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Incorporating Multivariate Weather Hazards into System Planning with Energy Storage

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2025 ESIG Forecasting & Markets Workshop

KEY QUESTION

- How do **extreme weather and changing weather patterns** affect the deployment potential for **energy storage** in power system planning?

Commentary

Extreme weather and electricity markets: Key lessons from the February 2021 Texas crisis

Todd Levin,[1,*] Audun Botterud,[1,2] W. Neal Mann,[1,3] Jonghwan Kwon,[1] and Zhi Zhou[1]

Joule

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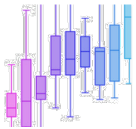
METHODOLOGY

WORKFLOW TO APPLY WEATHER IMPACTS TO CAPACITY EXPANSION PROBLEMS

Weather Scenarios

High-Frequency & High-Spatial Resolution Synthetic Weather

Analyze and screen possible future weather patterns

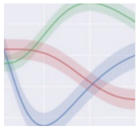


- Temperature
- Precipitation
- Wind/solar availability
- Extreme weather events

Weather to Grid Translation

Translation Models

Generate probabilistic grid event scenarios

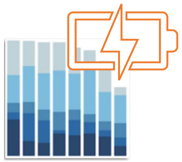


- Electricity demand
- Wind/solar profile
- Fuel supply constraints
- Grid asset de-rating
- Grid asset outage

Power System Planning

Argonne's Power System Model A-LEAF

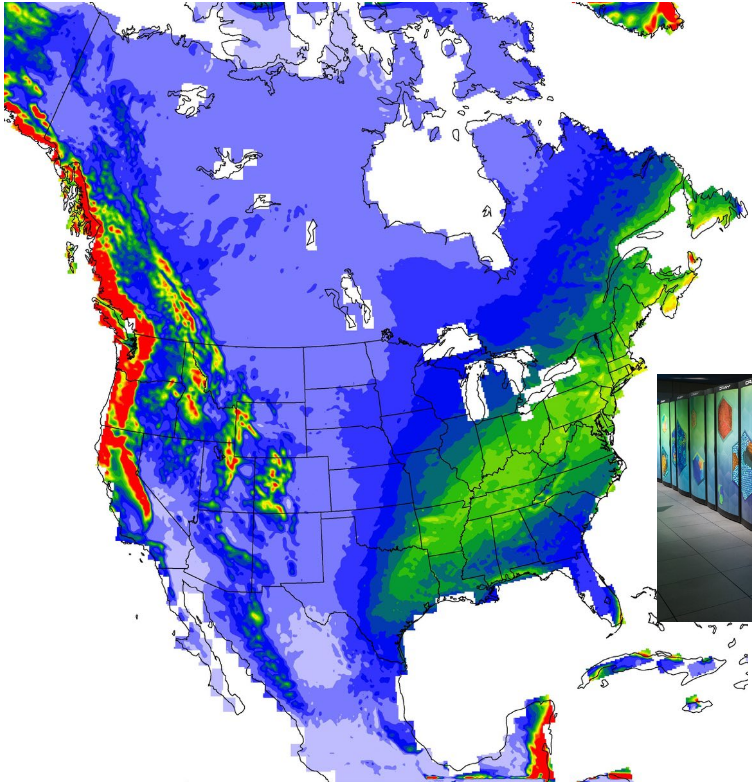
Power system capacity expansion planning and production cost simulations

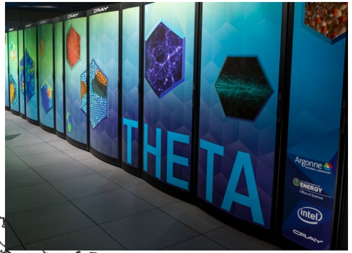


- Generation/energy storage mix and dispatch
- Transmission expansion and flows
- Energy and reserves prices

ARGONNE'S LARGE SYNTHETIC WEATHER DATASET

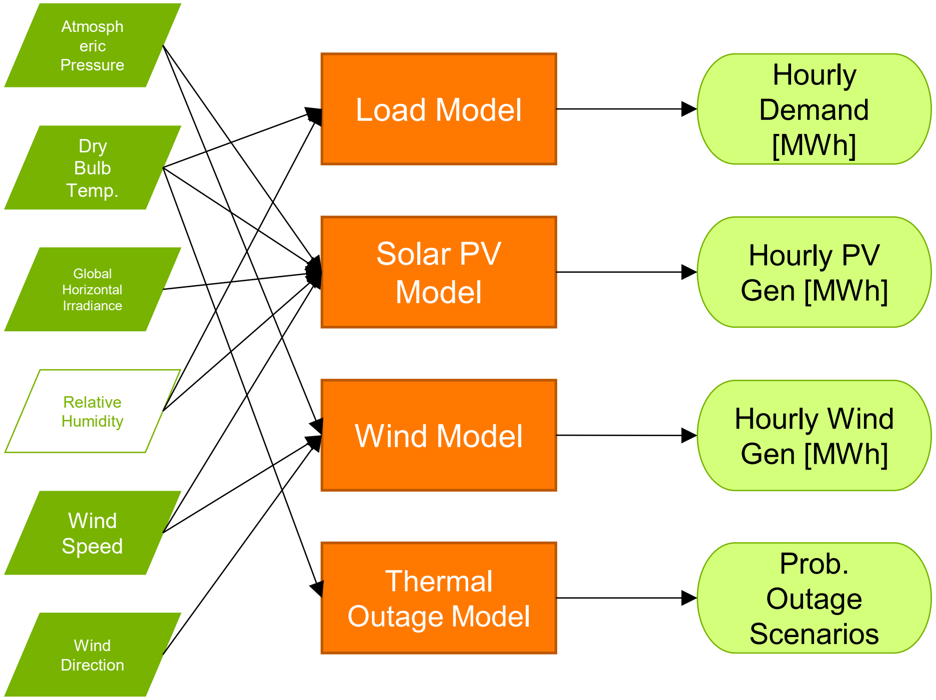
- High resolution, 12 km grid
- Scientific transparency: widely published and scientifically peer reviewed modeling and outcomes
- Dynamical downscaling offers improvements over statistical downscaling
  - Physics-based, addresses non-stationarity
  - Produces 60+ unique climate variables
- High- and low-emissions scenarios
- Three-member ensemble of GCMs
- Three decadal timeframes: historical, mid-century, end-of-century
- Over 100 scenario years @ 3-hourly or hourly time steps
- Summary statistics available on the ClimRR Portal





WEATHER TO GRID DATA PIPELINE

- **Current features**
  - Load and demand
  - Solar PV output
  - Wind output
  - Thermal generator outage scenarios
- **Work in progress**
  - Other generator deratings and outages
  - Transmission line deratings and outages
  - Water availability (hydro)



POWER SYSTEM MODELING
WITH A-LEAF

Argonne NATIONAL LABORATORY

ADVANCED OPTIMIZATION

- System least-cost planning and operations
- Strategic investments
- Sub-hourly dispatch
- Multiday representative periods
- Simultaneous generation and transmission, and storage expansion planning

DETAILED U.S. GRID DATABASE

- Extensive database of 9000+ U.S. generation resources
- Hourly load profiles for 130+ balancing authorities
- User-defined transmission zones at any scale
- 200+ zone county-level Texas system

CLIMATE AND WEATHER DATA

- Future weather years derived from climate models
- Extreme weather events
- Hourly wind and solar availability for current and future scenarios
- Temperature dependent thermal outages

WHOLESALE MARKET DESIGN

- Multi-stage market settlement
- Scarcity pricing mechanisms
- Forward market modeling

POLICIES AND REGULATIONS

- National and local policies and incentives
- Customizable critical material constraints
- Land use restrictions and resource availability

MULTI-SECTOR INTERDEPENDENCY

- Coupling with a global energy systems model (TIMES)
- Water-energy nexus
- Transportation systems
- Natural gas infrastructure

RELIABILITY AND RESOURCE ADEQUACY ASSESSMENT

- Probabilistic reliability assessment
- Capacity accreditation using ELCC
- System inertia requirements

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SUMMARY OF A-LEAF MODEL SETUP AND ASSUMPTIONS

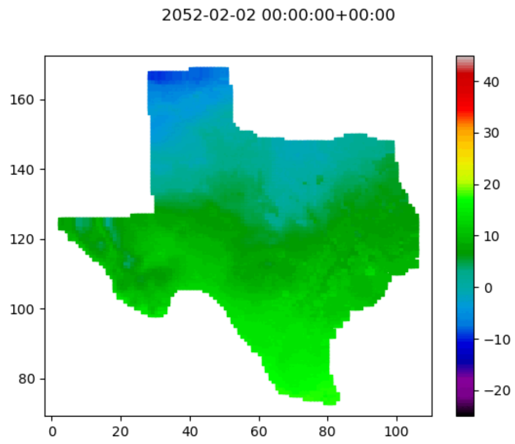
See Appendix for More Details

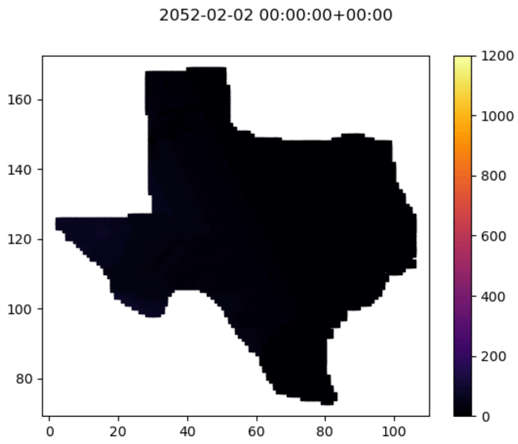
Parameter	Value
Planning stages	2050
Representative chronology	10 groups of 5 consecutive days
Network scope	ERCOT Weather Zones
Tax credits	None
Policy-based portfolio requirements	None
Generator expansion options	NGCC, NGCT, nuclear, solar PV, wind
Storage expansion options	Lithium ion (LFP) 100 MW @ 2, 4, 8 hours duration
Transmission expansion	None
Energy storage minimum investment	Thermal energy storage (TESS), 10 GW
Energy storage minimum investment scenarios	0, 10, 24, 100 hours duration (0 GWh, 100 GWh, 240 GWh, 1 TWh)
Weather years	8 selected for weather extremes

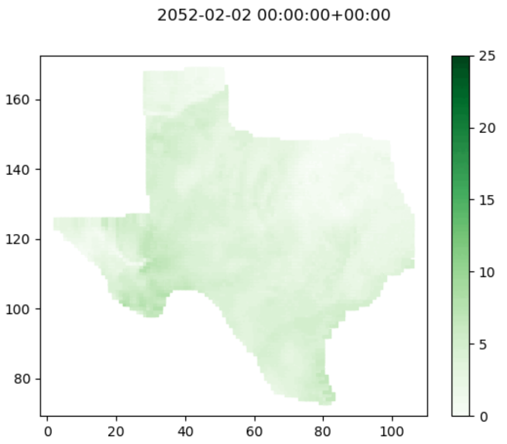
SELECTING MULTIVARIATE HAZARDOUS WEATHER EVENTS

- **From 20 synthetic weather years, 5-day multivariate hazard indices were calculated**
  - Spatial and daily average (across Texas) for three variables
  - Normalize and calculate geometric mean of three variables → hazard index
  - Calculate rolling 5-day average hazard indices
- **Eight potentially hazardous events were selected**
  - Low temperature, low wind speed, low solar irradiance → four events
  - High temperature, low wind speed, low solar irradiance → four events

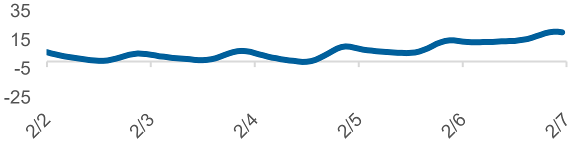
EXAMPLE EVENT: LOW TEMPERATURE, LOW GHI, LOW WIND SPEED



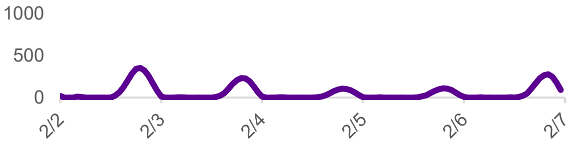




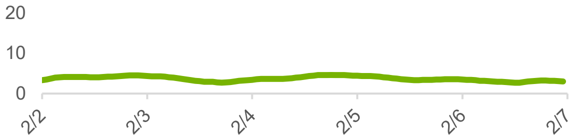
Air Temperature [°C]



Global Horizontal Irradiance [W/m^2]



Wind Speed [m/s]



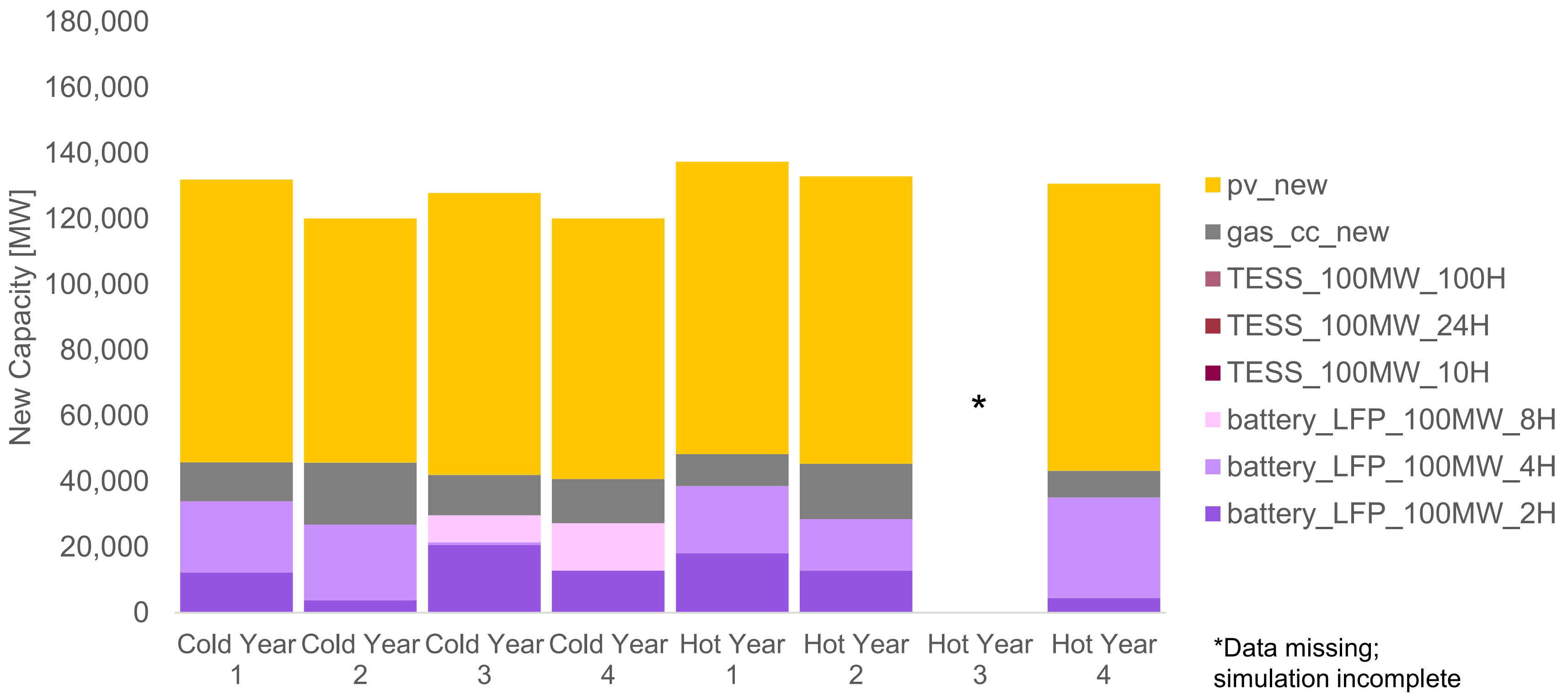
COMBINING REPRESENTATIVE PERIOD SELECTION WITH EXTREME EVENTS

- **The ScenRed[1] scenario reduction method was used first**
  - Samples a user-selected number of n-day periods from a year
  - The periods (day groups) are the scenarios
  - Each day group is given a probability (used as weight)
- **ScenRed output was combined with hazardous periods**
  - Hazardous periods were manually added to the ScenRed output
  - Hazardous period weights were adjusted from 1–50%
  - ScenRed weights were reduced proportionally

[1] See https://gitlab.com/supsi-dacd-isaac/scenred & https://doi.org/10.1007/s10107-002-0331-0

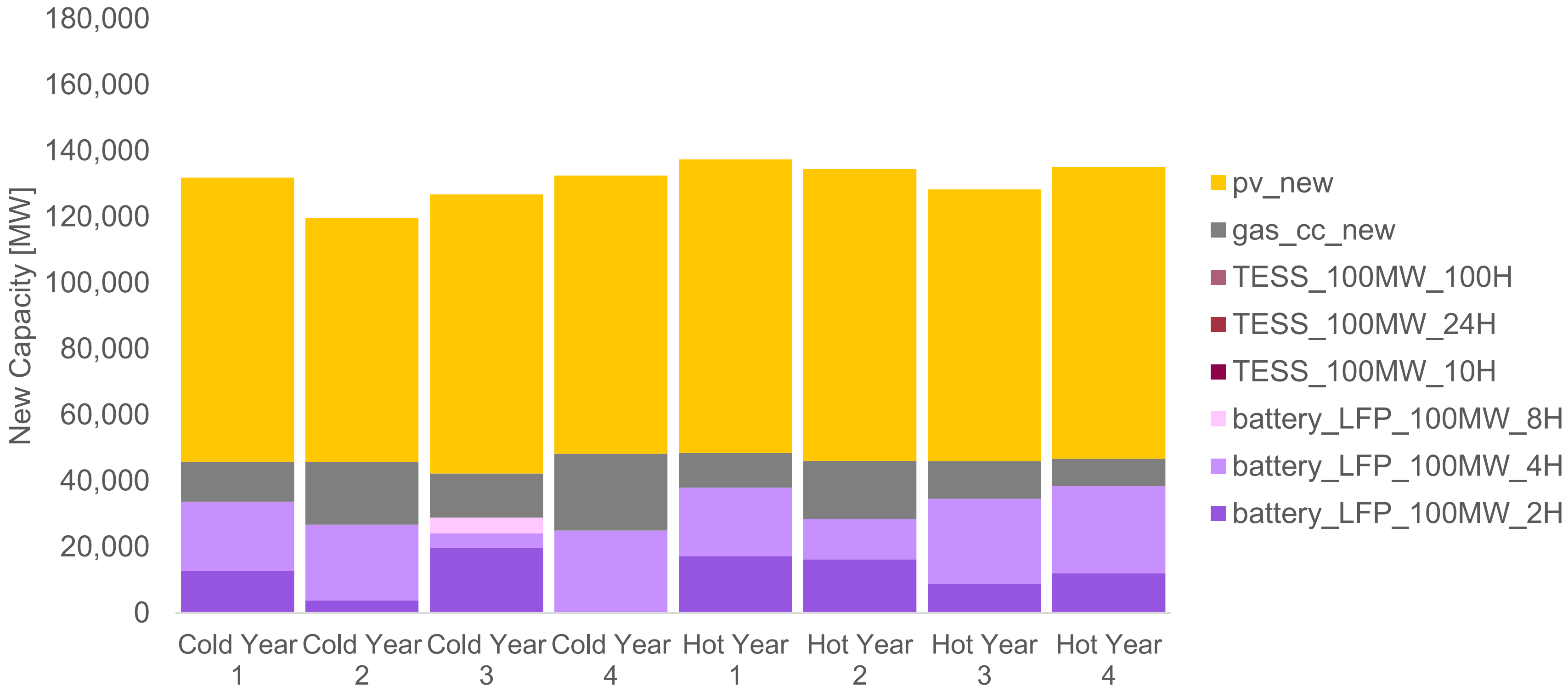
INITIAL RESULTS

NO THERMAL ENERGY STORAGE (TESS), NO EXTREMES



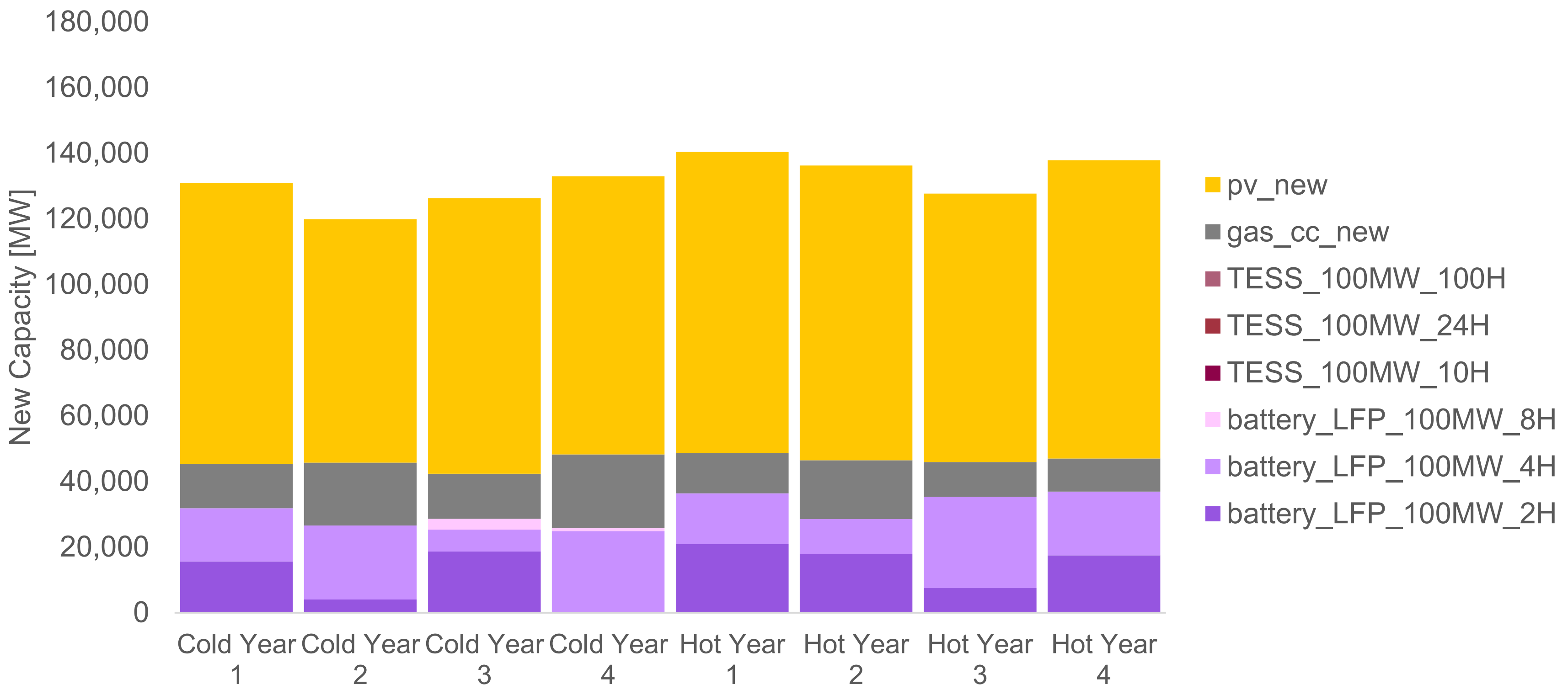
*Data missing; simulation incomplete

NO TESS, 1% EXTREMES WEIGHT

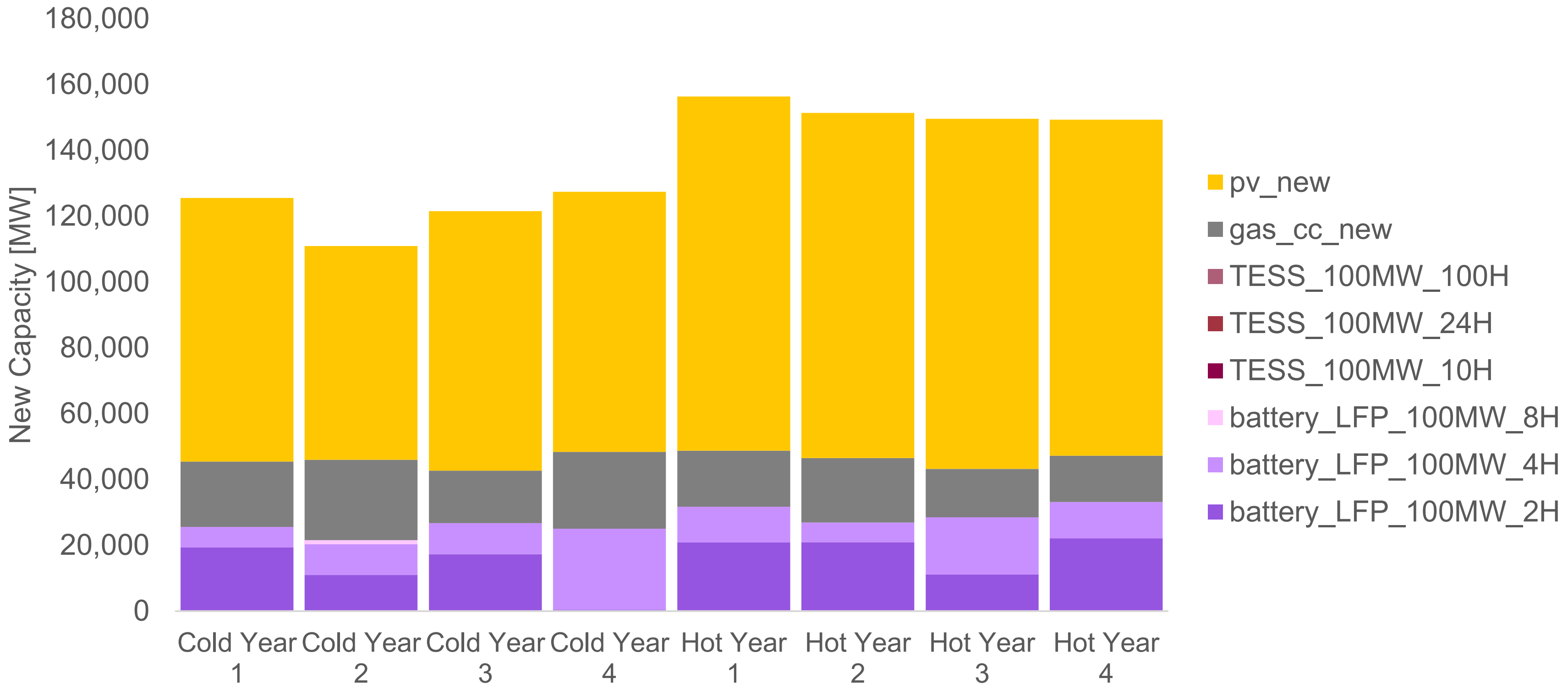


Note shifts in NGCC and storage

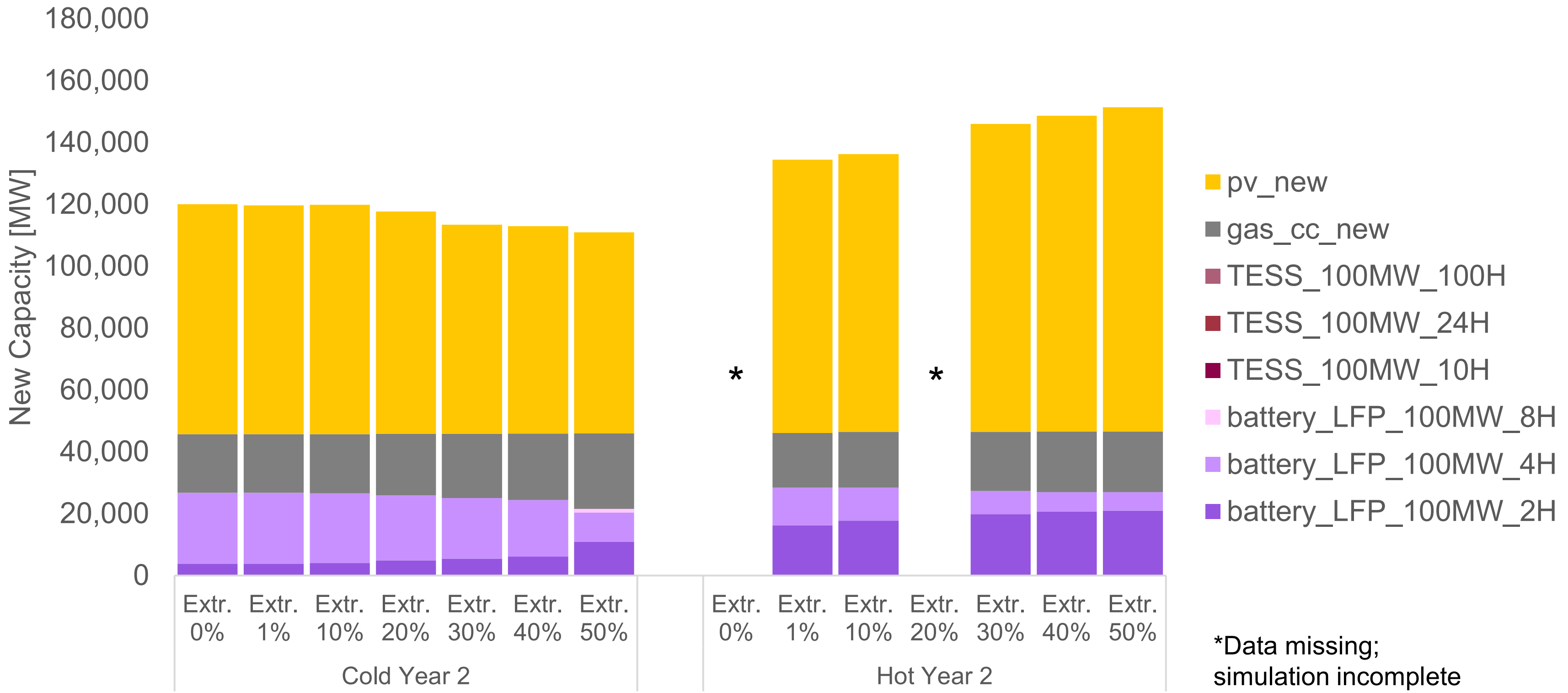
NO TESS, 10% EXTREMES WEIGHT



NO TESS, 50% EXTREMES WEIGHT

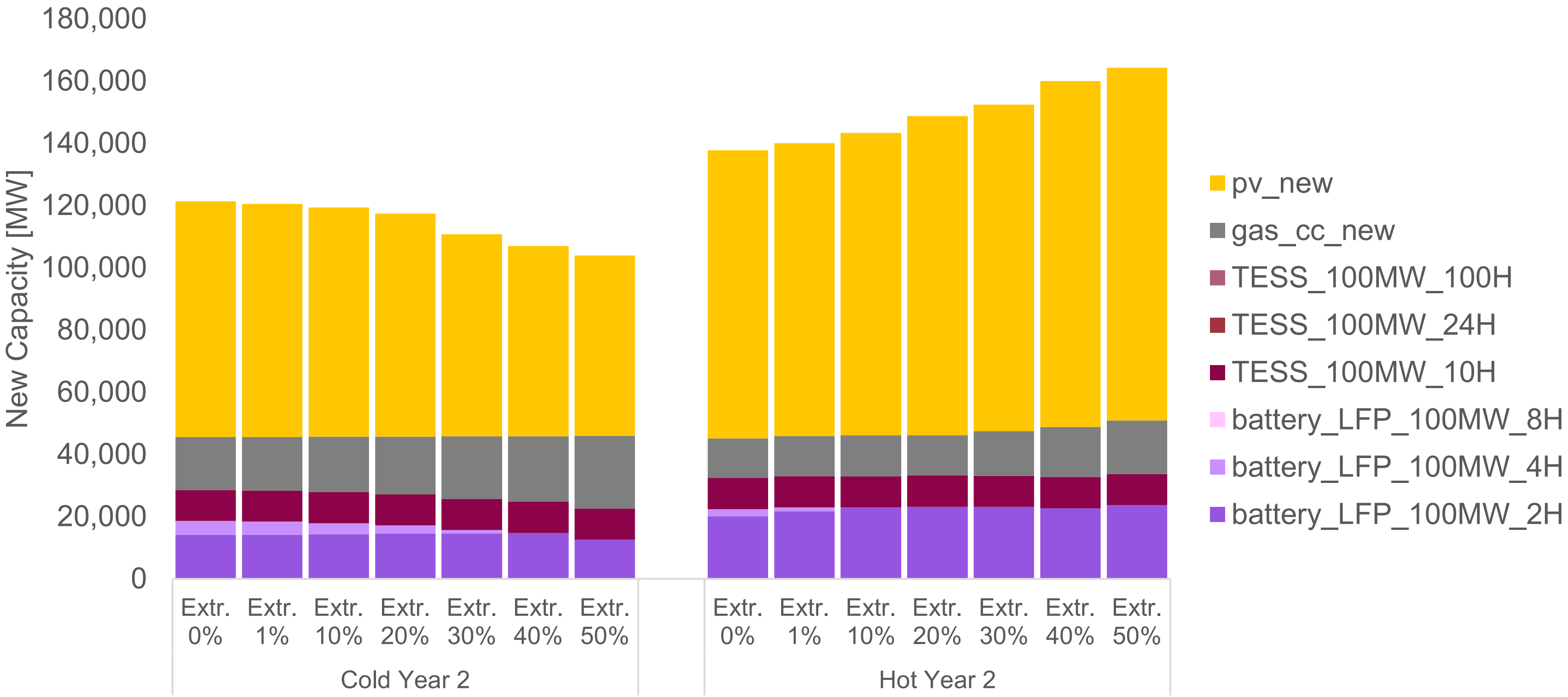


NO TESS, TWO EXAMPLE YEARS



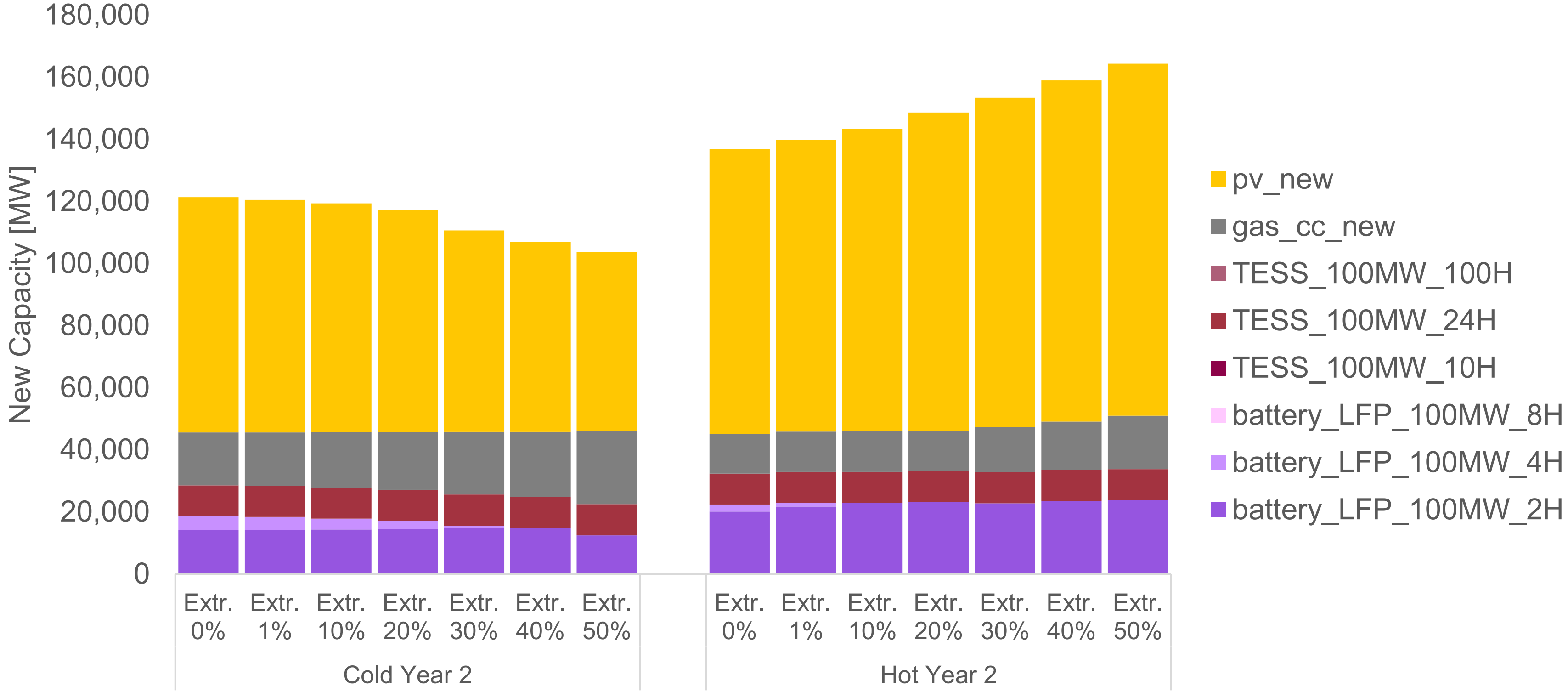
*Data missing; simulation incomplete

WITH TESS, 10 GW @ 10 HOUR DURATION



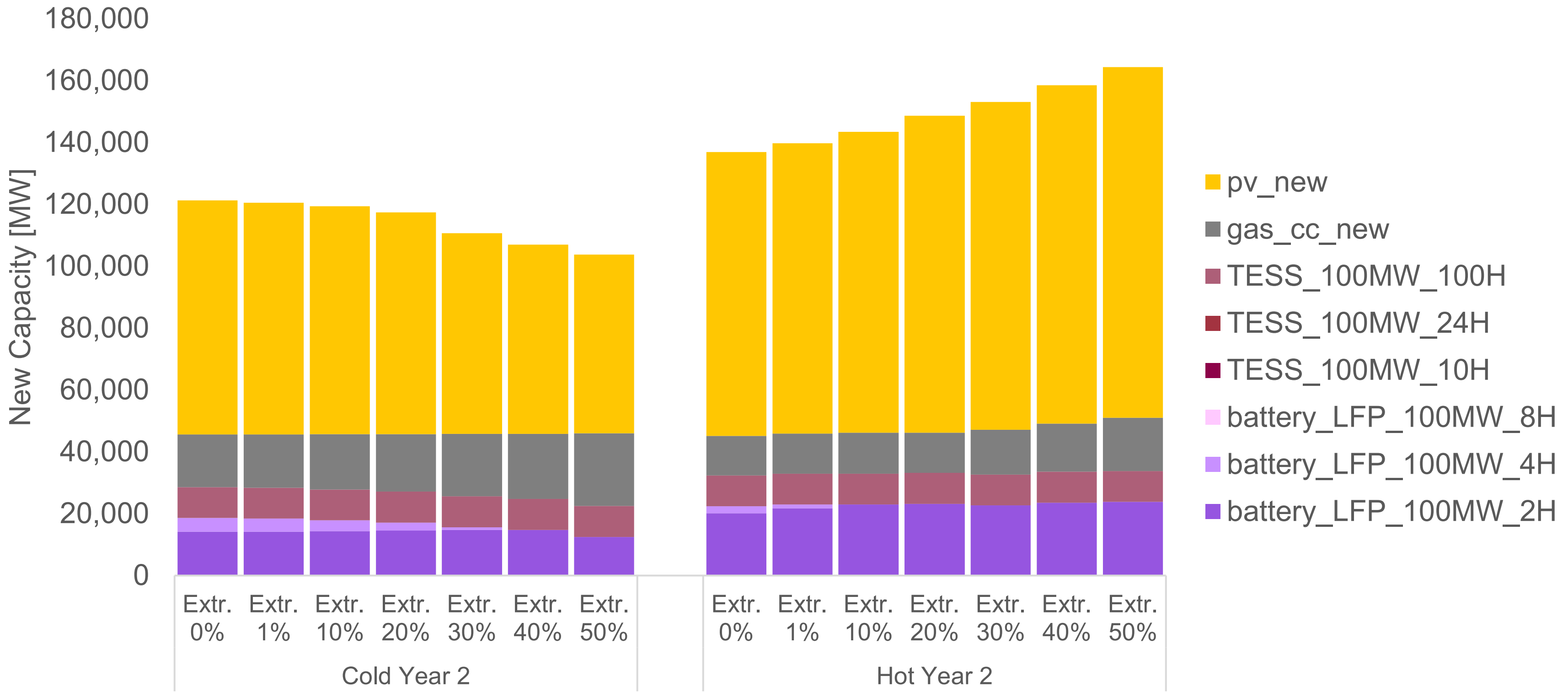
Note shifts in NGCC and storage

WITH TESS, 10 GW @ 24 HOUR DURATION



Little difference between 10, 24, 100 hours

WITH TESS, 10 GW @ 100 HOUR DURATION



Little difference between 10, 24, 100 hours

CONCLUSION

OBSERVATIONS

- **Developed a new workflow to incorporate extreme and hazardous weather events into power system planning**
- **Including multivariate hazardous weather events did change capacity expansion results**
- **As TESS duration was increased from 10 to 24 to 100 hours (all 10 GW), there was little change in the new capacity mix**
- **Heavier weighting of hazardous events had mixed effects on energy storage capacity**
  - Typically flat or less energy storage [MW] as weights were increased
  - 2-hour storage made up a larger proportion of total storage capacity [MW] at the expense of 4-hour storage
  - Interaction/competition with NGCC and solar PV
- **8-hour storage was seen in only a few scenarios**

FUTURE WORK

- Expand hazard indices to cover all permutations (in progress)
- Calculate hazard indices for events in all regions of the CONUS (in progress)
- Apply entire workflow to the rest of the CONUS (scalable from counties to whole interconnections)
- Include more detailed reliability simulations to verify results (including probabilistic outages)

ACKNOWLEDGEMENTS AND NOTICE

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Notice

THANK YOU!

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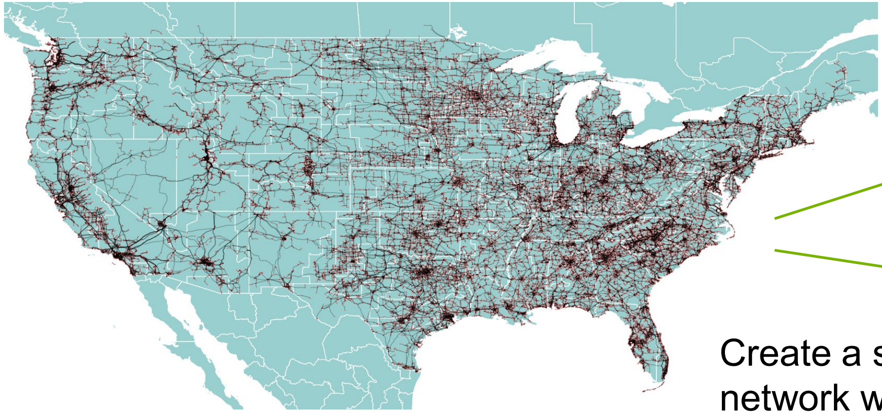
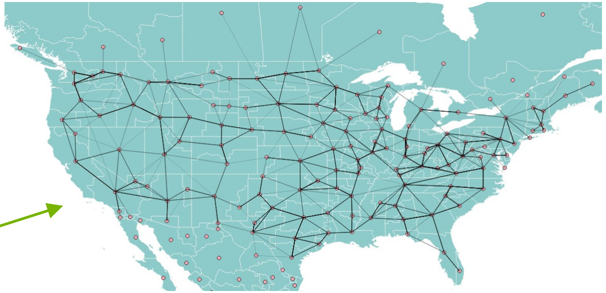
APPENDIX

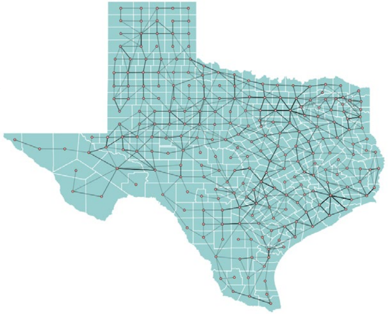
A-LEAF LC-GTEP: FLEXIBLY DETAILED TRANSMISSION MODEL

~90,000 US Transmission Lines in HIFLD Data



Bus
Transmission Line

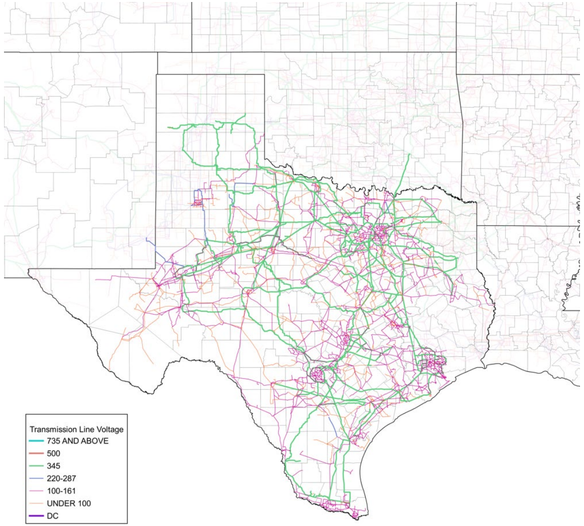


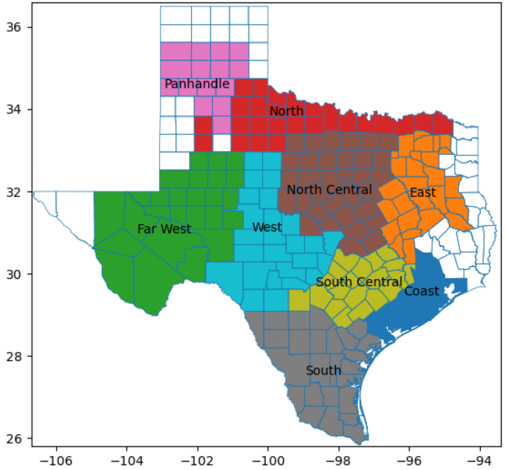


Create a simplified synthetic network with tunable level of detail

EXPANDED A-LEAF CAPACITY EXPANSION AND PRODUCTION COST MODEL

- ERCOT zonal aggregated transmission network with individual or aggregated generators





A-LEAF LC-GTEP: RESOLUTION AND DETAIL OPTIONS

Increased robustness, increased complexity →

Category	Key Features	Modeling Options in A-LEAF			
Planning	Planning Horizon	static		milestone-years (manual)	path optimization
	Type of decisions	investment		+ retirement	+ transmission expansion
Short-term System Operations	Temporal time resolution	hourly			five minute
	Representative days	time slices	one day	day groups	full
	Scheduling algorithm	economic dispatch (ED)			unit commitment (UC)
Transmission Network Modeling	Geographical Scope	regional			national
	Spatial Resolution	single zone		multi zone	*nodal*
	Transmission constraints	none	inter-zonal	*+selected intra-zonal*	*full*
	Power flow model	none		Network flow	*DC*

DETAILED A-LEAF MODEL SETUP AND ASSUMPTIONS

Parameter	Value
Model type	Least-cost generation and storage expansion
Planning stages	2050
Representative chronology	10 groups of 5 consecutive days
Scheduling	Economic dispatch only
Investment decisions	Linear
Retirements	Allowed
Network area	ERCOT
Network aggregation	Weather zone
Power flow mode	Pipe flow
Existing generator/storage aggregation	Individual units
Planning reserve margin	13%
Tax credits	None
Policy-based portfolio requirements	None

Parameter	Value
Generator expansion options	NGCC, NGCT, nuclear, solar PV, wind
Generator cost assumptions	ATB 2024, Moderate
Storage expansion options	Lithium ion (LFP) 100 MW @ 2, 4, 8 hours duration
Storage cost assumptions	ESGC 2024, Low Price/Fast Learning
Transmission expansion	None
Energy storage minimum investment	Thermal energy storage (TESS), 10 GW
Energy storage minimum investment scenarios	10, 24, 100 hours duration (100 GWh, 240 GWh, 1 TWh)
Fuel prices in 2050 (2021 USD)	Coal: $1.79 NG: $3.88 Nuclear: $0.83
Weather years	8 selected for weather extremes