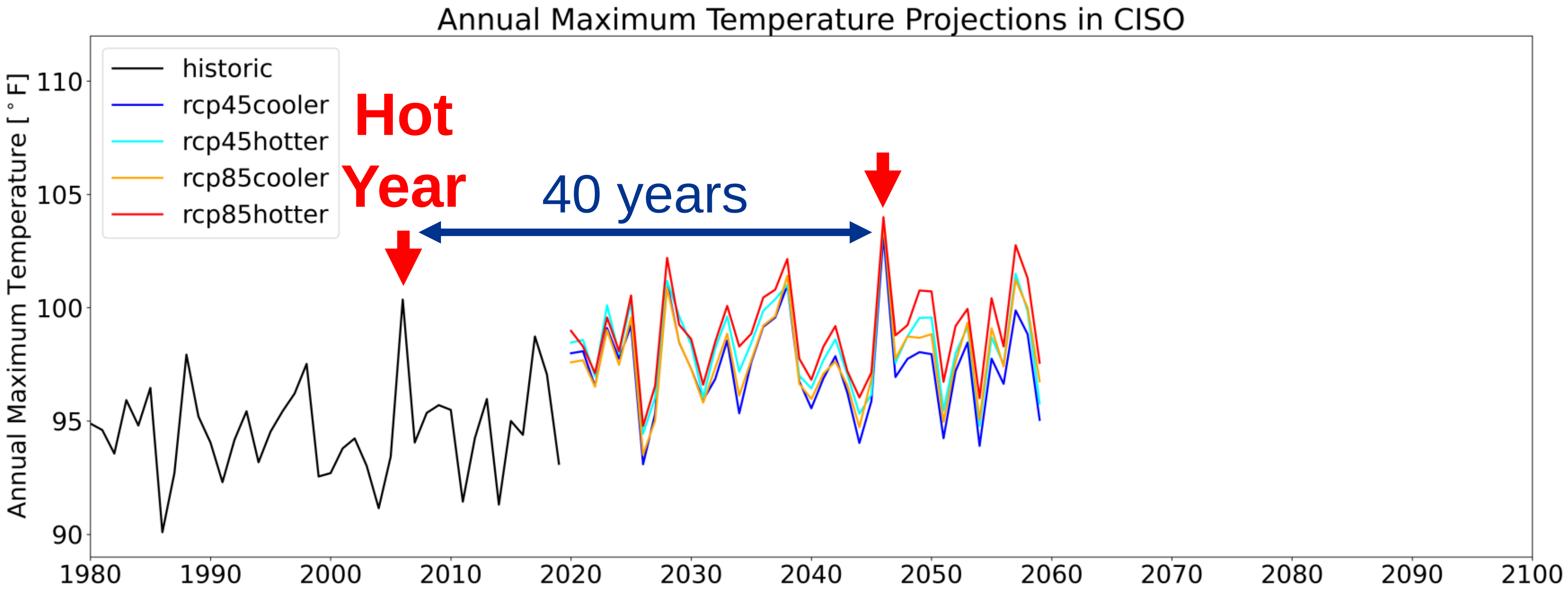

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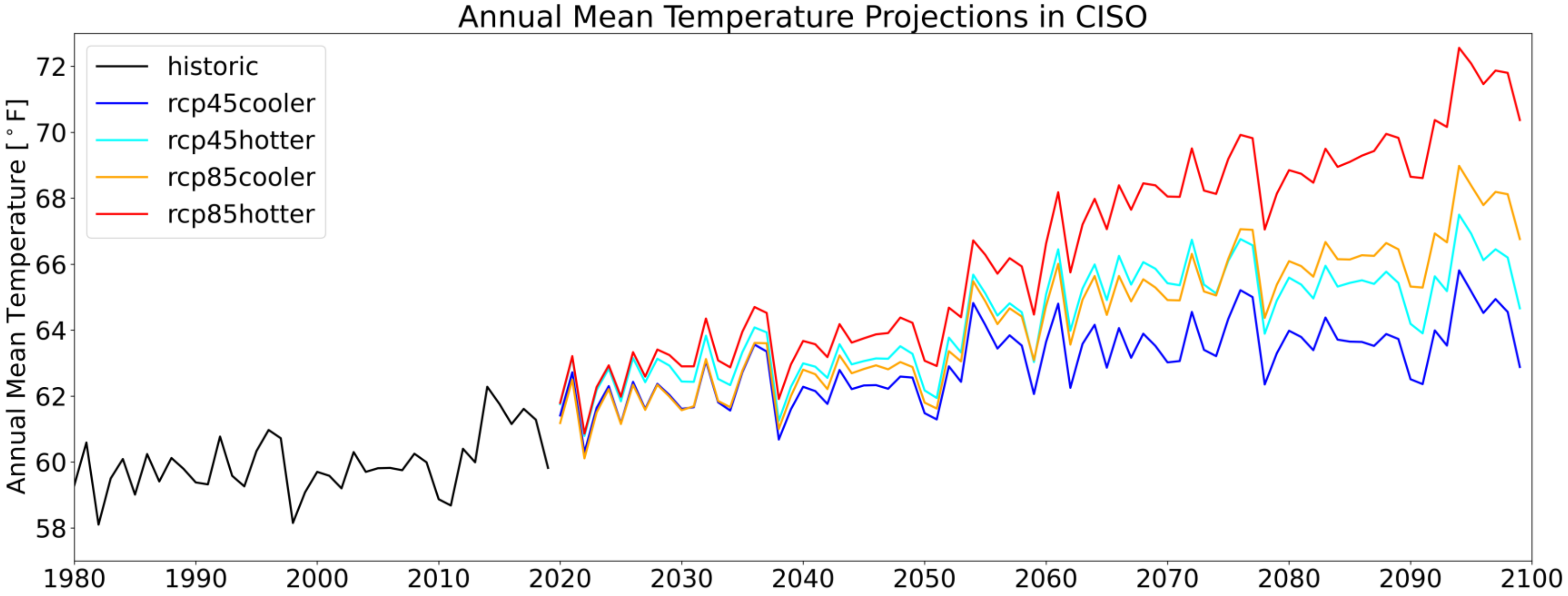

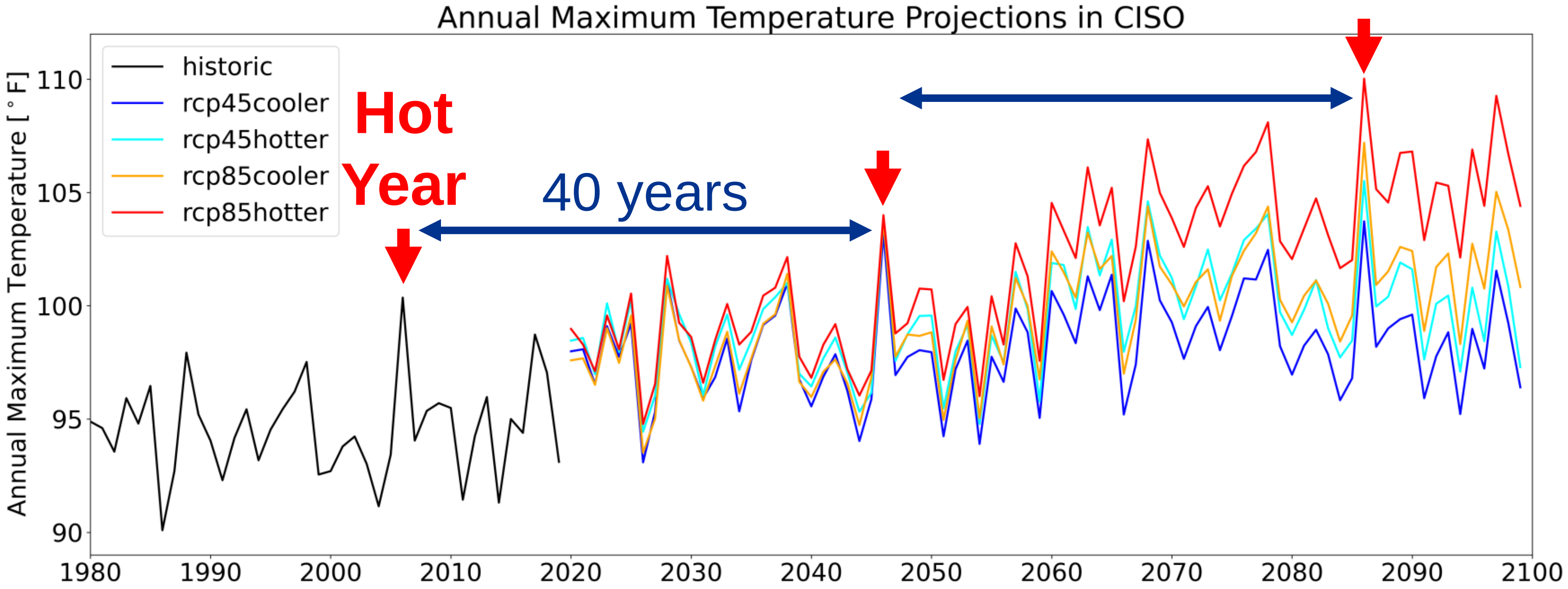

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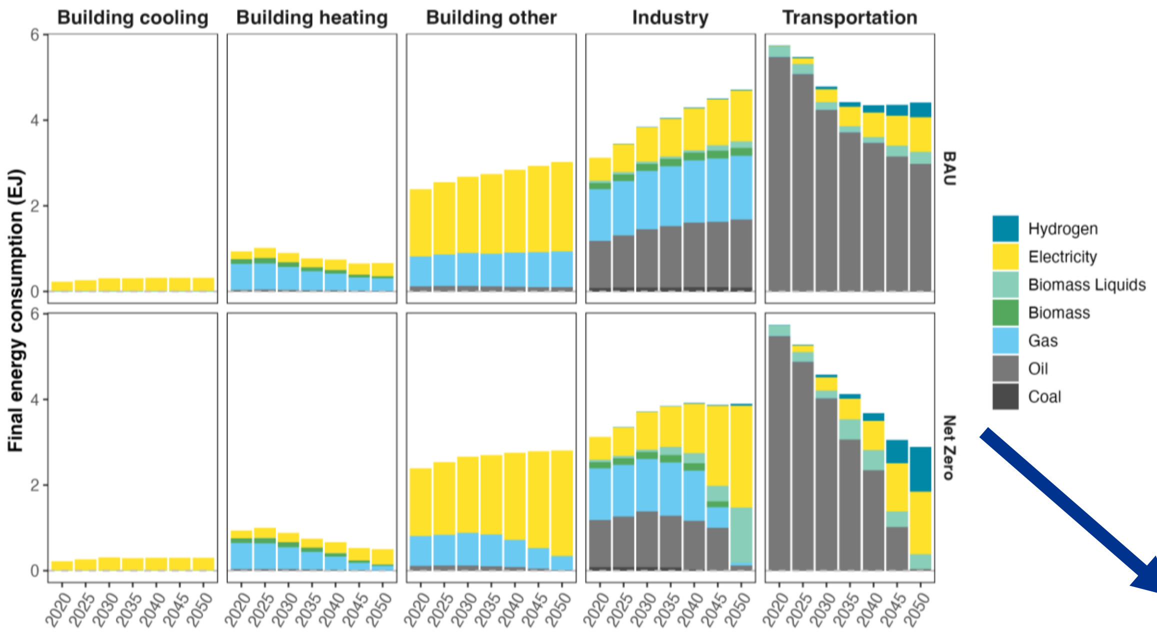
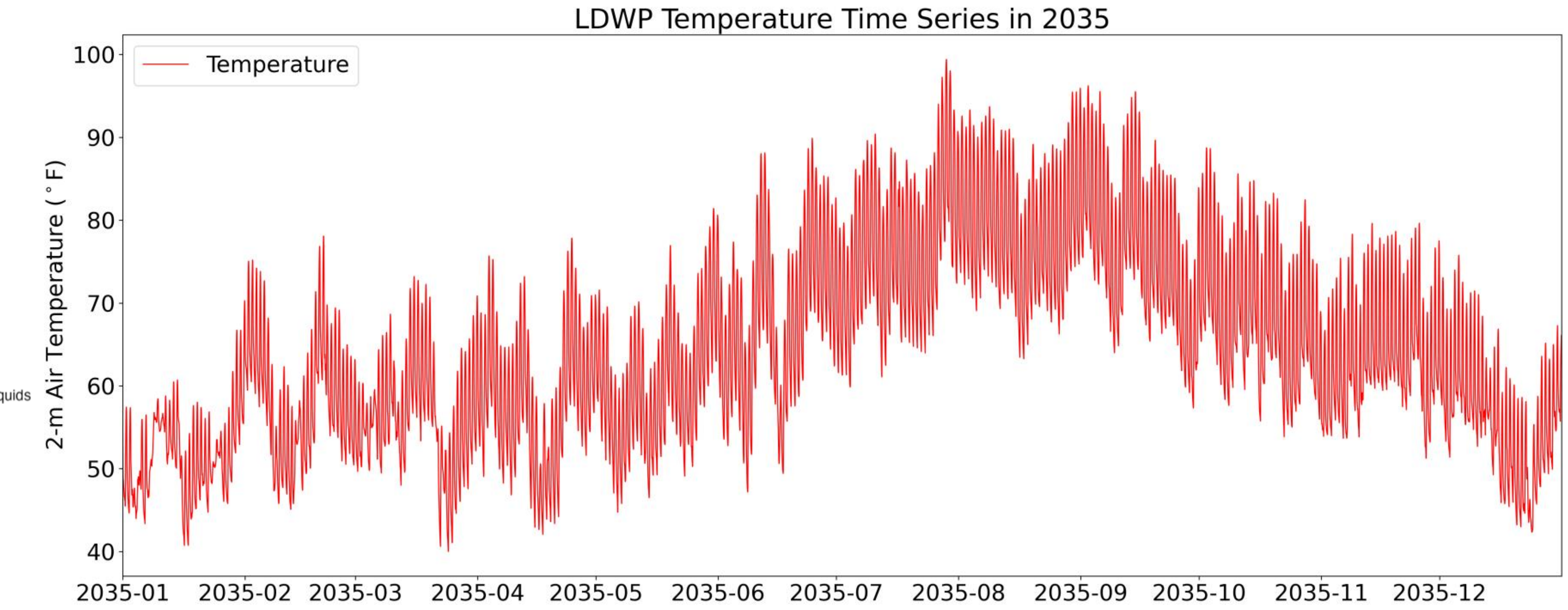
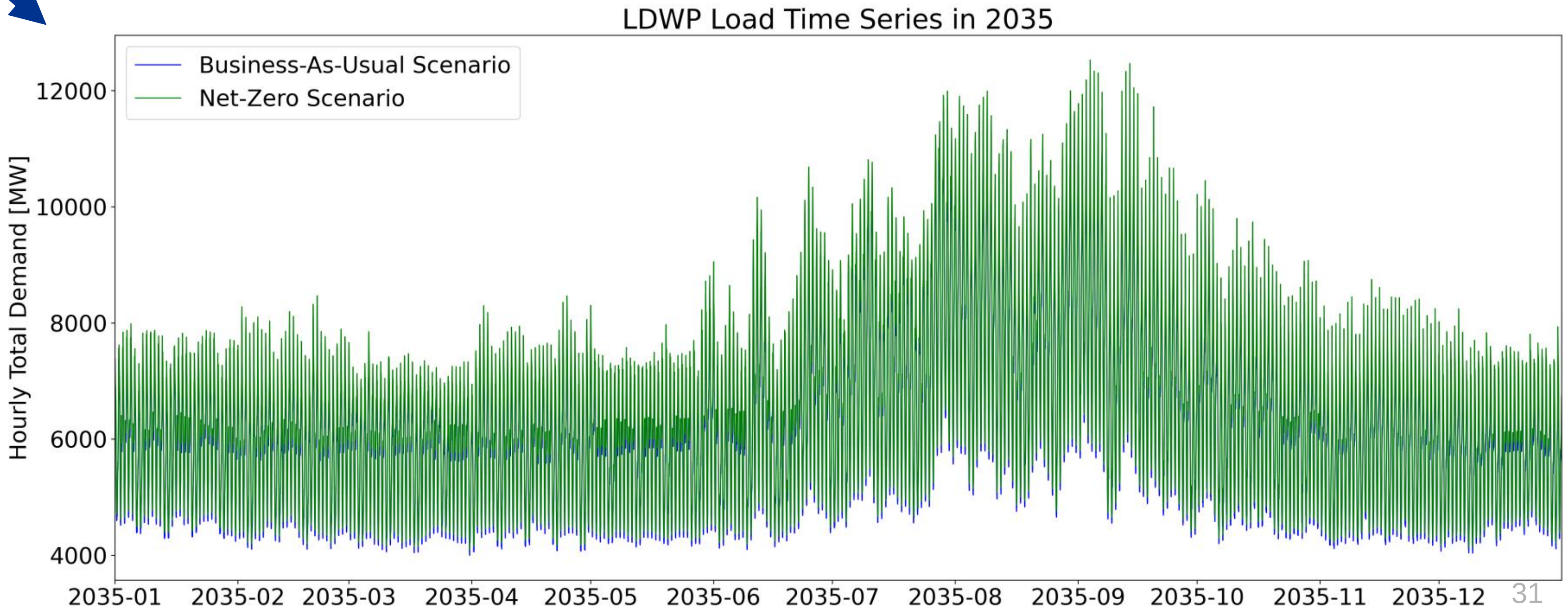
Projecting hourly load time series







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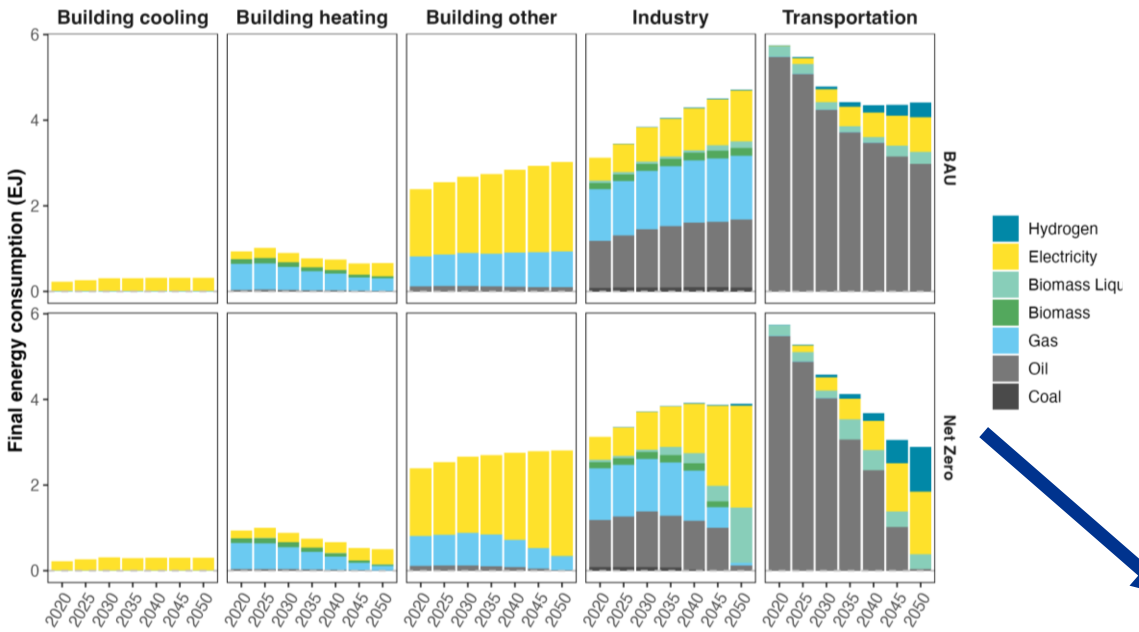

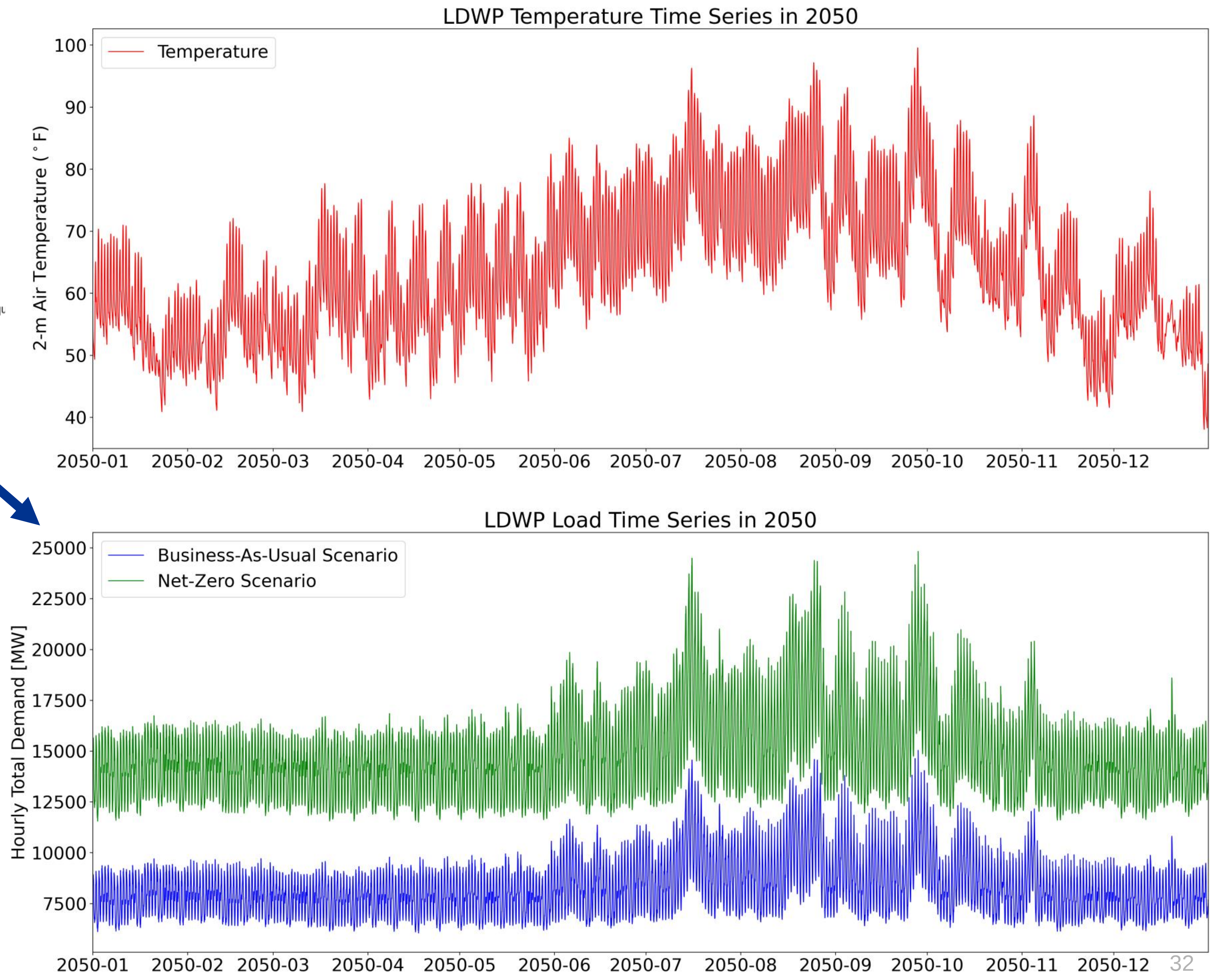

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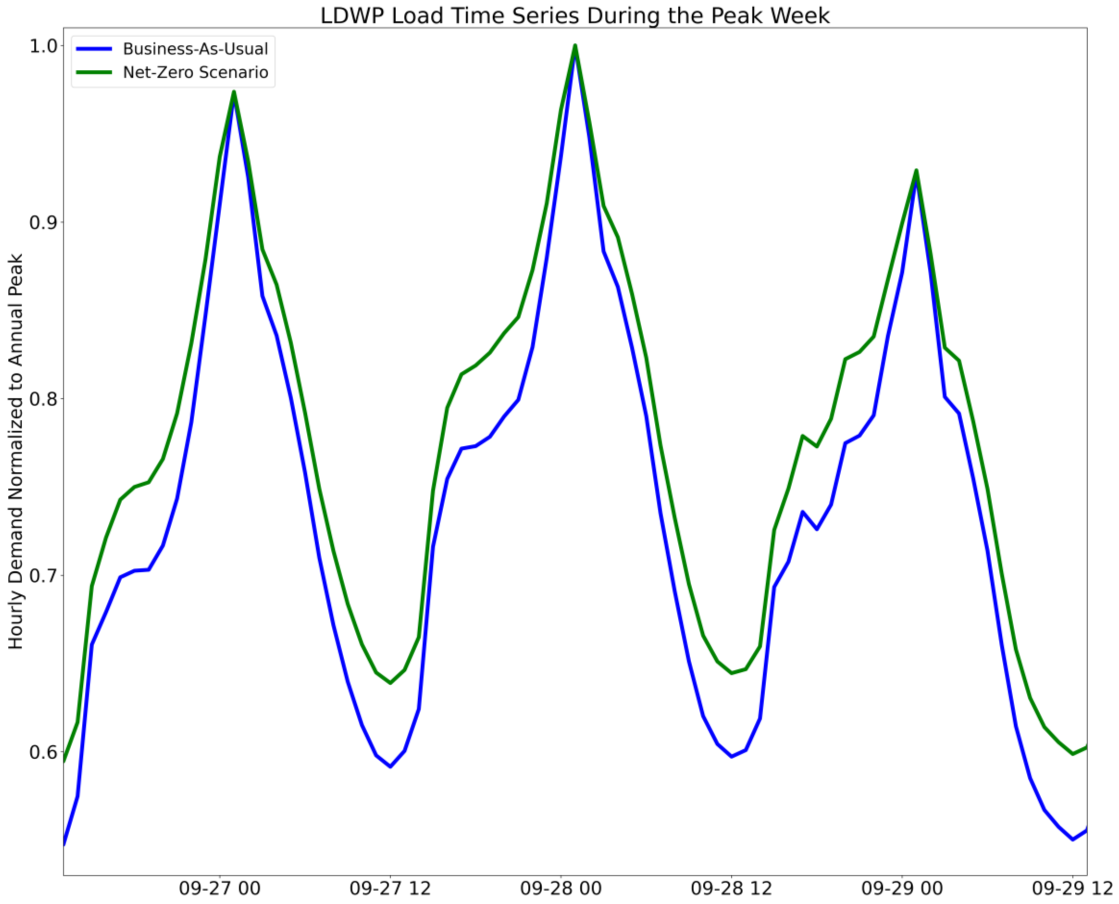
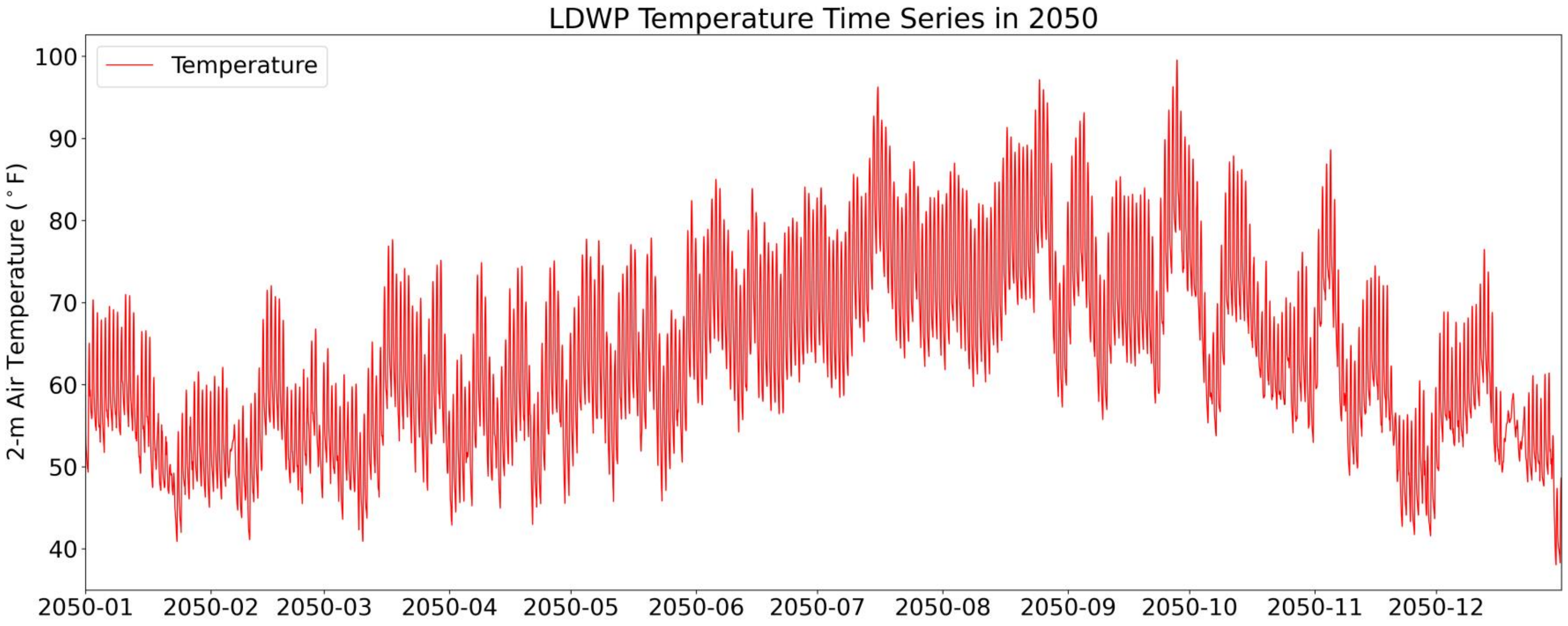
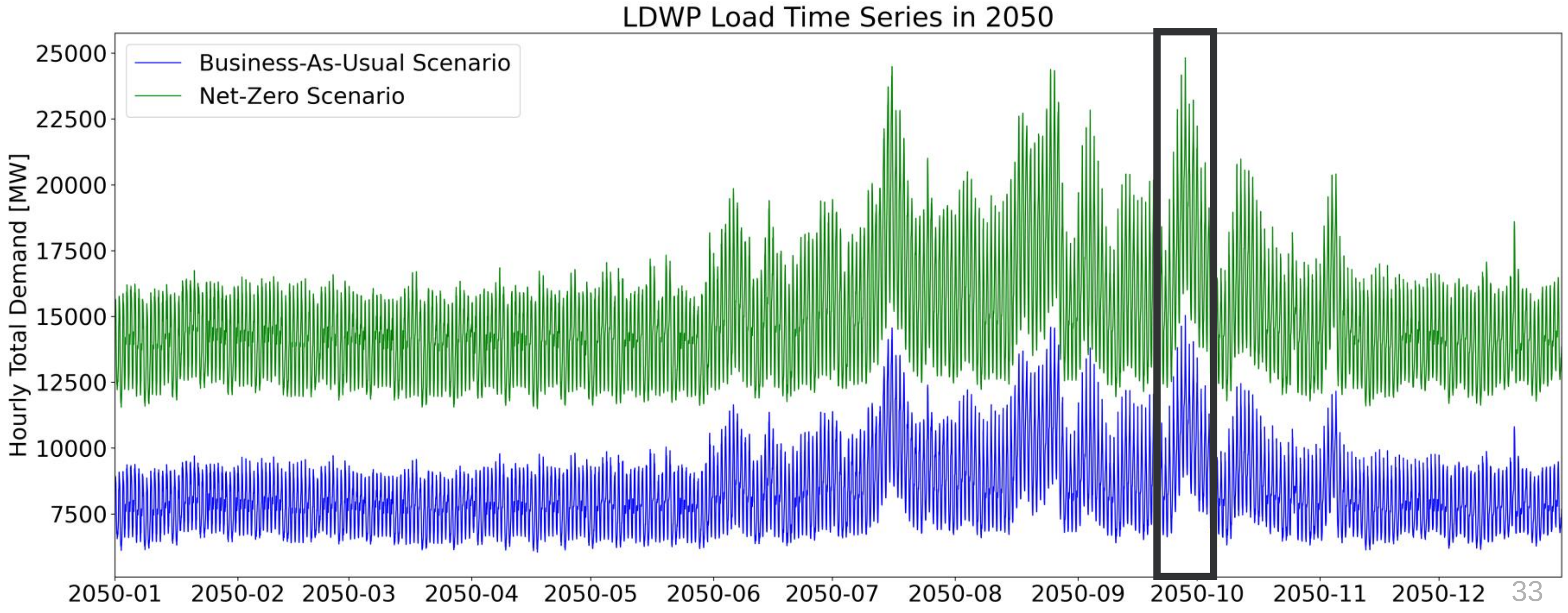
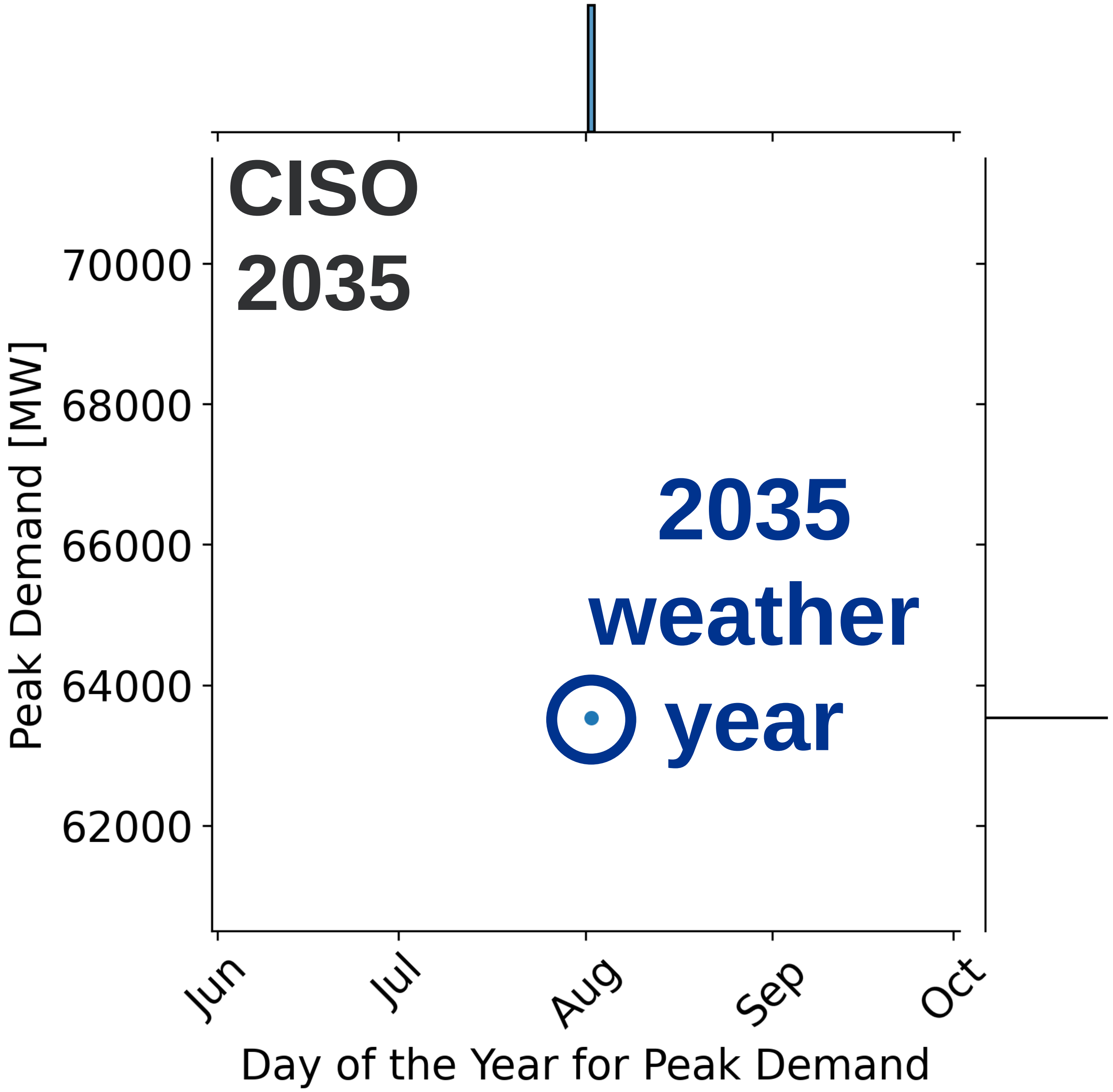


Peak Days





Exploiting the ability to simulate multiple weather years to explore uncertainty



- The prior example used a single weather year, but we can run many unique weather years through the TELL model
  - All years have the same total annual energy consumption due to scaling with GCAM-USA state-level projections, which are chronological
  - Absolute magnitude and timing of peak demand varies significantly depending on the weather each year

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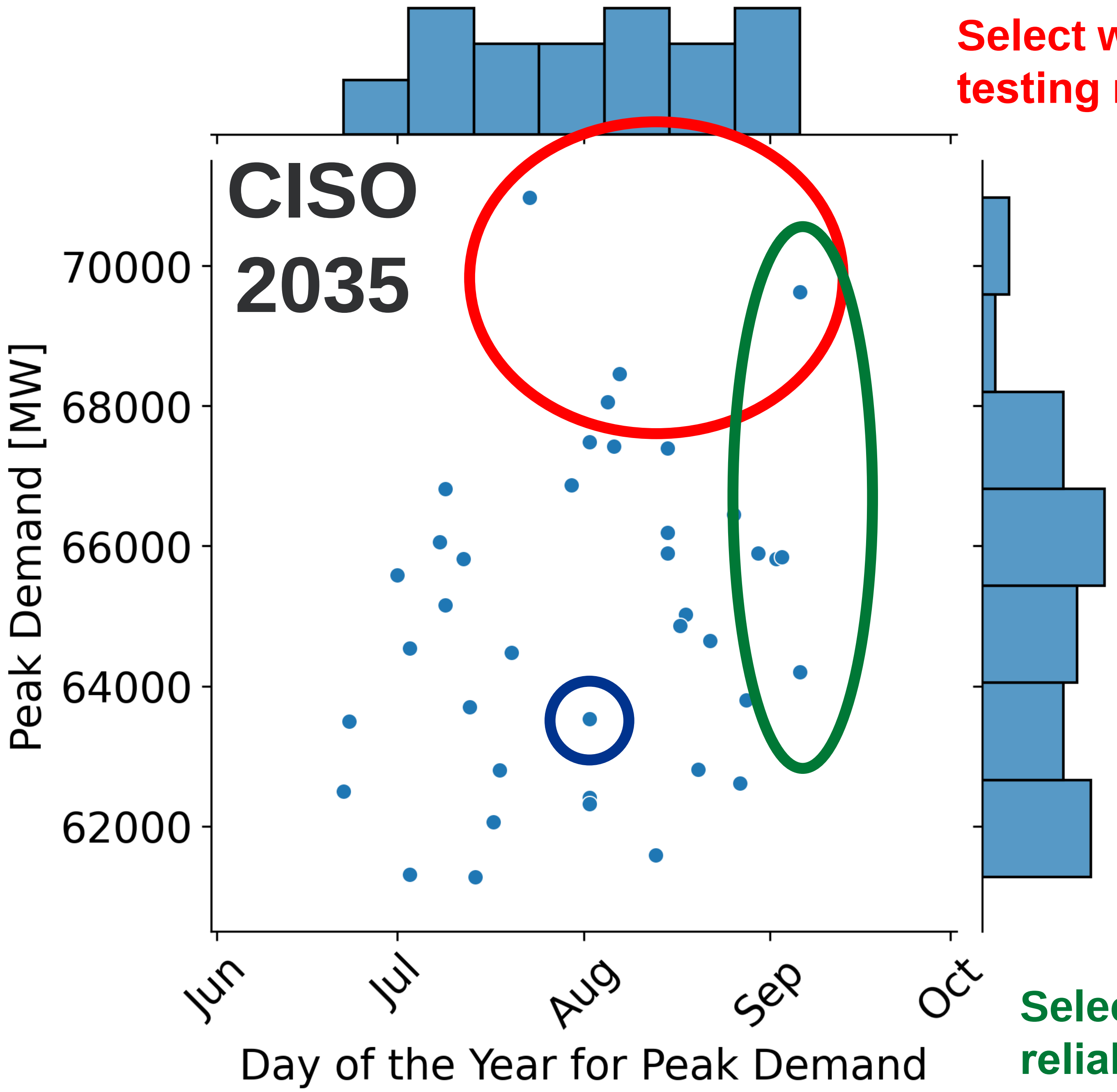


Select weather years with extreme peaks for testing resilience…

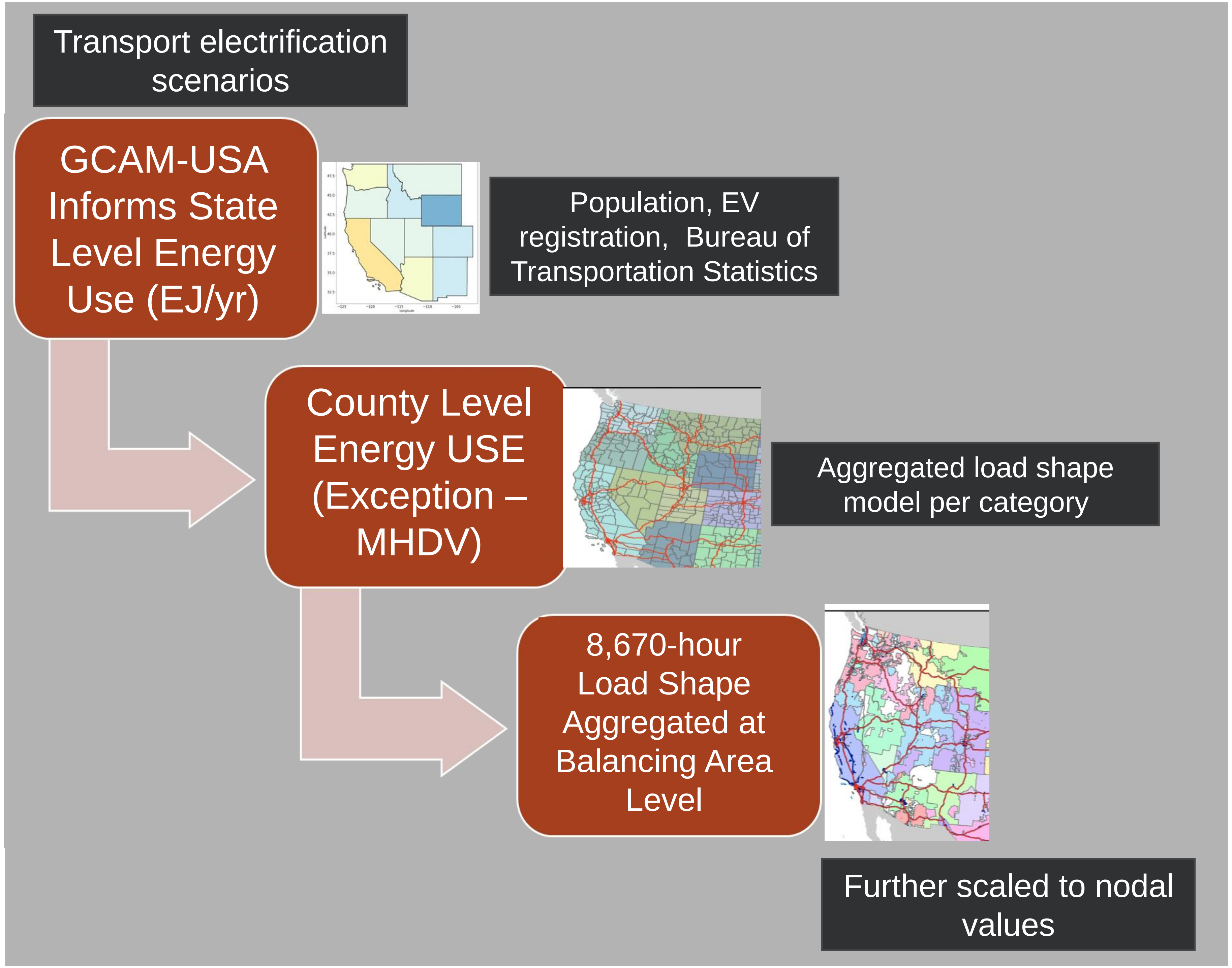
- The prior example used a single weather year, but we can run many unique weather years through the TELL model
  - All years have the same total annual energy consumption due to scaling with GCAM-USA state-level projections, which are chronological
  - Absolute magnitude and timing of peak demand varies significantly depending on the weather each year

Select weather years with late season peaks to assess reliability with low hydro…

Short Q&A

Developing transportation electric load profile

- Electrification of transport disrupts historical load shapes
- Informed by GCAM electrification scenarios and weather model
- Spatially distributed hourly time-series of transportation charging load profiles

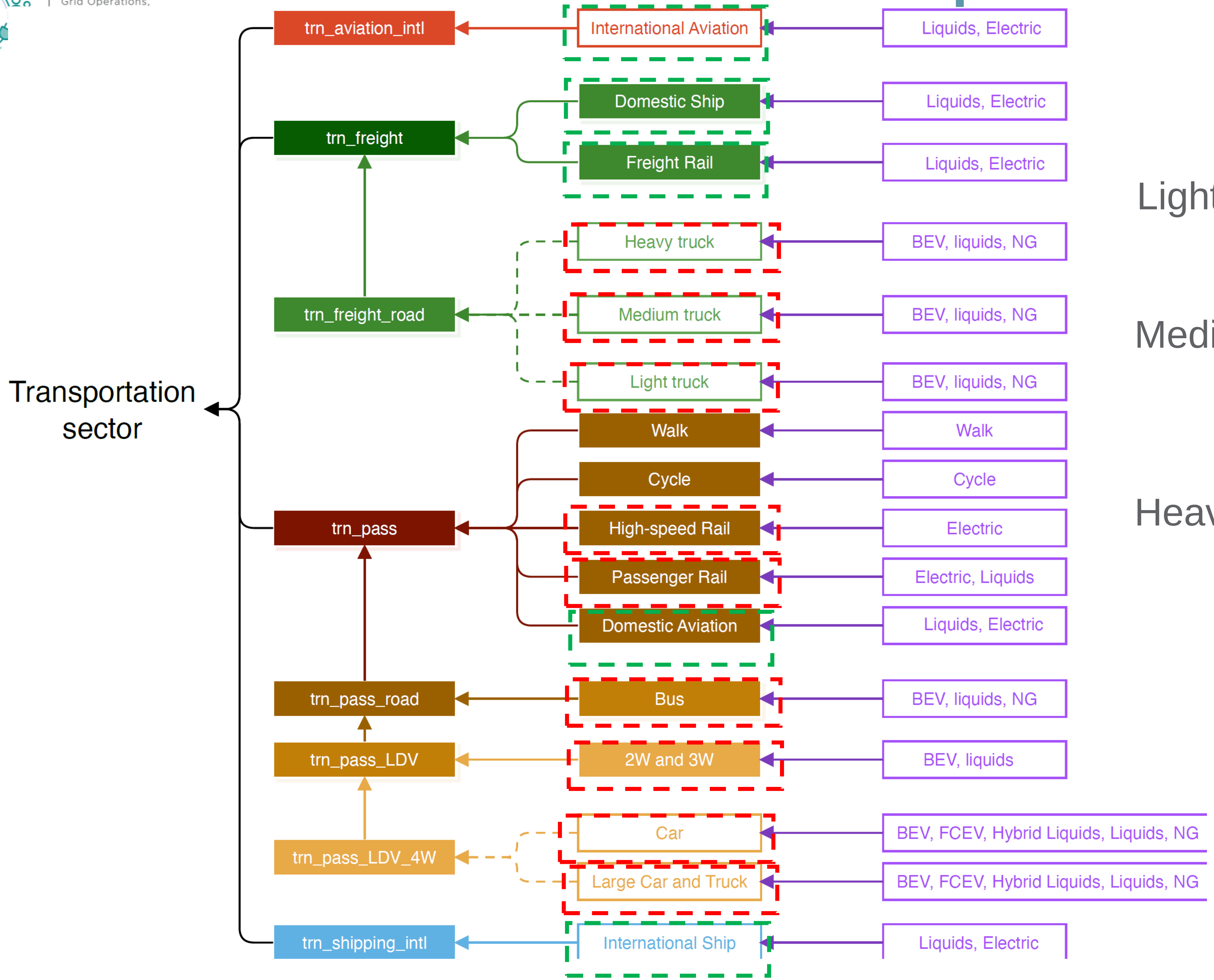


GCAM transportation structure

Aviation

Rail

Ship

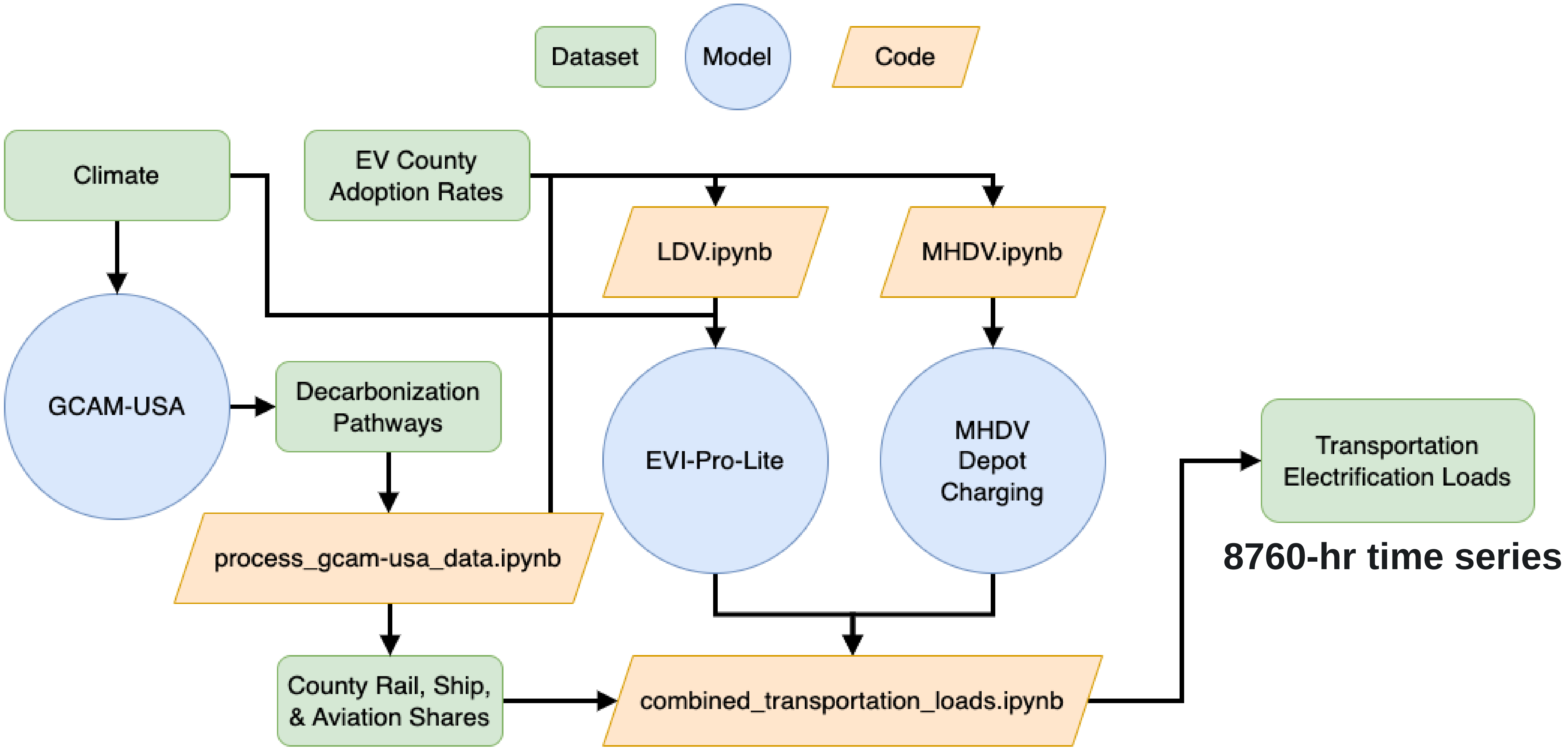


Light duty vehicles

Medium duty vehicles

Heavy duty vehicles

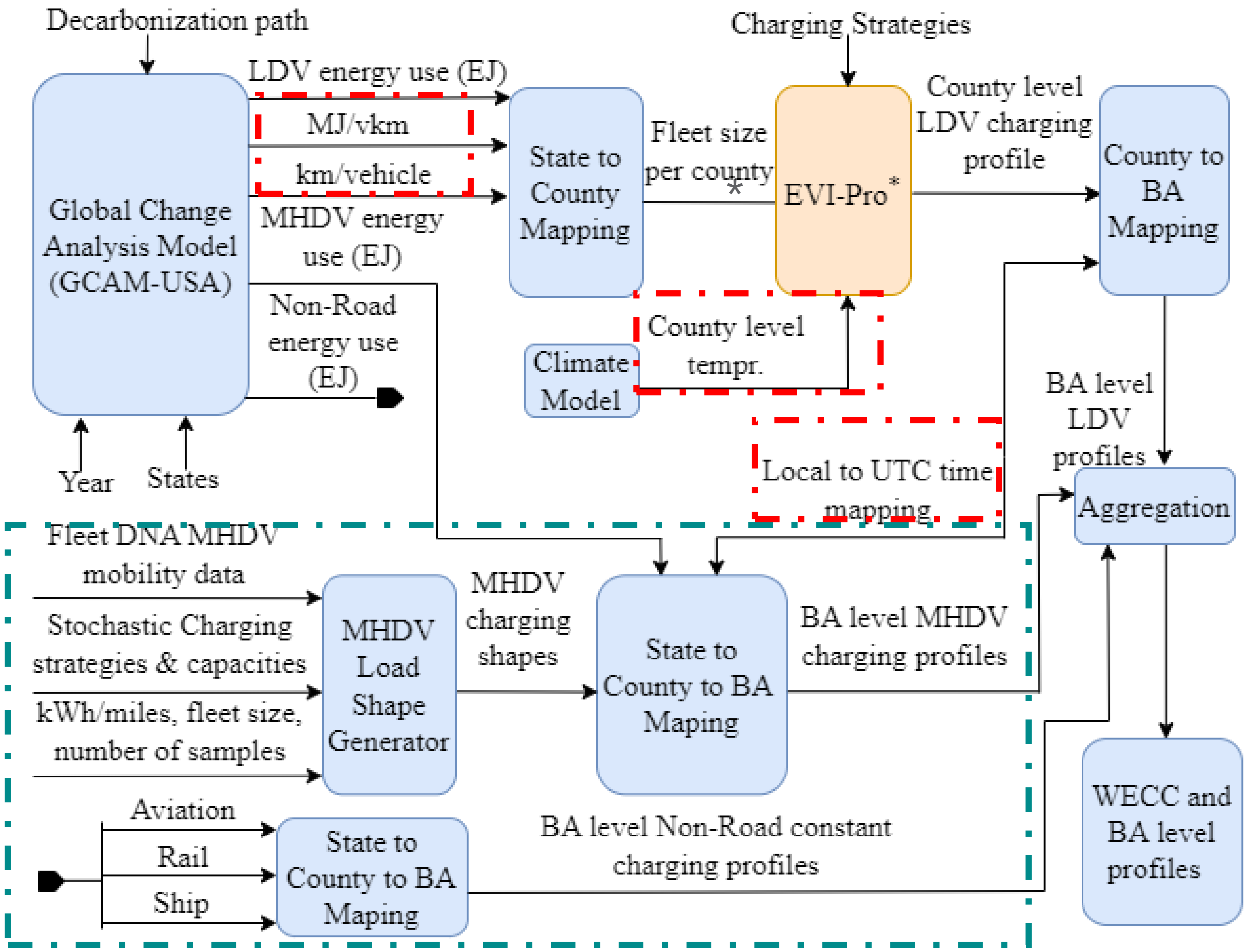
Overall framework



Overall framework for generating transportation electric loads

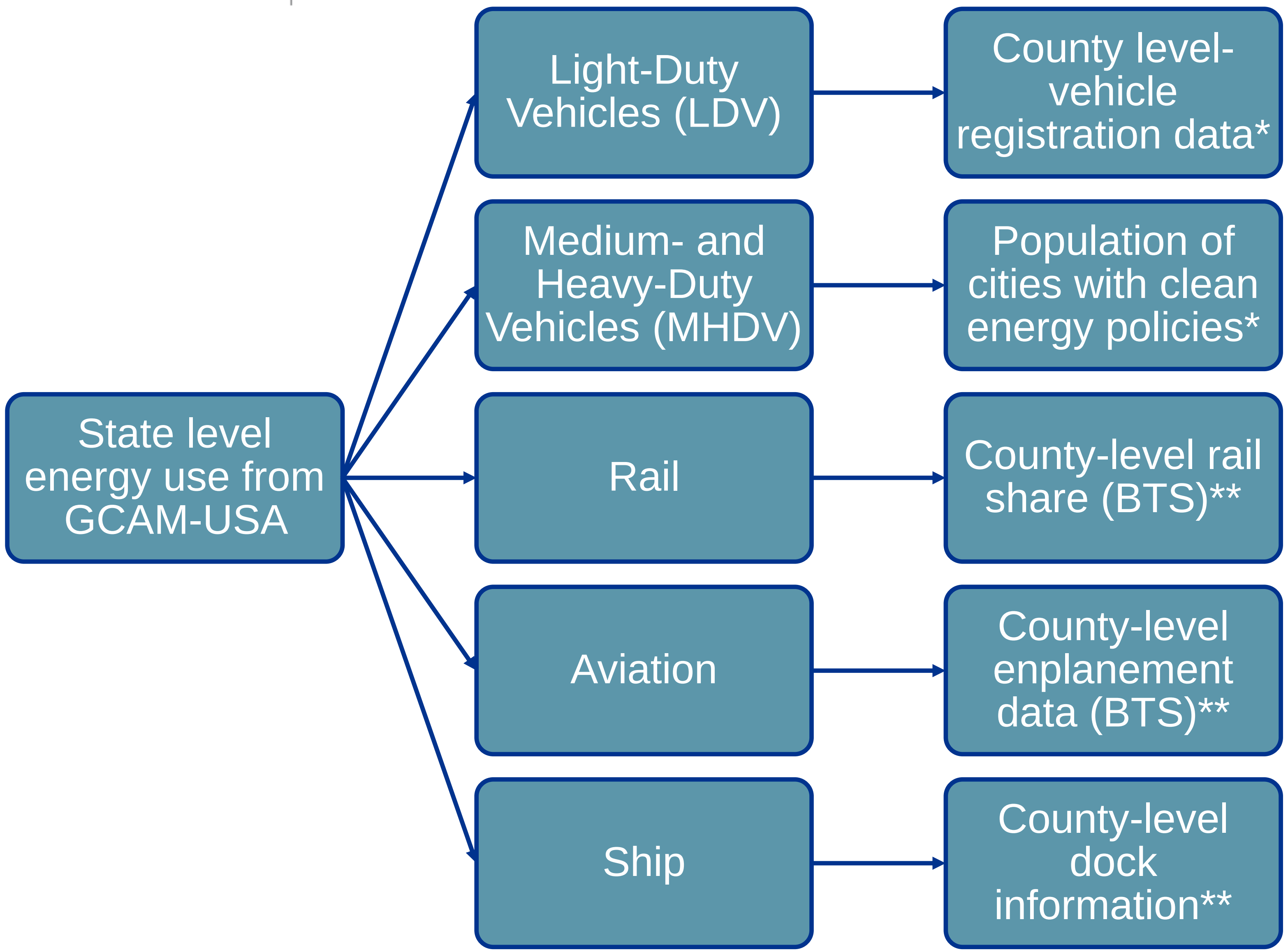
[GitHub - GODEEEP/transportation_electrification: Transportation electrification analysis for GODEEEP]()

Overall framework: Under the hood



*Muratori, Matteo, and Eric W. Wood. *Charging Infrastructure: What, Where, and How Many? NREL Perspective*. No. NREL/PR-5400-73733. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2019.

Spatial downscaling of transportation loads

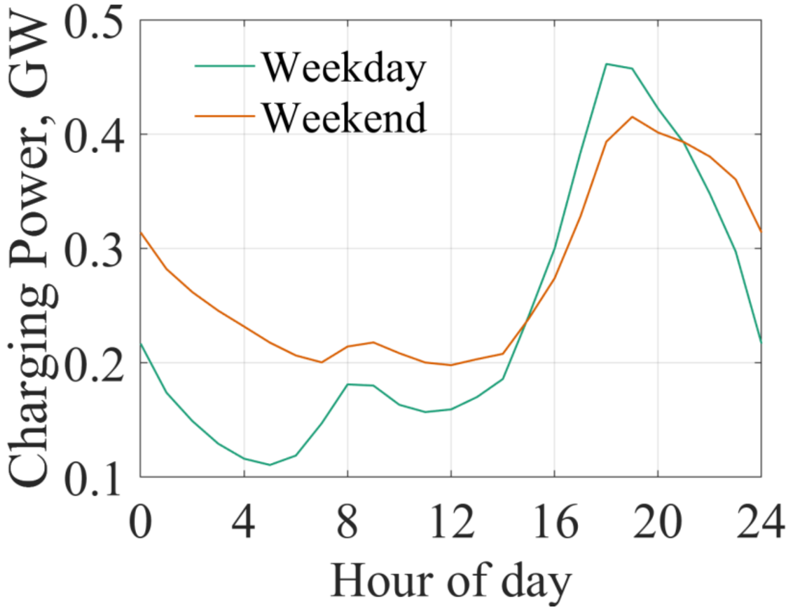


*Kintner-Meyer, M., et al. Electric vehicles at scale–phase I analysis: High EV adoption impacts on the western US power grid. No. PNNL-29894. 2020.

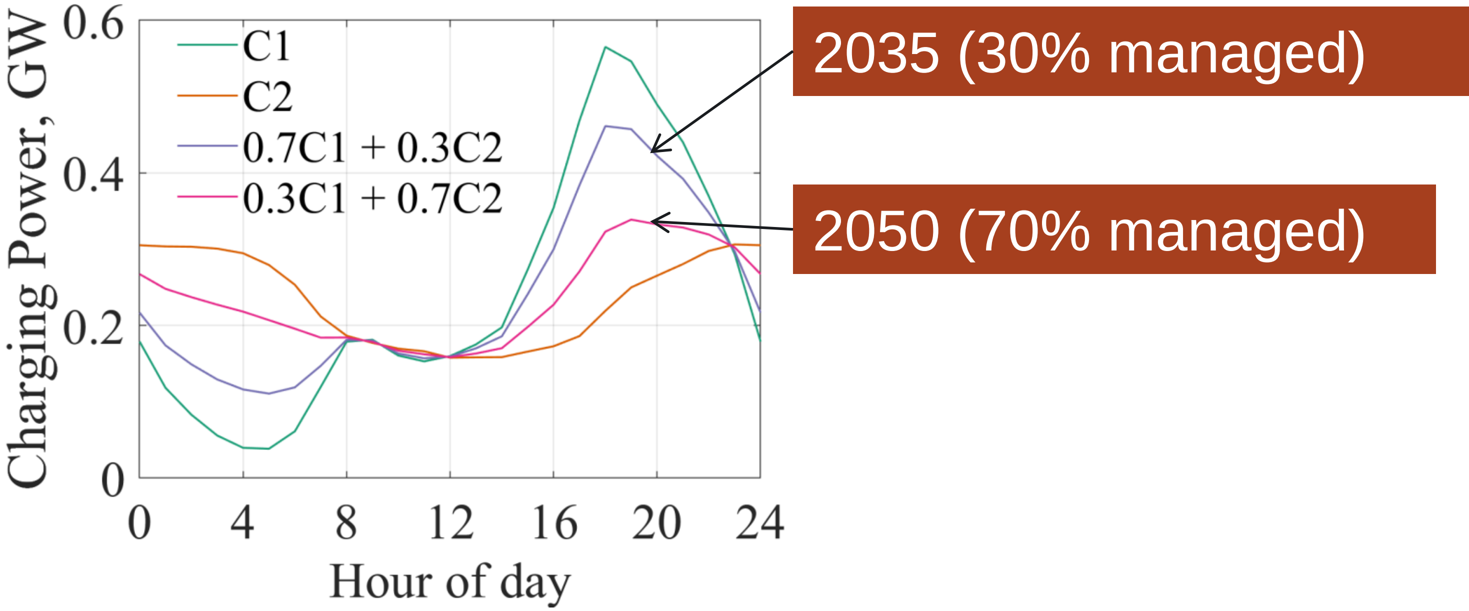
**Bureau of Transportation Statistics (BTS): https://www.bts.gov/

Sensitivity analysis for LDV load shapes

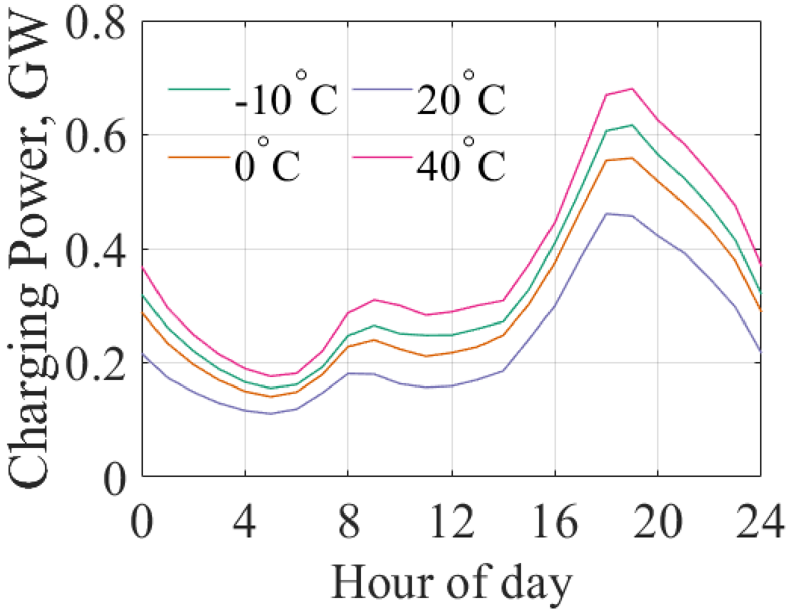
Sensitivity to weekday vs. weekend



Sensitivity to charging strategy



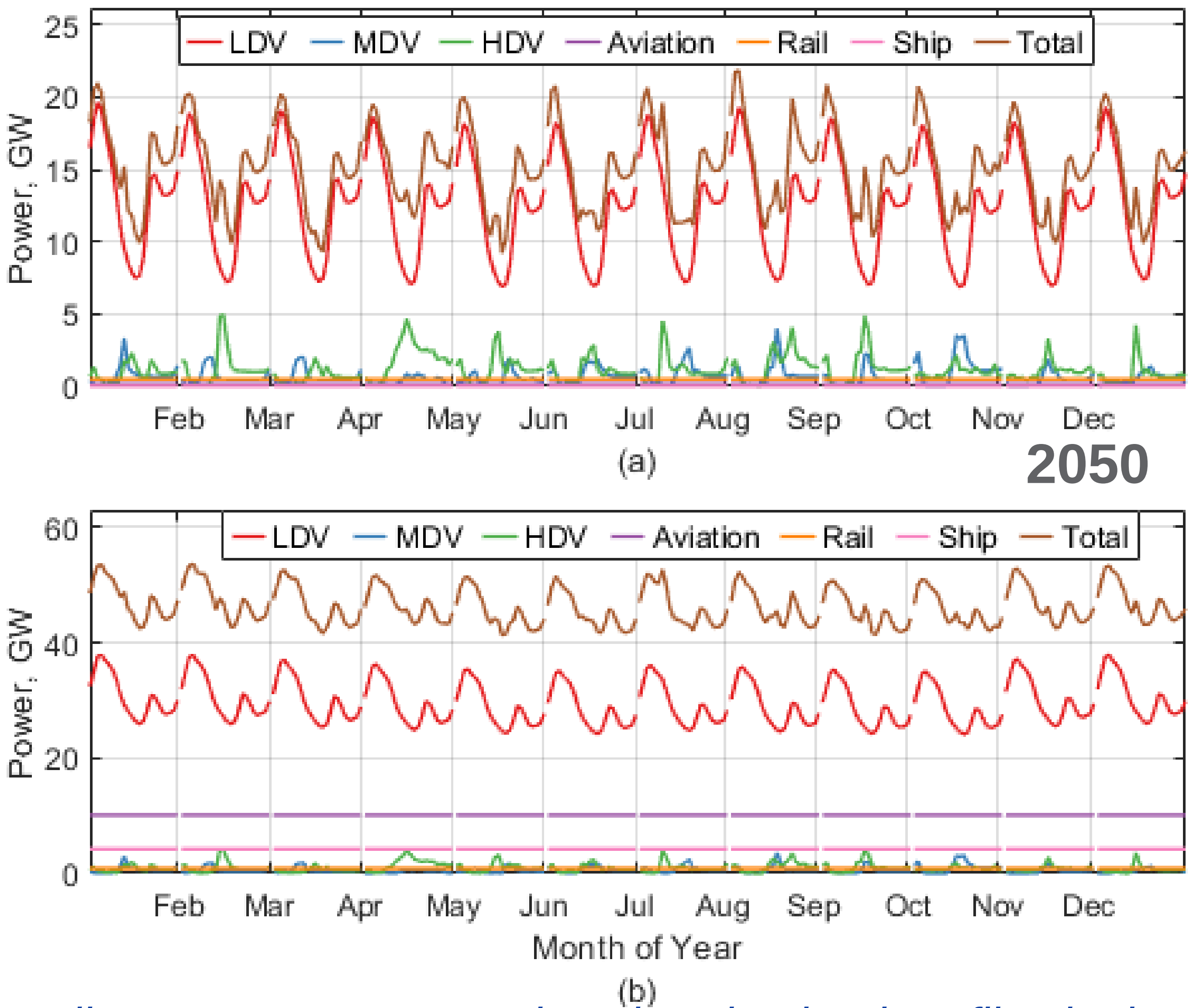
Sensitivity to temperature



- **Charging Strategy 1 (C1/Immediate):** Vehicle charges immediately after arriving at the base at fastest available charging speed – no charging management
- **Charging Strategy 2 (C2/Load leveling):** Vehicle charges immediately after arriving at the base at slowest available charging speed – managed charging

Results: Hourly load profiles

2035



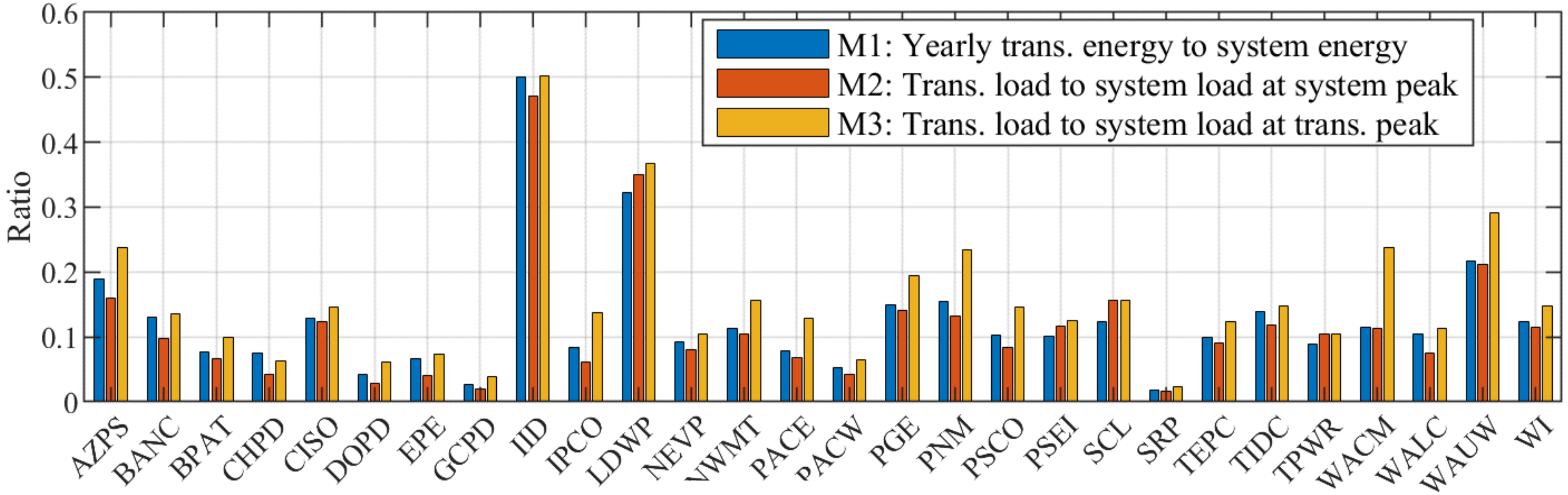
Daily average transportation charging load profiles in the WECC across months in for the NZ decarbonization pathway

- Managed charging is going to be more prevalent in 2050
  - In 2035, only 30% charging is done using load leveling
  - In 2050, 70% LDVs charge using the load leveling
- Charging strategy plays biggest impact on reducing peak

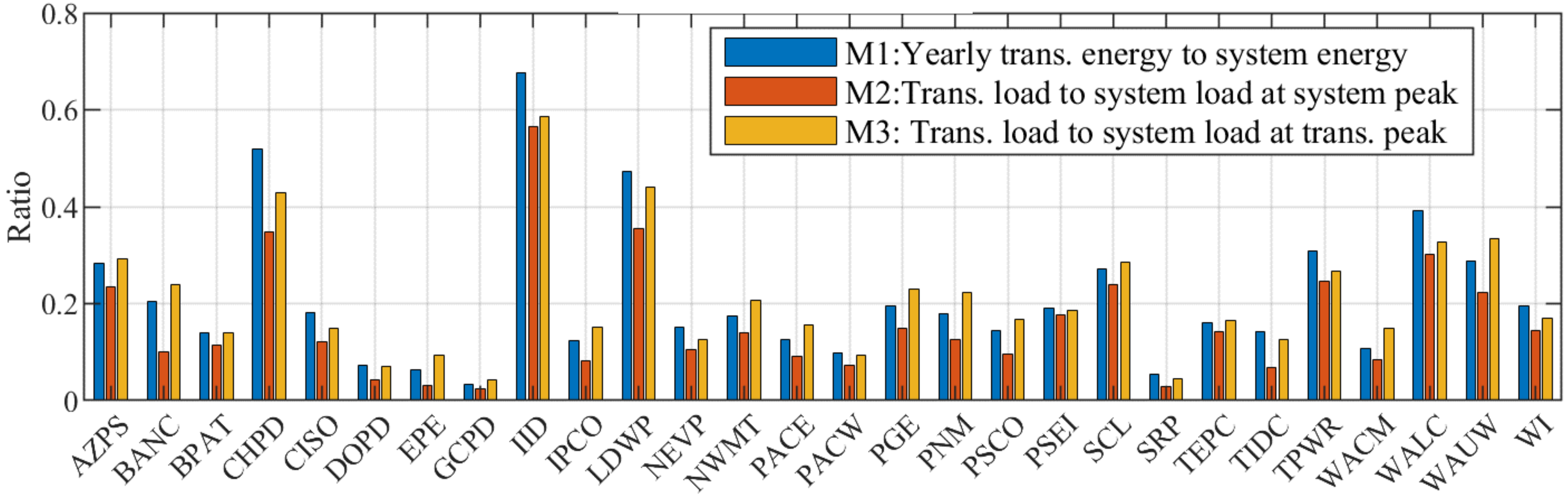
Results: System-relative loads

- Transportation load affects various BAs differently
- Approximately 10–20% of the system's peak load is impacted by transportation load for overall Western Interconnect (WI)
- BAs with predominantly residential and moderate climate regions experience more significant peak load penetration from transportation
- The peaks for transportation load and system load do not coincide

2035



2050



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Transportation dataset details

Available dataset and code for further research and policy analysis, enabling the development of charging load profiles for other regions:

- **Dataset:** “Transportation Electrification Load Profiles by Balancing Authority in the Western United States for GODEEEP”
- **Available:** https://zenodo.org/record/7888569
- **Years:** 2025, 2030, 2035, 2040, 2045, 2050
- **Climate scenarios:** RCP4.5 Cooler, RCP8.5 Hotter
- **Decarbonization Scenarios:** Business-as-usual (BAU) and Net Zero (NZ)

May 2, 2023 Dataset Open Access

Transportation Electrification Load Profiles by Balancing Authority in the Western United States for GODEEEP

Acharya, Samrat; Thurber, Travis B; Ghosal, Malini

Time-series electric charging load profiles for the transportation sector across Balancing Authorities (BAs) in the Western Electricity Coordinating Council (WECC) interconnect for the years 2025, 2030, 2035, and 2050. The data is provided for two different socioeconomic pathways and two different climate pathways, resulting in four total scenarios. The socioeconomic pathways--Business-As-Usual with Climate (BAU_Climate) and Net-Zero without CCS (NetZeroNoCCS_Climate)--are described by https://doi.org/10.5281/zenodo.7838871. The climate pathways--Representative Concentration Pathway 4.5 cooler (rcp45cooler) and Representative Concentration Pathway 8.5 hotter (rcp85hotter)--are described by https://doi.org/10.57931/1885756. The climate influence is only considered for Light Duty Vehicles (LDVs).

For additional details please consult the paper *Acharya et al 2023, Developing Spatio-Temporal Transportation Electric Load from Multi-Sector Dynamics Model, in prep*, and the code repository https://github.com/GODEEEP/transportation_electrification, in prep.

A brief summary of the files and directories in this data package is provided below. Text within chevrons implies a

- BAU_Climate
  - rcp45cooler
    - <balancing authority>_hourly_transportation_load_<socioeconomic pathway>_<climate scenario>_<year>.csv
  - rcp85hotter
    - <balancing authority>_hourly_transportation_load_<socioeconomic pathway>_<climate scenario>_<year>.csv
- NetZeroNoCCS_Climate
  - rcp45cooler
    - <balancing authority>_hourly_transportation_load_<socioeconomic pathway>_<climate scenario>_<year>.csv
  - rcp85hotter
    - <balancing authority>_hourly_transportation_load_<socioeconomic pathway>_<climate scenario>_<year>.csv
- WECC_hourly_transportation_load_<socioeconomic pathway>_<climate scenario>_<year>.csv

Each file is in comma-separated-value (CSV) format with the following columns:

- `time` - ISO 8601 timestamp representing the end of the hourly timestep; values are reported as the summation over the preceding hour
- `balancing_authority` - Acronym of the balancing authority for this data point
- `LDV_load_MWh` - Energy consumed by the charging of Light Duty Vehicles (LDVs) during the previous hour in Megawatt hours
- `MDV_load_MWh` - Energy consumed by the charging of Medium Duty Vehicles (MDVs) during the previous hour in Megawatt hours
- `HDV_load_MWh` - Energy consumed by the charging of Heavy Duty Vehicles (HDVs) during the previous hour in Megawatt hours
- `passenger_rail_load_MWh` - Energy consumed by the charging of passenger rail vehicles during the previous hour in Megawatt hours
- `freight_rail_load_MWh` - Energy consumed by the charging of freight rail vehicles during the previous hour in Megawatt hours
- `aviation_load_MWh` - Energy consumed by the charging of aviation vehicles during the previous hour in Megawatt hours
- `ship_load_MWh` - Energy consumed by the charging of ships during the previous hour in Megawatt hours
- `transportation_load_MWh` - Total energy consumed by the charging of vehicles during the previous hour in Megawatt hours (summation of the other columns)

Data and code are all publicly available

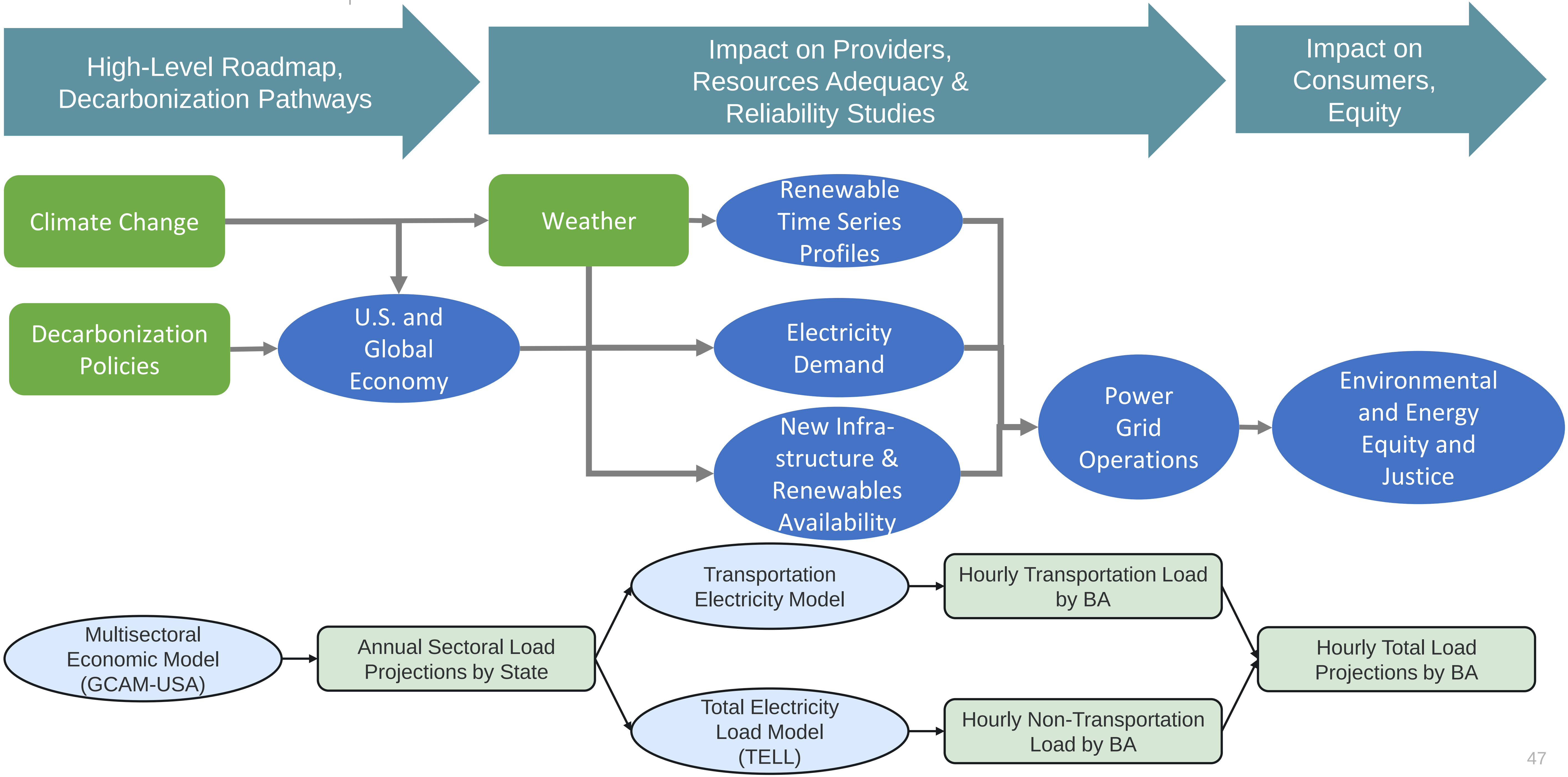
Key Datasets

- **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*
  - *Burleyson, C., Thurber, T., & Vernon, C. (2023). Projections of Hourly Meteorology by Balancing Authority Based on the IM3/HyperFACETS Thermodynamic Global Warming (TGW) Simulations (v1.0.0) [Data set]. MSD-LIVE Data Repository. https://doi.org/10.57931/1960530*
- **GCAM-USA Decarbonization Pathways**
  - Ou, Yang, & Iyer, Gokul. (2023). GCAM-USA Decarbonization Pathways for GODEEEP (2.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7838872
- **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
- **Transportation Electrification Load Profiles by Balancing Authority**
  - Acharya, Samrat, Thurber, Travis B, & Ghosal, Malini. (2023). Transportation Electrification Load Profiles by Balancing Authority in the Western United States for GODEEEP (v1.0.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8065137

Code

- https://github.com/GODEEEP and https://github.com/IMMM-SFA/tell

Climate and decarbonization impacts on hourly load projections



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Incorporating Socioeconomic and Natural Resources Impacts into New Infrastructure Siting

Presented by Kendall Mongird, Konstantinos Oikonomou, and Stefan Rose

Monday, July 10, 10 a.m. PT

July 10

DEEP DIVE THREE

Vulnerability of the Decarbonized Grid to Energy Droughts and Climate Extremes

July 24, 10 a.m. PT

July 24

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Decarbonization Impacts on Disadvantaged Communities

August 7, 10 a.m. PT

Aug 7

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Q&A

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

Casey.Burleyson@pnnl.gov
Yang.Ou@pnnl.gov
Malini.Ghosal@pnnl.gov

https://godeeep.pnl.gov/