Resource Adequacy and the Energy Transition in the Pacific Northwest

Technical Appendix

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Energy+Environmental Economics

Technical Appendix Content

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- **Resource Adequacy Analysis**
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Regional Trends and Challenges

Since 2017, NW regional studies have changed from indicating future RA deficits to immediate reliability risk with a growing resource gap

2017

E3's PNW Low-Carbon Scenario Analysis

CO2 reductions can be met with efficiency, renewables and gas. **Prohibiting new gas or relying on RPS alone may be expensive and ineffective.**

PNUCC 2017

Winter deficit identified in near term, growing going forward. **Concerns that non-firm capacity is more restricted in summer.**

2018

PNUCC 2018

Report cites worsening summer deficit; winter deficit was narrower but persistent.

2019

E3's RA in the PNW

Capacity deficits identified. Risk of supply shortages increasing. **7 GW of new resources by 2030 required.** Firm, dispatchable capacity must be a part of the solution.

PNUCC 2019

Concerns of tightening resource availability become stronger, citing increasing renewables, tightening hydro, tightening RA margins, coal retirements.

2021

NW Power Plan & Adequacy Assessment for 2029

System only **adequate if upper end of the 2021 plan is implemented.** If energy efficiency falls short or data center load growth increases, adequacy requirements are not met.

2024

BPA's PNW Loads and Resources Study

Annual demand is expected to surpass firm energy by 2027, and **winter 2025 energy deficit** is a risk.

WECC WARA

Identifies severe RA challenges if forecasted demand is realized and resource builds **are delayed or cancelled.**

PNUCC 2024

Immediate reliability risk in the NW, with annual, seasonal, energy and peak capacity deficits in 2025 and beyond. **Projects ~10-12 GW needed by 2030.**

2025

PNUCC 2025

Immediate reliability risk in the NW, projects a gap of ~13.7 GW by 2034 for winter peaking.

2021-2024 Extreme Summer Peak Events

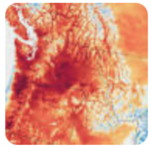
- The region experienced an historical extreme heat event in history in June 2021
- Each summer since then (2022, 2023, 2024) has continued to show extreme heat and peak demand near the 2021 peak of ~33,000 MW
  - 2020-2022 all experienced summer peaks near or above winter peaks

Climate.gov Home

Astounding heat obliterates all-time records across the Pacific Northwest and Western Canada in June 2021

One of, if not the, worst heat wave in the region's modern records impacted the Pacific Northwest of the United States and western Canada...

Jun 30, 2021

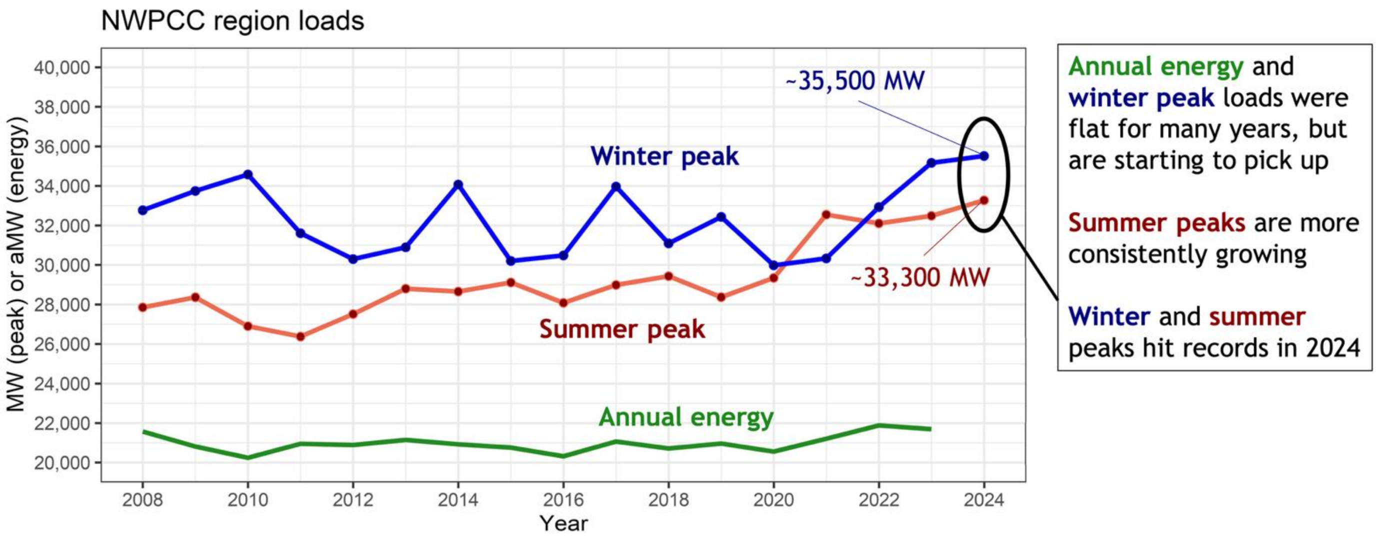


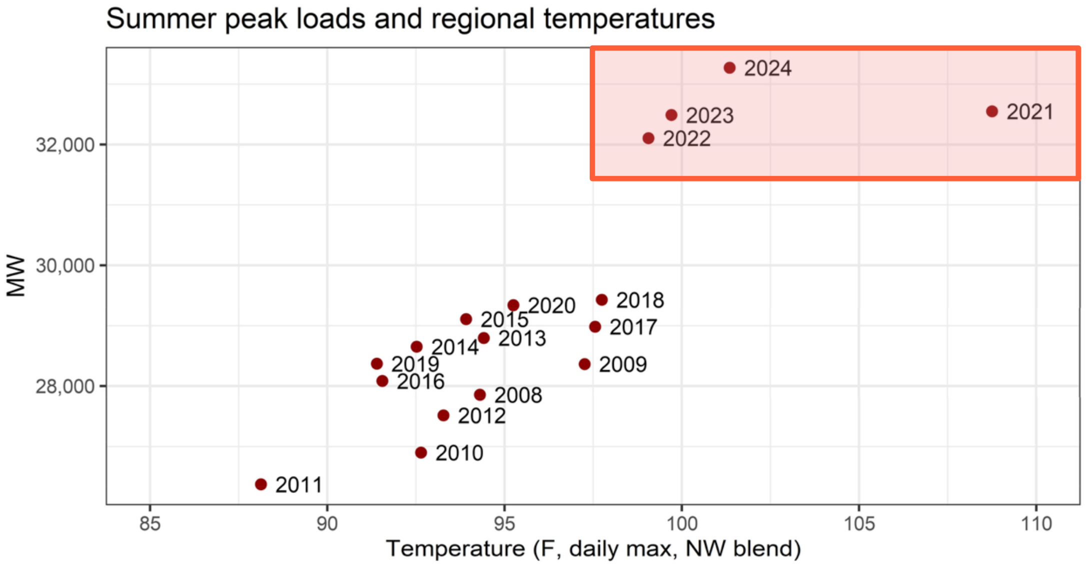
The Guardian

Record-breaking US Pacific north-west heatwave killed almost 200 people

Officials reported 116 deaths in Oregon and 78 in Washington after extreme temperatures in normally moderate region.

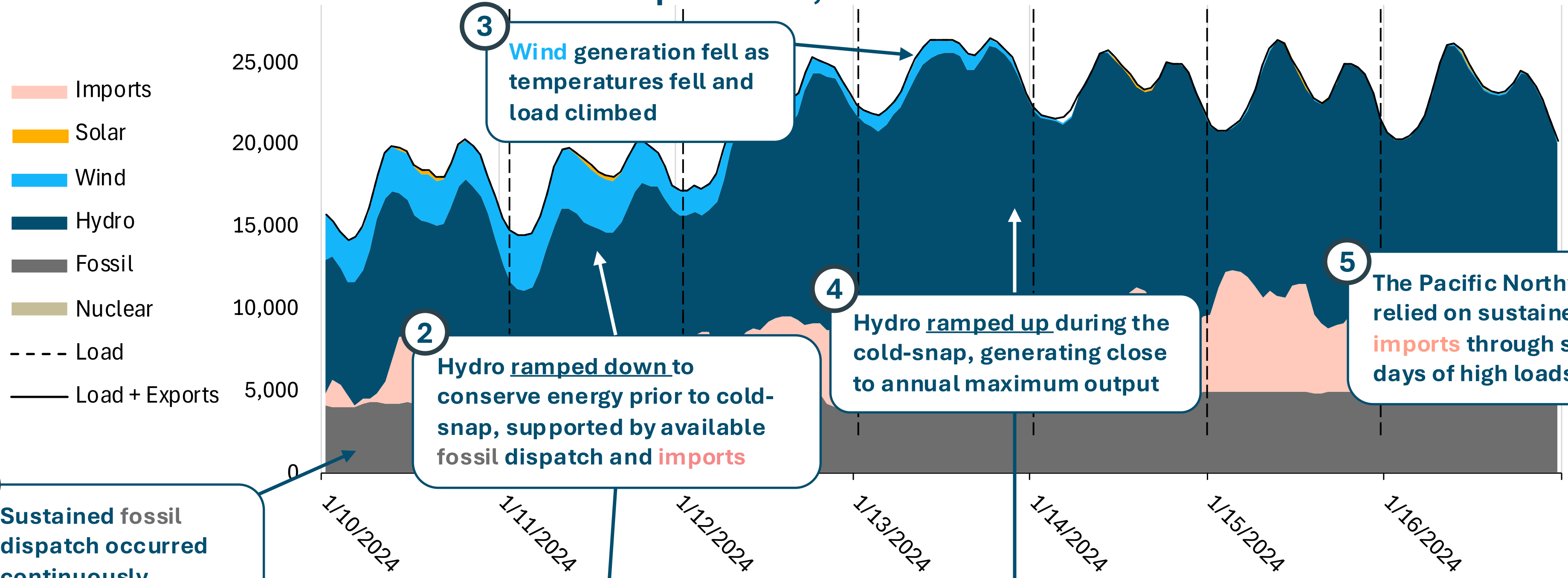
Jul 8, 2021





January 2024 Cold Snap Event

Pacific Northwest Operations, *MW*



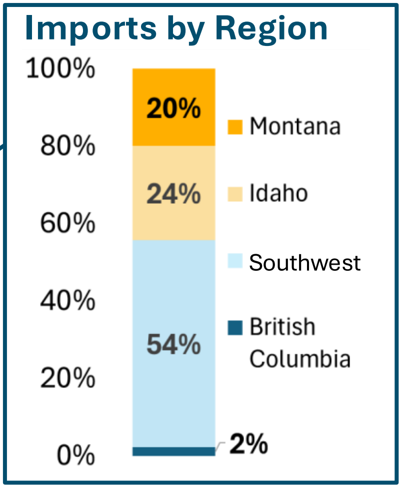
1 Sustained fossil dispatch occurred continuously throughout the week

2 Hydro ramped down to conserve energy prior to cold-snap, supported by available fossil dispatch and imports

3 Wind generation fell as temperatures fell and load climbed

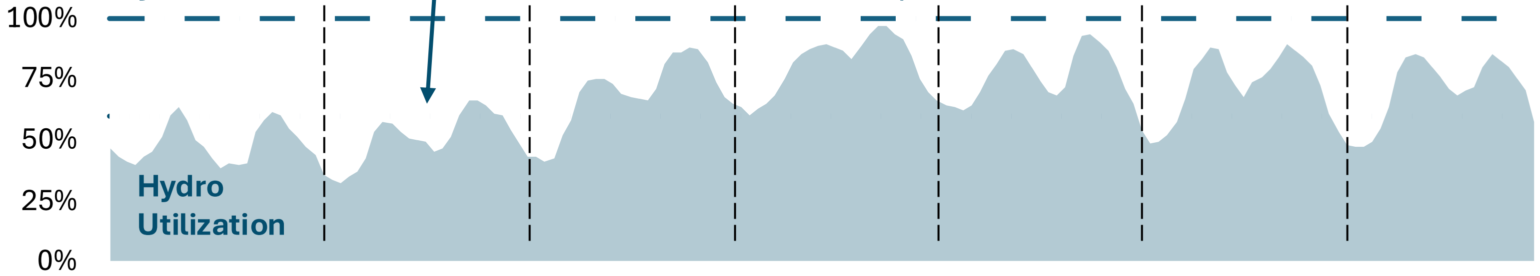
4 Hydro ramped up during the cold-snap, generating close to annual maximum output

5 The Pacific Northwest relied on sustained imports through several days of high loads



Over half of imports were from outside the Greater NW region (via CA transmission)

Hydro Fleet Utilization, % of maximum 2024 output



Max Hydro Output in 2024

Average Hydro Output for Jan. 2024

"The amount of inter-regional support necessary to manage… operations through the cold weather event is **indicative of the pressing need to address RA and potential capacity shortfalls as soon as practicable**, highlighting the value of an RA program with a broad geographic footprint and diversity of load and resources." – Western Power Pool Jan 2024 Event Assessment

Challenges remain to addressing regional RA needs

+ **Since E3's previous Pacific NW studies (2017 and 2019) highlighted a multi-GW growing regional shortfall, resource adequacy concerns in the region remain, driven by:**
   1. Changing climate patterns and extreme events have stress-tested the system more than ever before in cold-snap and heat-wave events
   2. Faster than-expected electrification and data center load growth continue to increase load forecasts
   3. Not enough new resources have been built to fill the previously identified gap

Prior Recommendation	Status	Summary
Develop formal mechanism for regional sharing of planning reserves	**Delay**	WRAP was established in 2022 to support regional RA sharing and is now just on the verge of becoming operational. To date it was not designed to provide long-term accreditation forecasts that would allow market participants to conduct adequate forecasting, though there are discussions to consider doing so.
Ensure sufficient firm generation to maintain system reliability as coal retires and load grows	**Set-back**	Natural gas is the only near-term commercialized firm resource option. OR has a ban on new gas capacity, new gas in WA is expected to face siting and permitting challenges and may require pipeline expansion, creating a challenge for new firm capacity in the most RA constrained areas. Outside OR/WA, several planned coal retirements will now be coal-to-gas conversions, and some new gas has been built in MT/UT/ID/WY.
Maintain existing clean energy infrastructure	**Under threat**	Existing hydro and nuclear fleet have been maintained, though there is ongoing advocacy for some hydro dam removal.
Build clean energy resources at a fast pace to meet decarbonization targets and growing energy needs	**Critical**	IRPs identified 35+ GW of new resources between 2018-2032 (nearly all renewable or short-duration energy storage), annual capacity additions would need to rapidly increase to stay on that path while new growth faces key constraints incl. limited firm transmission

Resource Adequacy Analysis

RECAP Methodology, Inputs & Assumptions, Subregional Results

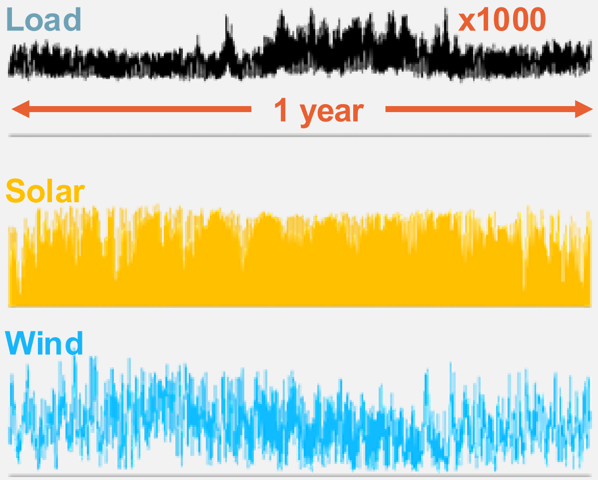
Energy+Environmental Economics

Three Key Steps for Reliability Planning

Part 1: Model + Data Development

Develop a robust dataset of the loads and resources, typically in a loss of load probability (LOLP) model

LOLP modeling evaluates resource adequacy across all hours of the year under a broad range of weather conditions

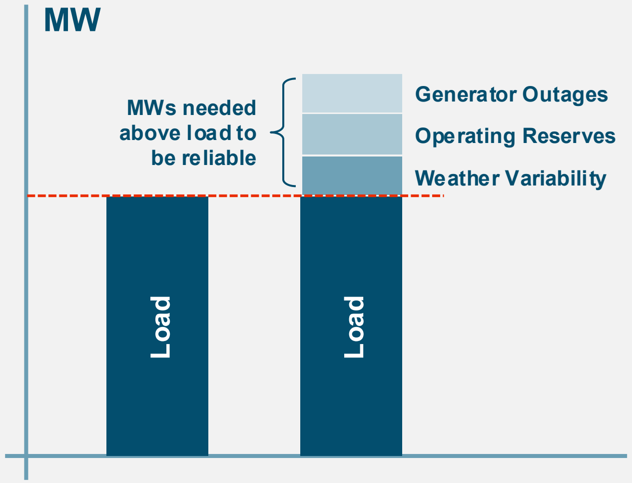


Robust probabilistic models + datasets are the foundation of any resource adequacy analysis

Part 2: Need Determination

Identify the Total Reliability Need to achieve the desired level of reliability

Factors that impact the amount of effective capacity needed include load & weather variability, operating reserve needs

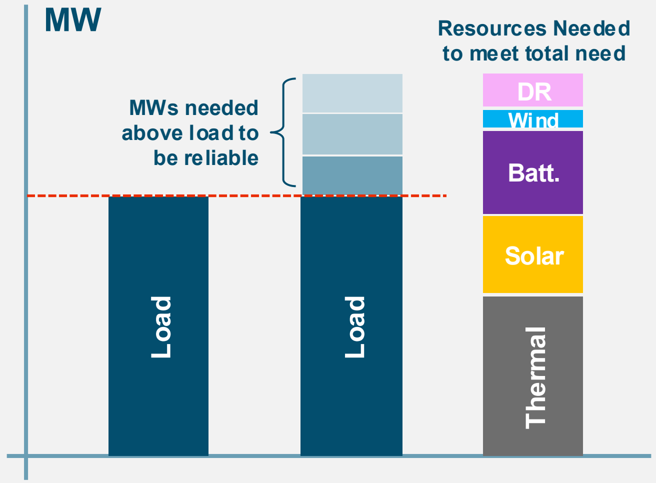


The total reliability need is calculated to meet a target reliability standard (e.g. 0.1 LOLE)

Part 3: Resource Accreditation

Calculate resource capacity contributions

Measures a resource's contribution to reliability needs relative to target reliability, accounting for performance across all hours



Resource accreditation determines how much each resource counts towards the total reliability need

E3's RECAP loss-of-load probability model was used to study resource adequacy needs and resource contributions

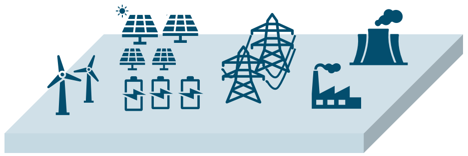
+ **RECAP is a loss-of-load-probability model developed by E3 to study the reliability dynamics of high-renewable electricity systems**
+ **RECAP simulates the operations of the electricity system under thousands of scenarios to capture different conditions**
  - Including load variability, weather variability, renewable output variable, forced outage events,
+ **Key RECAP outputs:**
  - System reliability
  - Target Planning Reserve Margin
  - Capacity Shortfall
  - Capacity Value of Resources

Temperature and Load Artificial Neural Network Simulation

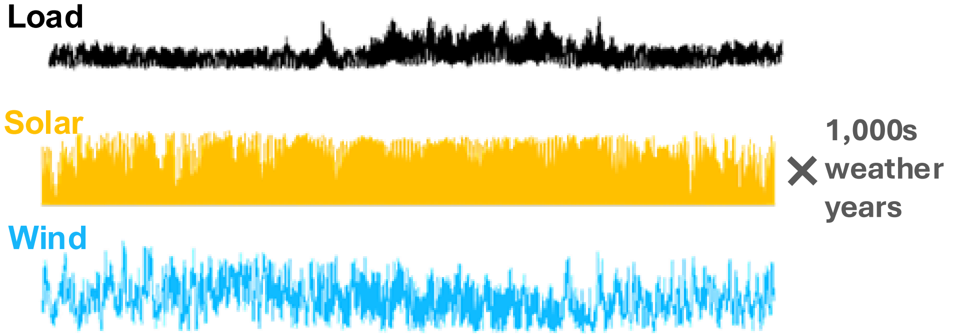
Capturing hourly load conditions under mild and extreme historical weather

Operational Module

Dispatching resources based on outage characteristics, weather dependency, state of charge availability, and demand-side management

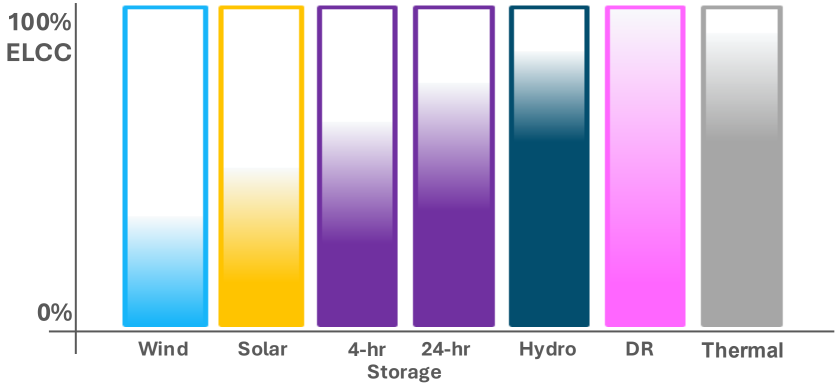


System Reliability: simulates the operations of the electricity system under thousands of scenarios to capture different conditions

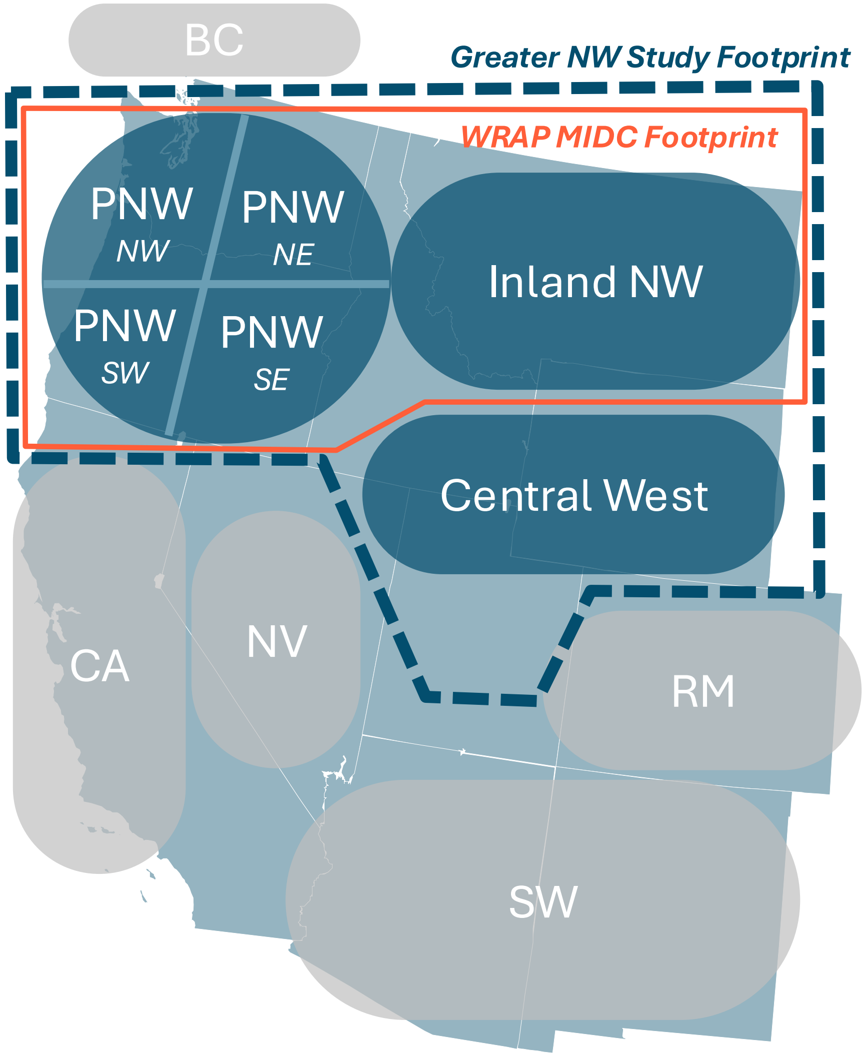


Resource Capacity Value: measures resource's ability to contribute to reliability under a marginal or average ELCC methodology

Illustrative ELCC Values Across Technologies

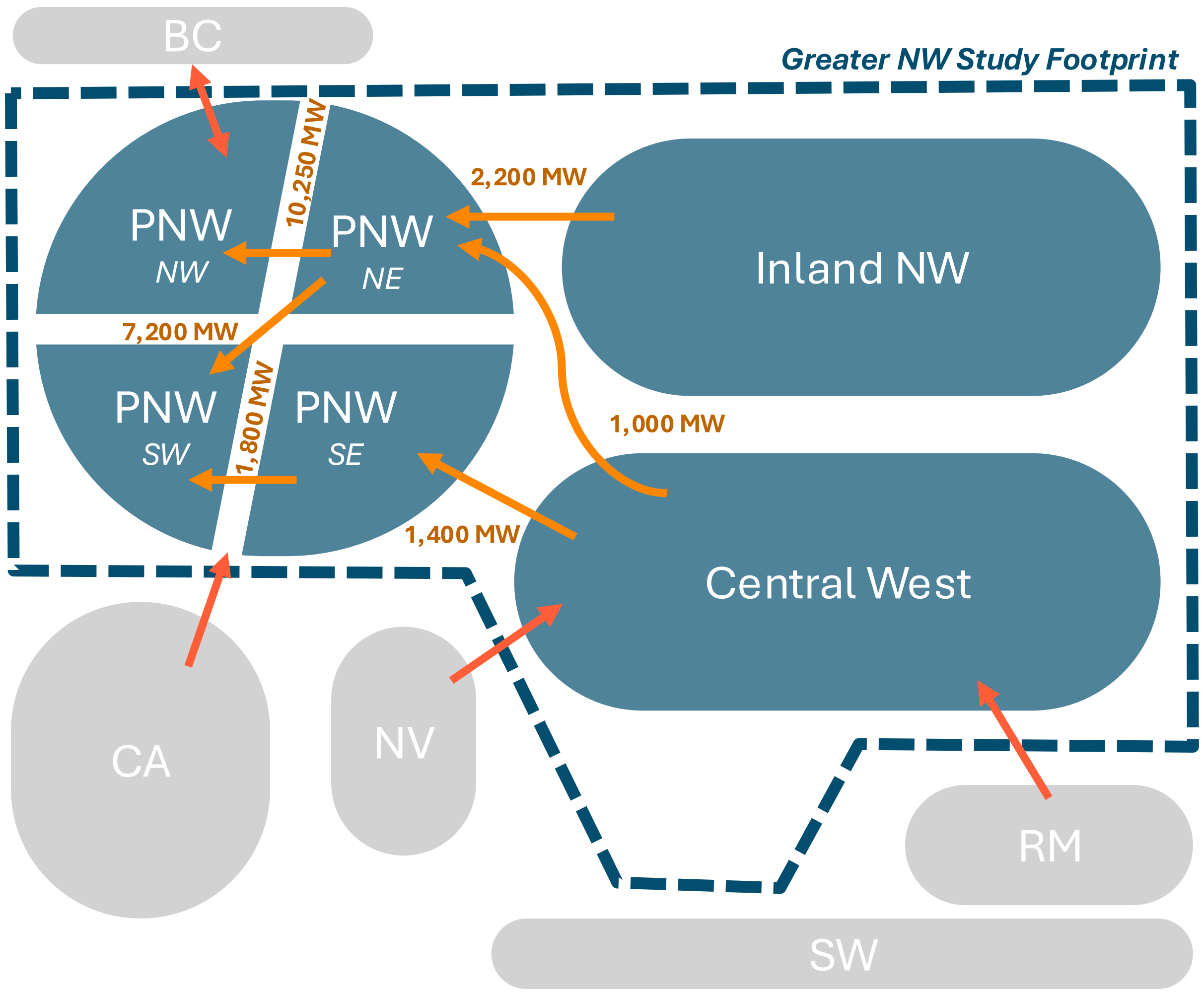


The entire northwest system is modeled in this study with subregional representation to capture local resource adequacy challenges



- **In this study, we define the study area as the following three regions within what we call the "Greater Northwest":**
  - **Pacific NW subregion** includes most of the participating utilities and is the main WRAP MIDC Subregion, with transmission constraints between 4 subregions
  - **Inland NW subregion** includes NorthWestern Energy, which is also in WRAP MIDC
  - **Central West subregion** includes Idaho Power and PacifiCorp East, and is in the WRAP SWEDE subregion
- **Resource adequacy assessments were performed on:**
  - Greater NW
  - Pacific NW subregion (OR + WA)
  - West of Cascades subregion (PNW_NW + PNW_SW)

Analysis captures the sharing of the resource adequacy capacity across the study regions and to/from neighboring regions



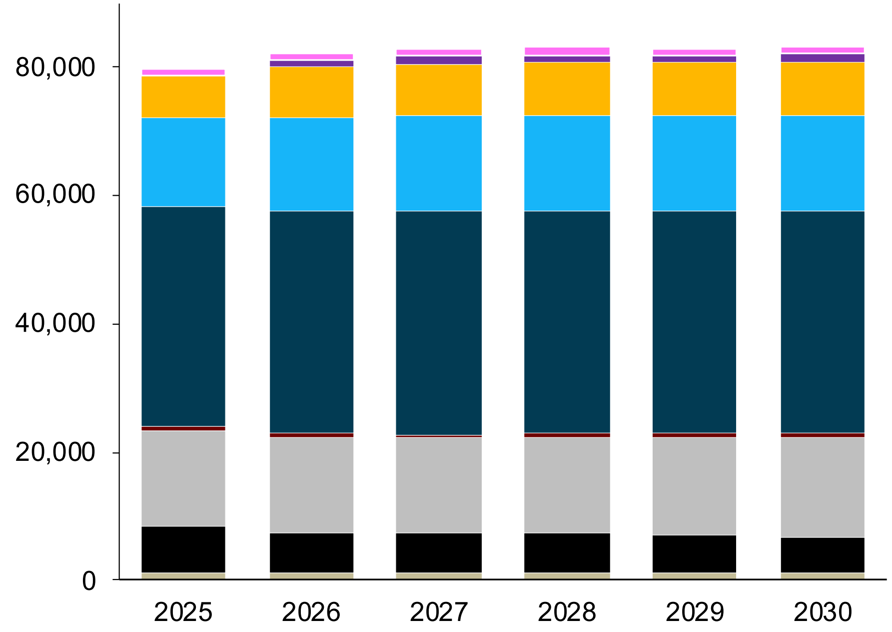
- **Firm import assumptions from outside the Greater Northwest**
  - British Columbia: 1,250 MW in the Summer, into the **Pacific Northwest subregion**
  - Nevada and Rocky Mountains: 1,250 MW in the Winter, into the **Central West subregion**
  - California: 2,500 MW in the Winter, into the **Pacific Northwest subregion**
- **Transmission availability within Greater Northwest – for sub-regional RA**
  - 4,600 MW from Inland NW and Central West into Pacific Northwest
  - 19,250 MW from East to West of Cascades (PNW-NE and PNW-SE into PNW-NW and PNW-SW)
- **Firm export obligations** at **660 MW** of capacity are included to British Columbia based on the **Columbia River Treaty Regime**

Existing and planned resources in the Northwest

- **E3's near-term resource adequacy analysis assessment includes existing and high-likelihood planned resources in the Greater Northwest study footprint 2025-2030**
  - For long-term analysis, E3 uses RESOLVE to optimize resource builds across the Greater NW footprint. Outside of the Greater NW, RESOLVE dispatches a representative future portfolio of WECC resources.
- **Baseline list of existing and planned resources taken from the WECC 2034 Anchor Data Set (ADS)**
  - Only high-likelihood planned projects were retained
    - Projects with specific siting and selected developer were retained
    - Generic resource additions were removed
  - Minor data quality adjustments made (e.g., correct assignment of resource to subregion, double counted planned projects)
- **Near-term plans were adjusted to reflect latest public announcements and contract information**
  - Review of most recent IRPs, BPA 2024 White Book, and news presses
  - Coal plans based on PacifiCorp's 2025 IRP Draft, Northwestern's 2023 IRP, & Northwestern acquisition of Colstrip

Existing and In-Development Resources

Installed Capacity, MW

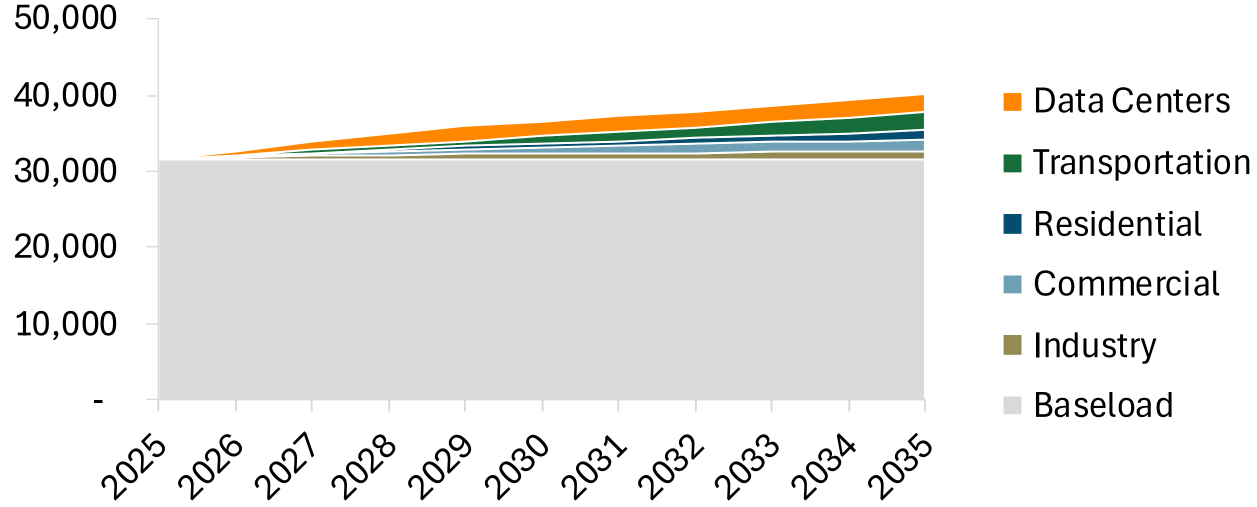


	2025	2026	2027	2028	2029	2030
Demand Response	1,122	1,122	1,122	1,122	1,122	1,122
Battery Storage	-	1,058	1,098	1,137	1,137	1,292
Solar	6,742	8,031	8,210	8,263	8,263	8,263
Wind	13,630	14,444	14,904	14,904	14,822	14,912
Hydro	34,451	34,722	34,696	34,785	34,785	34,792
Other	678	672	662	662	581	581
Gas	14,705	14,824	14,913	15,026	15,231	15,591
Coal	7,390	6,280	6,050	6,050	5,823	5,463
Nuclear	1,169	1,169	1,169	1,169	1,169	1,169

Near-term demand growth in the Greater Northwest is ~3%/yr, driven by data centers and electrification

- **Load growth projections for the Greater Northwest were developed based on E3's in-house PATHWAYS model in alignment with economic trends by sector and projected growth driven by state energy policies**
  - This forecast accounts for recent federal policy changes, such as the revocation of ACC II and ACT
  - Annual energy demand is projected to grow by 3%/yr across the Greater Northwest region, which is in line with the 3.2%/yr growth seen in PNUCC's 2025 Load Forecast (note: these correspond to slightly different geographies)

Load Growth Projection, Reference Scenario
Annual aMW

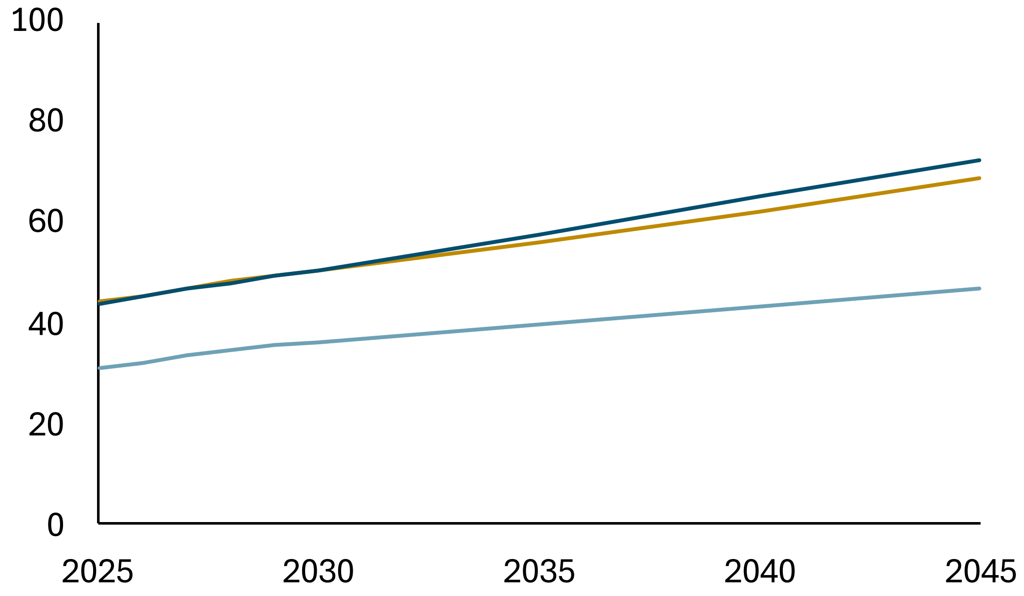


	2025		2030	
	aMW	Peak MW	aMW	Peak MW
Greater Northwest	**31,900**	**45,300**	**36,700**	**52,400**
Pacific Northwest	21,500	30,900	24,500	35,600
West of Cascades	14,200	20,900	16,100	24,300

Regional Reference Load Forecasts

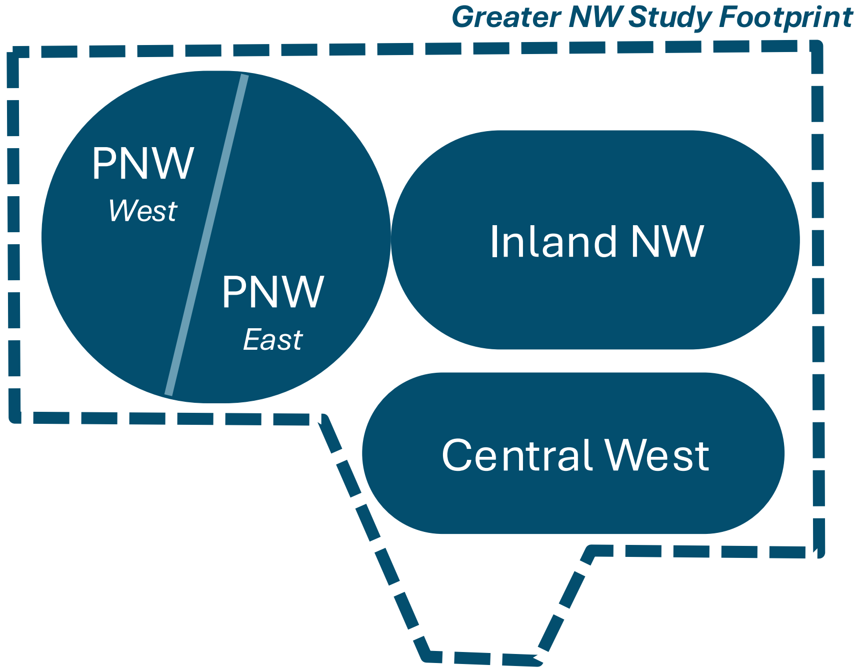
Greater Northwest

Greater Northwest
Reference Load Forecast (GW)



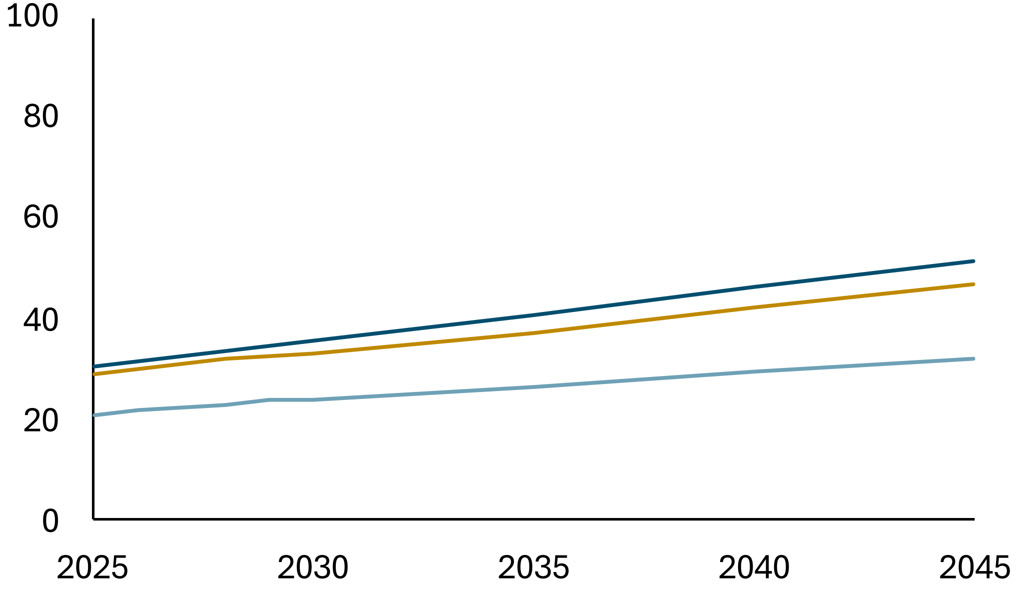
2025	2030	2035	2040	2045	
44.0	50.8	58.0	65.6	72.7	**Winter Peak** Coincident, GW
44.4	50.5	56.3	62.5	69.1	**Summer Peak** Coincident, GW
31.9	36.7	40.4	44.2	47.9	**Annual Load** aGW

- **Between 2025-2035 summer and winter peak loads grow by 2.7%/yr and 3.2%/yr, respectively, due to data electrification and center load growth**
- **Seasonal peaks gradually diverge as heating electrification accelerates**



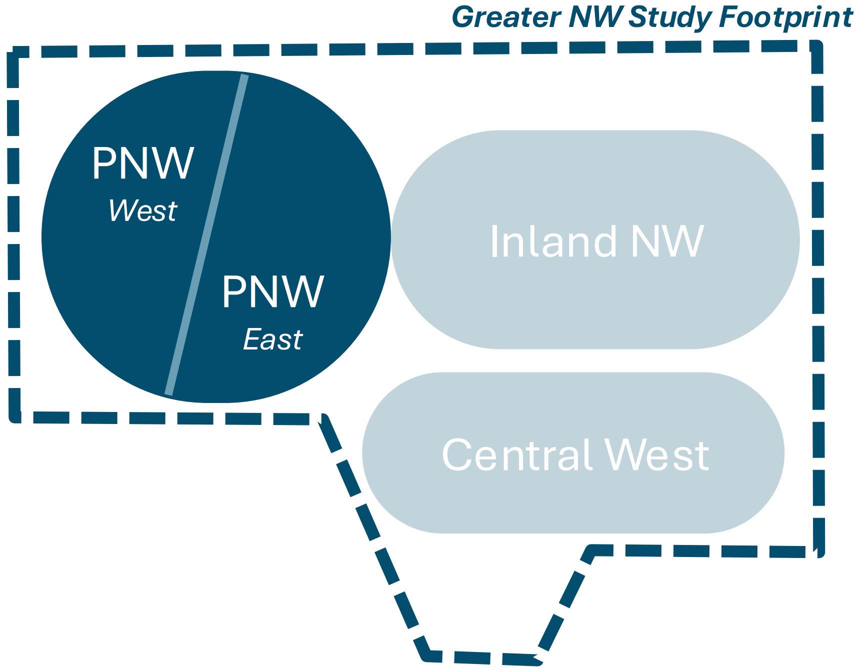
Regional Reference Load Forecasts
Pacific Northwest

Pacific Northwest
Reference Load Forecast (GW)



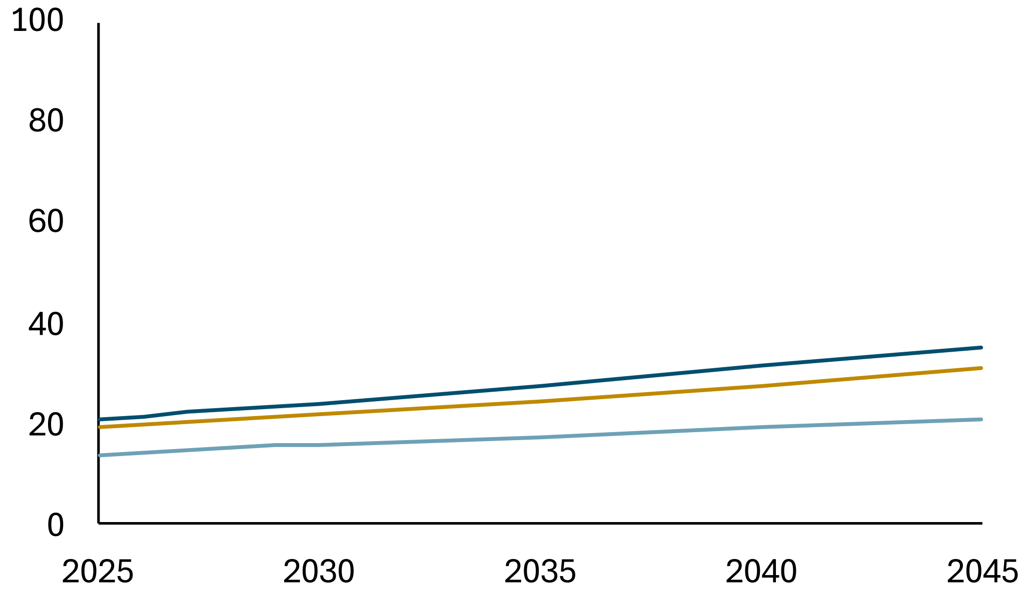
30.8	**35.6**	**40.8**	**46.5**	**51.9**	**Winter Peak** Coincident, GW
29.2	**33.4**	**37.4**	**42.2**	**47.2**	**Summer Peak** Coincident, GW
21.5	**24.5**	**27.1**	**29.9**	**32.5**	**Annual Load** aGW

- **Between 2025-2035 summer and winter peak loads grow by 2.8%/yr and 3.2%/yr, respectively, due to data electrification and center load growth**
- **Seasonal peaks gradually diverge as heating electrification accelerates**



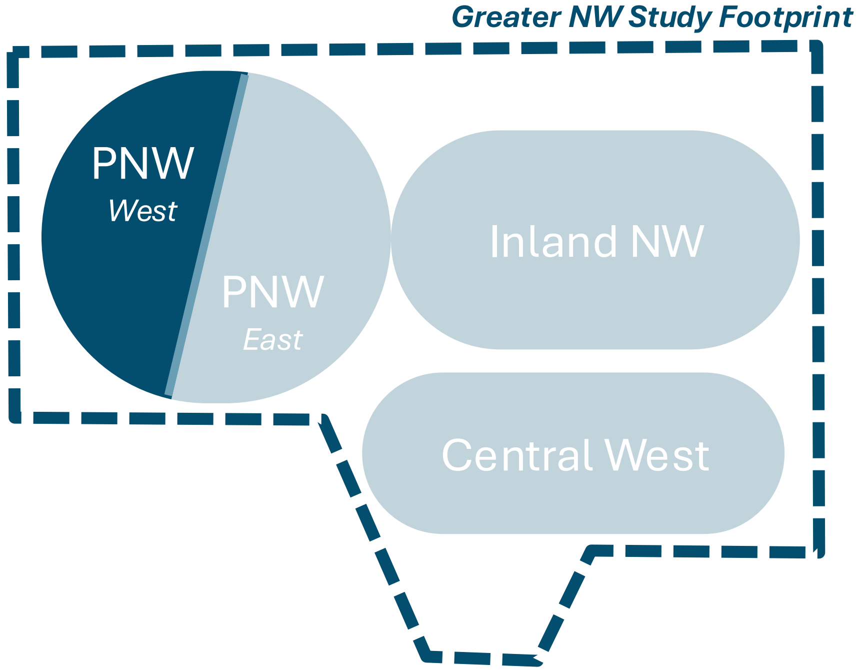
Regional Reference Load Forecasts
West of Cascades

West of Cascades
Reference Load Forecast (GW)



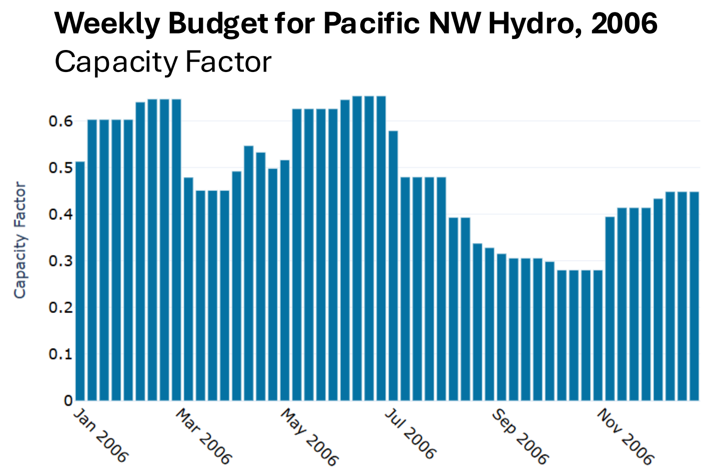
2025	2030	2035	2040	2045	
20.9	**24.3**	**27.8**	**31.7**	**35.4**	**Winter Peak** Coincident, GW
19.2	**21.9**	**24.7**	**27.8**	**31.1**	**Summer Peak** Coincident, GW
14.2	**16.1**	**17.9**	**21.5**	**23.1**	**Annual Load** aGW

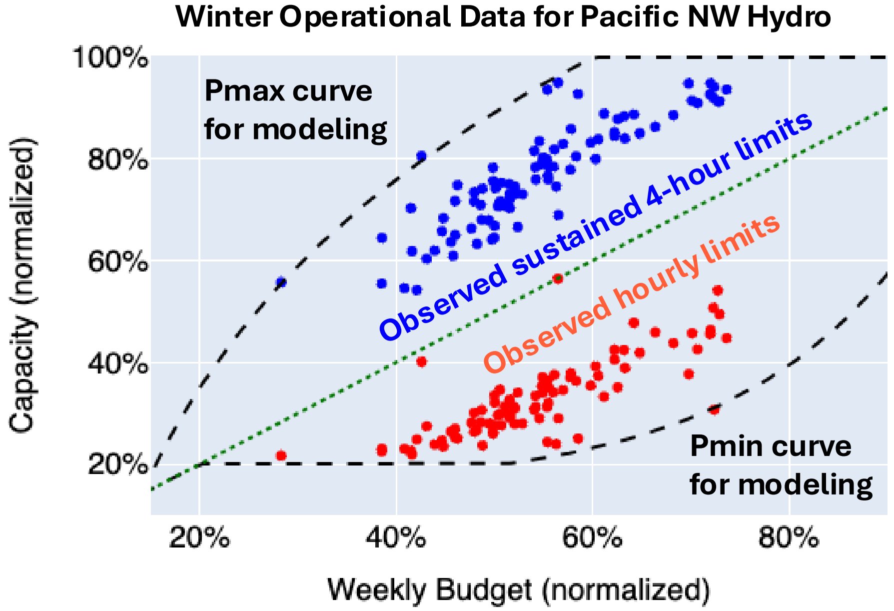
- **Between 2025-2035 summer and winter peak loads grow by 2.8%/yr and 3.3%/yr, respectively, due to data electrification and center load growth**
- **Seasonal peaks gradually diverge as heating electrification accelerates**



Hydro Modeling Approach

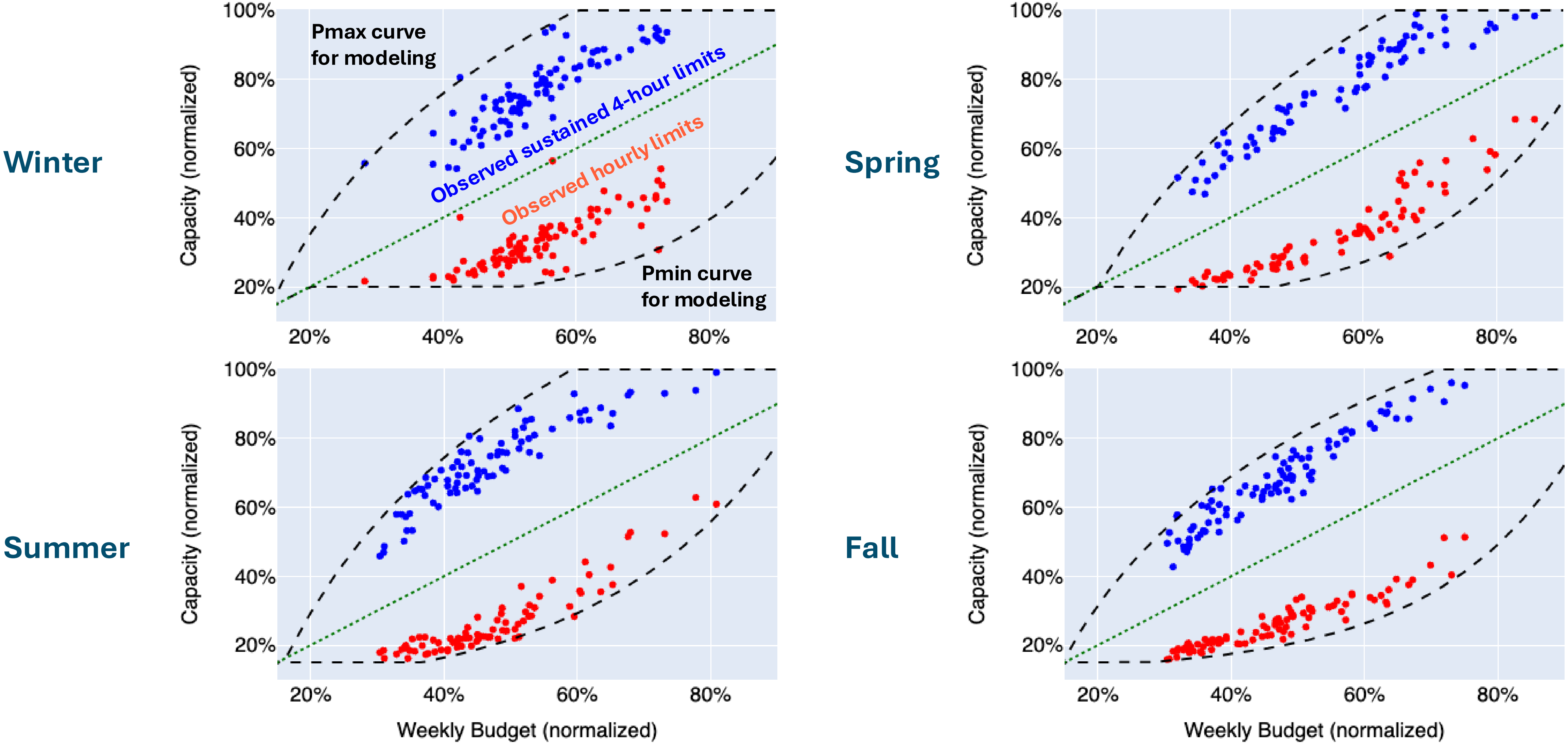
+ **The 2018 RA study used 1929-2008 hydro conditions**
+ **After consulting with BPA, this current study uses BPA's recent past 30-year generation profiles reflective of current weather patterns, downscaling them to weekly resolution**
  - Aligns with BPA's current near-term resource planning methods
  - Avoids anomalous low hydro water conditions in 1930s and 1940s not representative of current expected precipitation patterns
+ **These profiles capture the seasonal variability of hydro, as well as the distribution of annual hydro output across decades of weather years**
  - Hydro operations are modeled using weekly budgets with 5% of inter-week budget sharing, reflecting the flexibility observed in real-world hydro operations
+ **The analysis uses 7 years of hourly hydro generation (2018-2024) to characterize the minimum and maximum power constraints on output by season based on weekly hydro availability**
  - Pmin values fit to historical 1-hour limits
  - Pmax values fit to historical 4-hour limits[1]





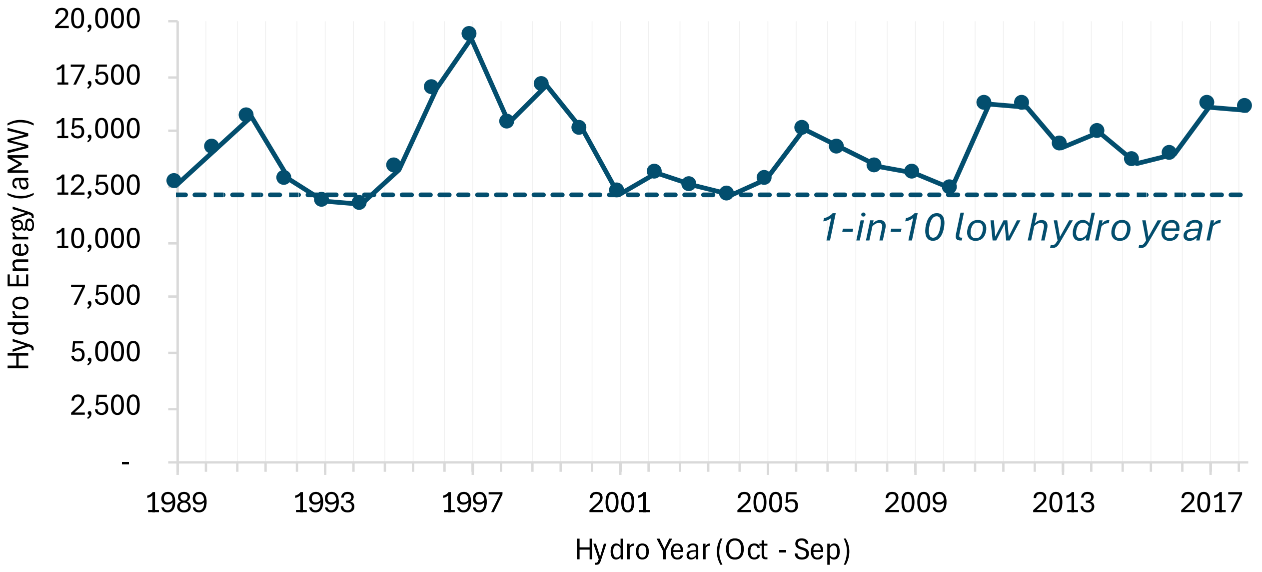
1. Pmax values use the historical 4-hr limit, which is more conservative than historical 1-hr limits, recognizing there can be sustained peaking limits to operating at maximum capacity.

Hydro Hourly Dispatch Limits

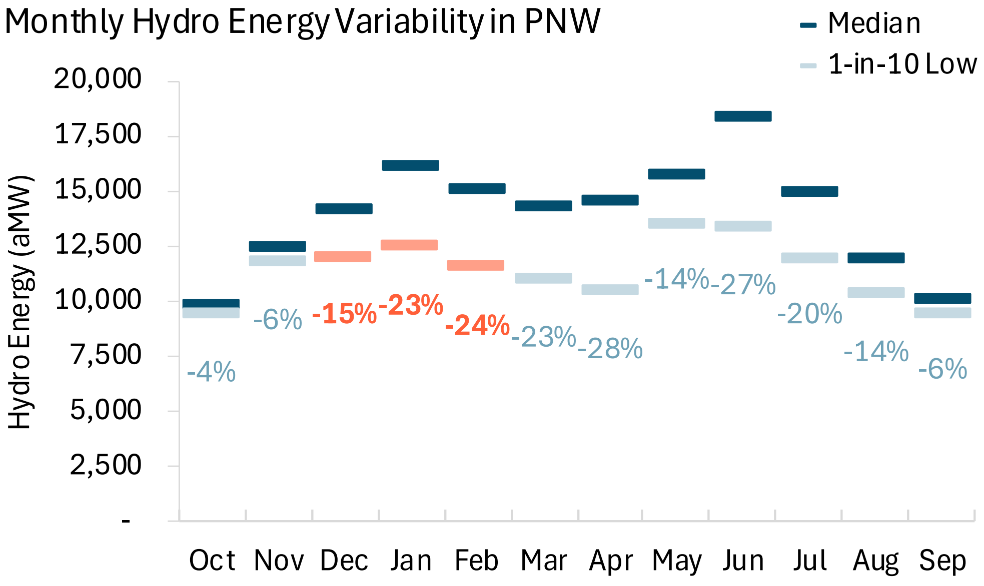


Hydro Energy Variability

Annual Hydro Energy over 30 years - BPA's 2024 White Book



Monthly Hydro Energy Variability in PNW

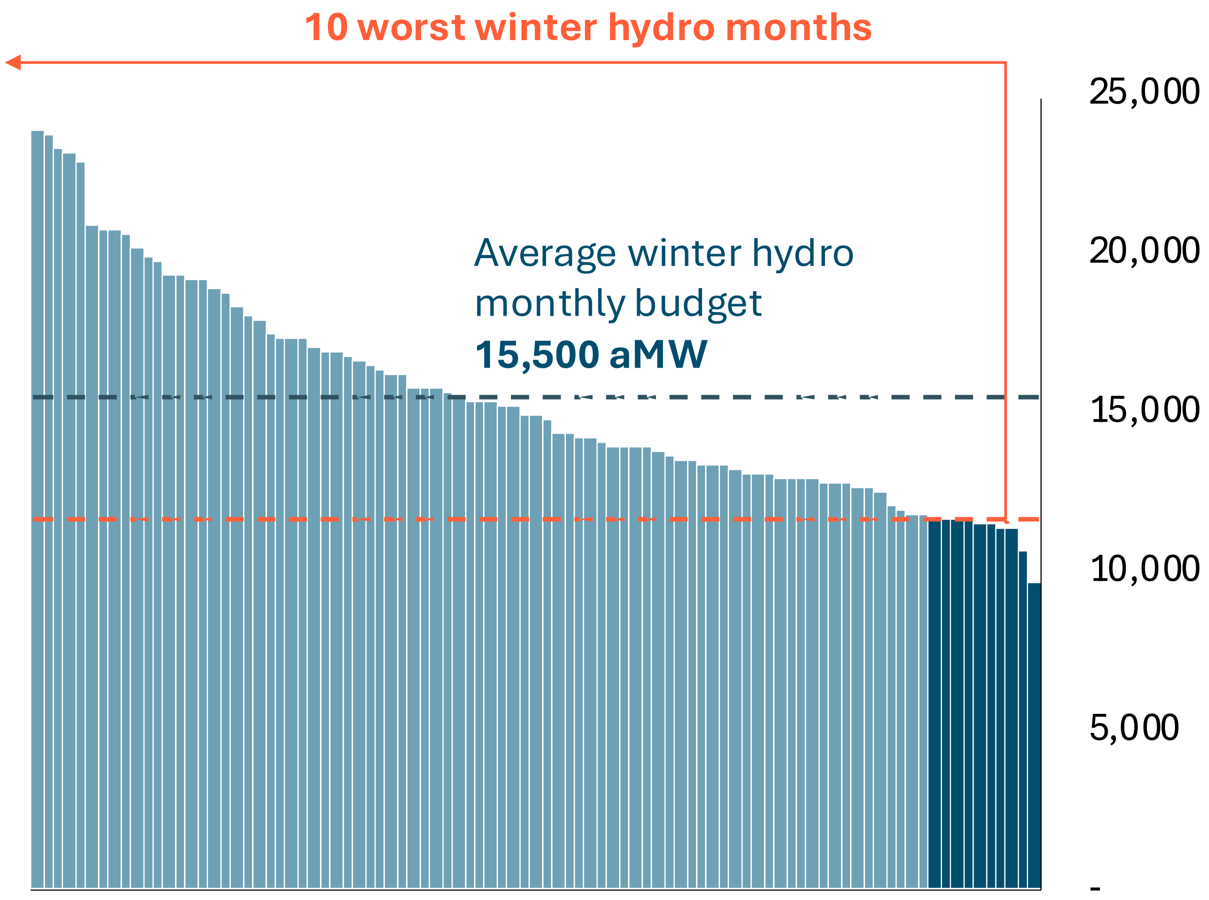


Hydro Energy (aMW)	Median Year	1-in-10 Low Year	Variability
Annual	14,076	12,175	-13.5%
Critical Winter Months *Dec - Feb*	**15,595**	**12,201**	**-21.8%**

Monthly Hydro Energy Variability

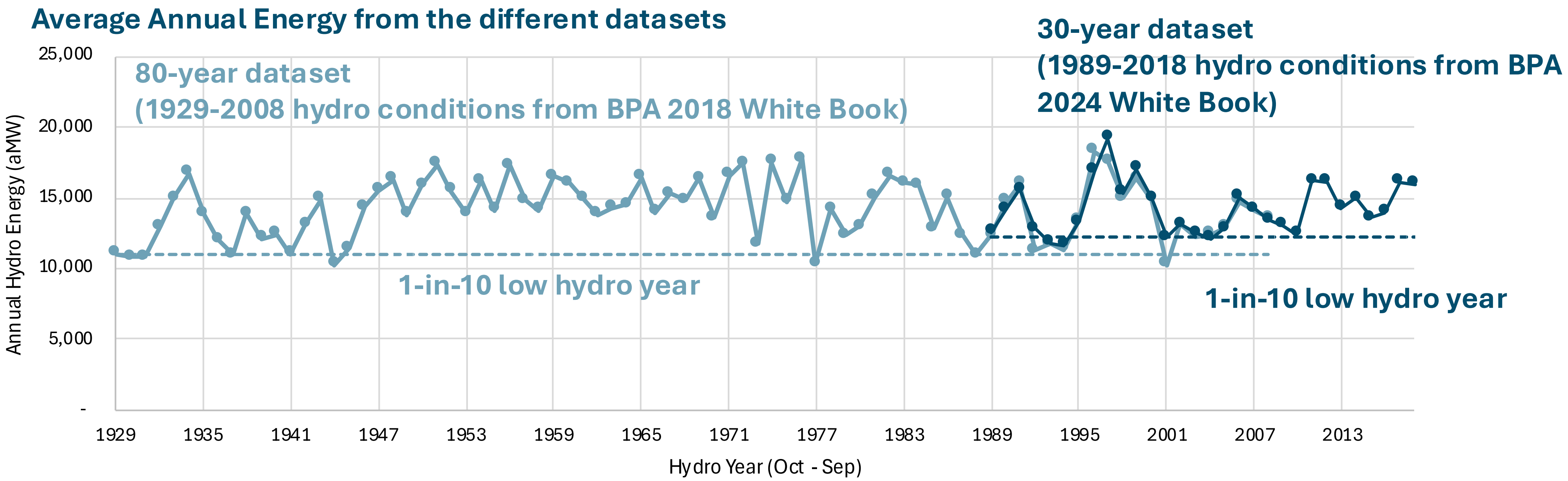
Year	Month	Monthly Hydro Output (aMW)	vs. Monthly Average
1993	February	**9,655**	-39%
1989	February	**10,619**	-33%
2004	February	**11,402**	-28%
1992	December	**11,404**	-21%
2010	February	**11,517**	-27%
1993	January	**11,600**	-29%
1994	February	**11,609**	-26%
2001	January	**11,643**	-29%
2001	February	**11,662**	-26%
1993	December	**11,708**	-19%

Average	December	**14,478**
	January	**16,408**
	February	**15,781**



1989–2018 Winter Months (Dec-Feb)
Monthly Hydro Generation (aMW)

Updated 30-year Hydro Dataset vs. Prior 80-Year Dataset



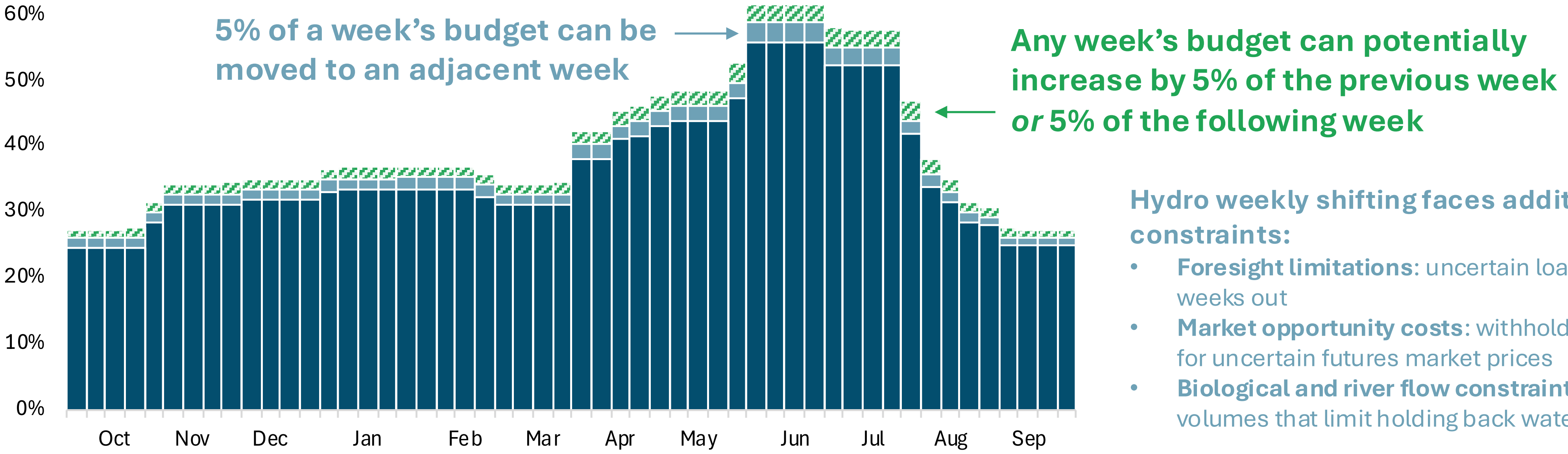
	Median Annual aMW	Median Winter aMW	1-in-10 Annual aMW	1-in-10 Winter aMW
80-year	14,191	14.457	11,092	10,682
30-year	**14,076**	**15,595**	**12,201**	**12,175**
Change	*-1%*	*+8%*	***+10%***	***+14%***

Decreased winter low hydro extremes in 30 year vs. 80 year dataset
→ net increase in hydro RA contributions

Hydro Budgets and Weekly Energy Shifting

+ **E3 incorporated 5% of hydro flexibility across different weeks to allow the most constrained periods to get some additional hydro energy beyond the average for that month**
  - This additional energy a week can use still needs to be dispatched within the Pmax hourly operational constraints already set for the given season and hydro budget
  - A week's hydro budget can be reduced by 5% to support an adjacent week while still maintaining its dispatch above its Pmin hourly operational constraints

Weekly Budgets for 2002 Hydro Year – PNW-NE



Hydro weekly shifting faces additional practical constraints:

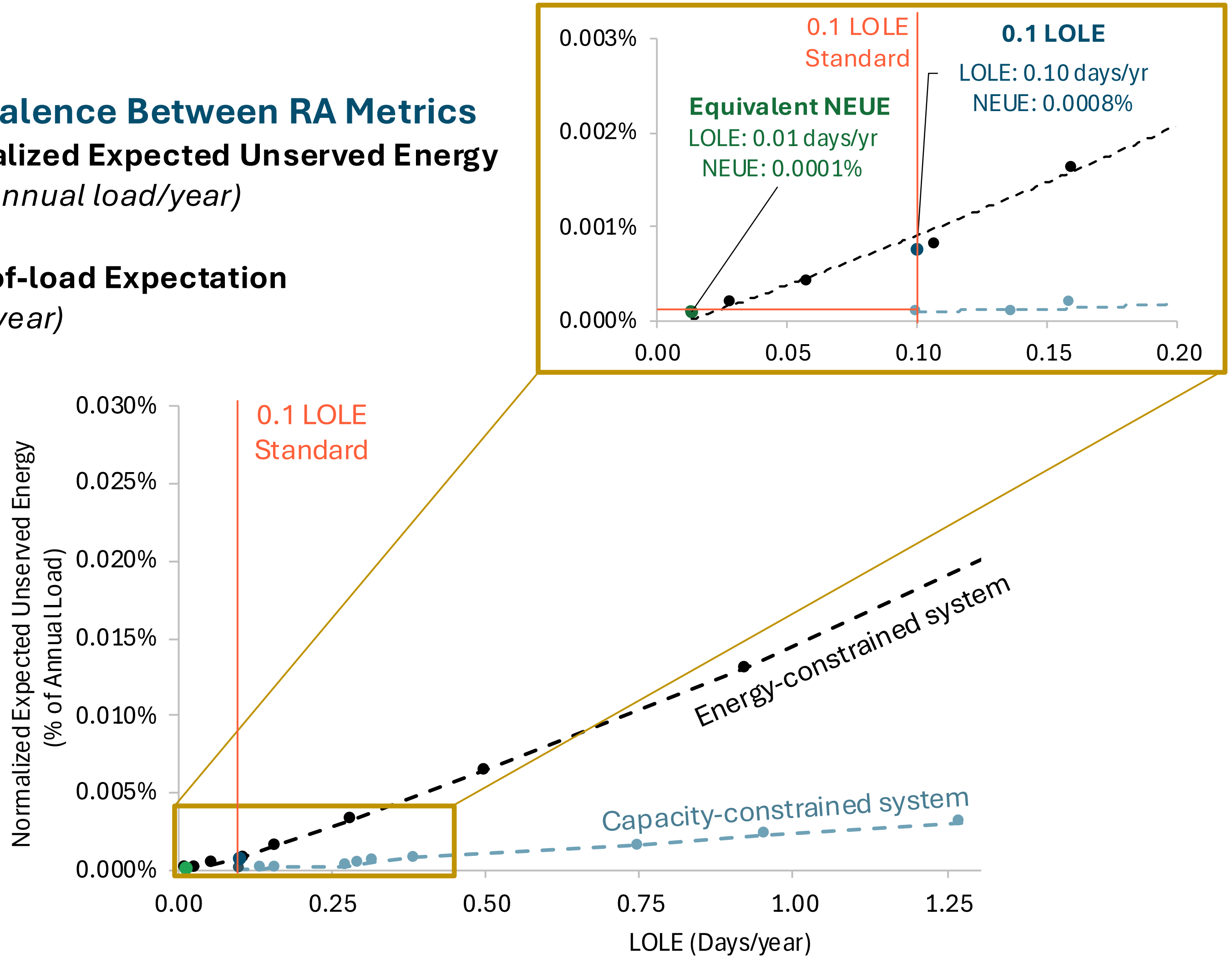
- **Foresight limitations:** uncertain load conditions 1-2 weeks out
- **Market opportunity costs:** withholding hydro capacity for uncertain futures market prices
- **Biological and river flow constraints:** impact Pmin volumes that limit holding back water

How to define reliability in a hydro-heavy system?

- In capacity-constrained systems, **reliability is typically defined though one day in ten years loss-of-load expectation, or 0.1 LOLE, which usually corresponds to infrequent and short loss-of-load events** across plausible weather conditions
- In a hydro dominated system with energy shortfall risk, **the typical 0.1 LOLE standard can be met even when events are severe and last entire days**, and thus **could be considered not stringent enough** relative to what is considered reliable in other systems
  - A hydro dominated system which needs to stay below an equivalent amount of unserved energy as a capacity-constrained system is, on the other hand, too constrained
- **For this study, the reliability criteria for calculating system resource needs and ELCCs was set based on the equivalent normalized expected unserved energy (NEUE) of today's system at 0.1 LOLE**
  - This maintained a consistent metric as the system evolves in future years with increased peak loads and energy-limited resource additions.

Equivalence Between RA Metrics

Normalized Expected Unserved Energy
(% of annual load/year)
vs.
Loss-of-load Expectation
(days/year)



The Pacific Northwest subregion faces a local supply deficit in 2026 which grows to 5,000 MW of effective capacity by 2030

- **Load growth and retirements mean the region faces a power supply shortfall in 2026**
  - The region currently relies on 5,750 MW of imports to maintain reliability
- **Nearly 5,000 MW of new effective capacity is needed by 2030**
- **Projects currently in active development account for only 2,300 MW of new effective capacity**
  - 1,000 MW from new firm import capacity (B2H)
  - 340 MW from hydro upgrades

Pacific Northwest Subregion Load and Resource Balance
Effective Capacity (ELCC) MW

System Needs (ELCC MW)	2025	2026	2027	2028	2029	2030
Total Resource Need*	35,309	36,441	37,717	38,922	40,066	40,846
Existing Portfolio w/ Retirements	29,581	28,890	28,826	28,820	28,743	28,738
Existing Firm Imports	7,100	7,100	7,100	7,100	7,100	7,100
Reliability Position Surplus (+) / Shortfall (-)	**+1,373**	**-451**	**-1,791**	**-3,002**	**-4,224**	**-5,008**
New Firm Import Capacity**	-	-	-	1,000	1,000	1,000
ELCC from "In-Development"*** Hydro Upgrades	-	244	244	335	335	335
ELCC from "In-Development" Wind, Solar and Battery projects	-	86	350	541	966	996

** Total Resource Need includes peak load + planning reserve margin as well as obligation to serve the Columbia River Treaty Regime*
*** Firm Import Capacity into the PNW subregion increases with new transmission from within the Greater Northwest as long as the broader region remains reliable overall*
**** In-development resources are WECC ADS 2034 facilities with confirmed project location, project name, and can be verified online*

The West of Cascades subregion rapidly trends towards a local supply deficit by ~2030

- **Load growth and retirements mean the subregion might face a local supply deficit in the near term**
  - The subregion currently relies on 14,500 MW of imports to maintain reliability, which are only available if the broader Pacific Northwest subregion is reliable
- **Projects currently in active development account for only 1,900 MW of new effective capacity**
  - 1,500 MW from new firm import capacity

West of Cascades Subregion Load and Resource Balance
Effective Capacity (ELCC) MW

System Needs (MW)	2025	2026	2027	2028	2029	2030
Total Resource Need*	24,525	25,240	26,047	26,796	27,527	28,016
Existing Portfolio w/ Retirements	10,057	9,309	9,216	9,163	9,051	9,030
Existing Firm Imports	19,250	19,250	19,250	19,250	19,250	19,250
Reliability Position Surplus (+) / Shortfall (-)	**+4,782**	**+3,319**	**+2,419**	**+1,617**	**+774**	**+264**
New Firm Import Capacity**	-	-	-	-	-	1,500
ELCC from "In-Development"*** Firm Resources	-	153	153	205	205	205
ELCC from "In-Development" Wind, Solar and Battery projects	-	168	168	168	168	168

** Total Resource Need includes peak load + planning reserve margin as well as obligation to serve the Columbia River Treaty Regime*
*** Firm Import Capacity into the WOC subregion increases with new transmission from within the Pacific Northwest as long as that subregion as well as the broader Greater Northwest region remain reliable overall*
**** In-development resources are WECC ADS 2034 facilities with confirmed project location, project name, and can be verified online*

Portfolio Analysis

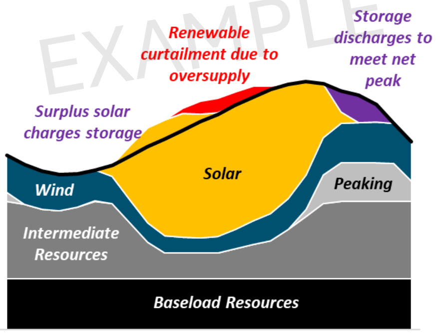
RESOLVE Methodology, Inputs & Assumptions, Detailed Portfolio Results

Energy+Environmental Economics

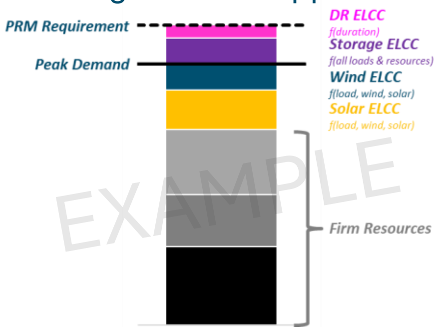
E3's RESOLVE optimal capacity expansion model was used to study long-term portfolio optimization

- **RESOLVE is a linear optimization model tailored to study electricity systems with high renewable & clean energy policy goals**
- **Optimization balances fixed costs of new investments with variable costs of system operations, identifying a least-cost portfolio of resources to meet needs across a long-time horizon**
- **Has been used to study low-carbon portfolios in California, Pacific Northwest, Hawaii, New York, and other places**

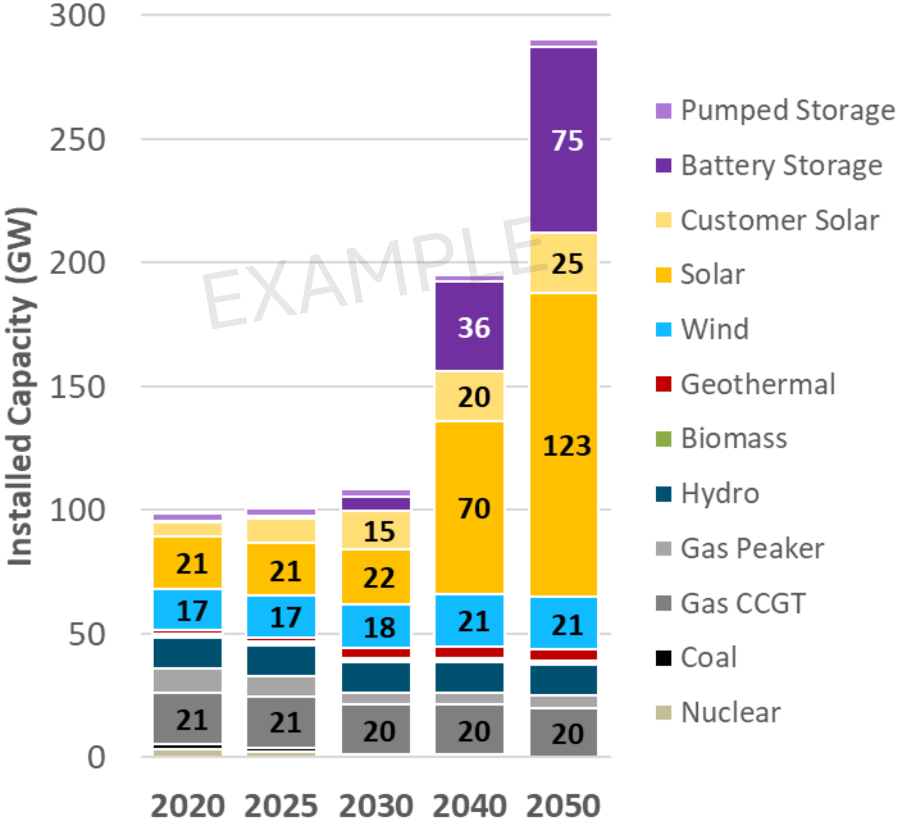
Operational module simulates hourly system operations for a sample of representative days



Reliability module ensures portfolio can meet load during extreme conditions using an ELCC approach



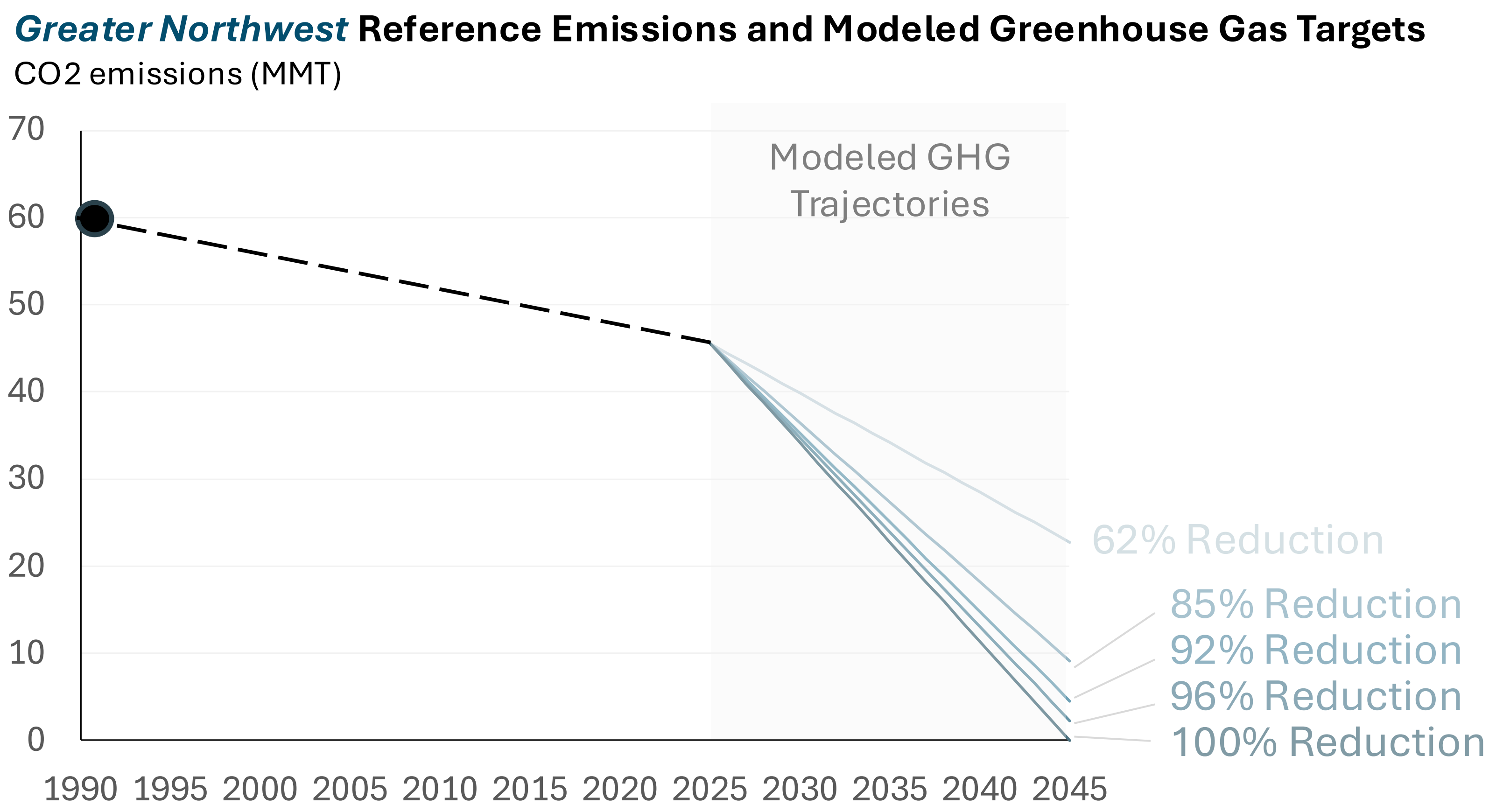
Least-cost plan co-optimizes investments and operations to meet clean energy policy targets, selecting from a diverse set of potential resources including wind, solar, storage, DSM, and natural gas



Example RESOLVE result from *Long-Run Resource Adequacy under Deep Decarbonization Pathways for California* (Calpine, 2019)

Modeled greenhouse gas (GHG) trajectories

- GHG emissions reductions are relative to 1990 emissions of 60 MMT[1]
- GHG emissions in 2025 are benchmarked to statewide historical emissions
- Emission trajectories between 2025 and 2045 are linear
- GHG emissions target is applied to the entire GNW region in RESOLVE



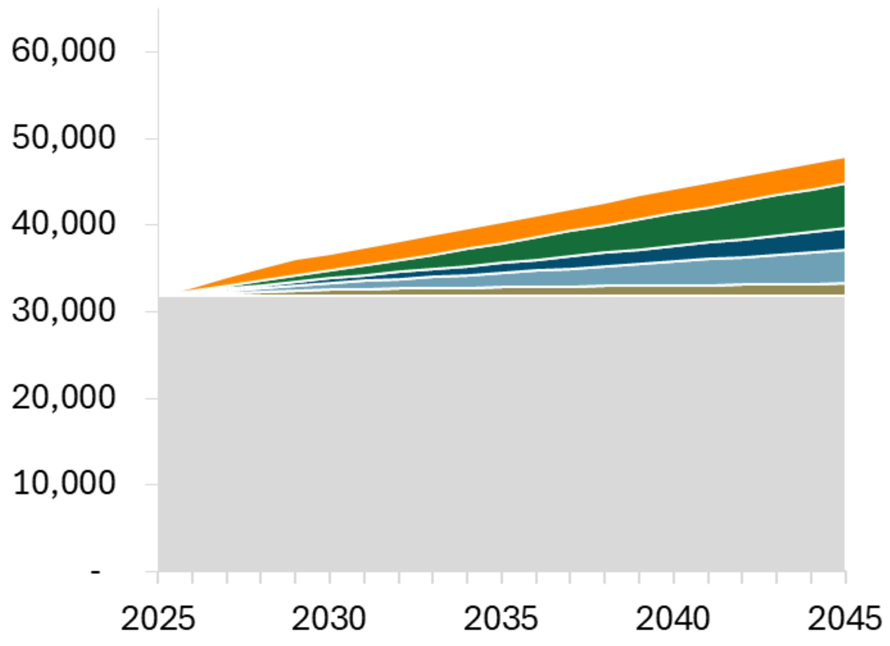
1. Resource Adequacy in the Pacific Northwest (2019)

Regional Load Forecasts
Electrification Scenarios

Category	Reference	High Loads
Policy	Assumes **rollback** of all federal policy finalized under the Biden administration and state transportation policy	Includes all **finalized** state policies and all federal policies finalized under the Biden administration Includes additional state targets to achieve net-zero emissions in the **Greater Northwest**
Space Heating Electrification	Heat pump market share increases based on historical trends from AHRI and state electrification programs	All-electric heat pump market share increases to 100% of new sales by 2040
Transportation Electrification	Passenger and freight vehicle electrification consistent with current ZEV market trends	ZEV sales reach 100% by 2035 for passenger vehicles, 100% by 2040 for freight vehicles
Energy Efficiency and Other Sources	Levels consistent with state policy and market trends	Increased efficiency and electrification consistent with net-zero emissions, including building shell upgrades and industrial efficiency
Data Centers	3.1 aGW of new data center load by 2045	
Climate Change	Annual changes in Cooling and Heating Degree-Days from EIA's Annual Energy Outlook	

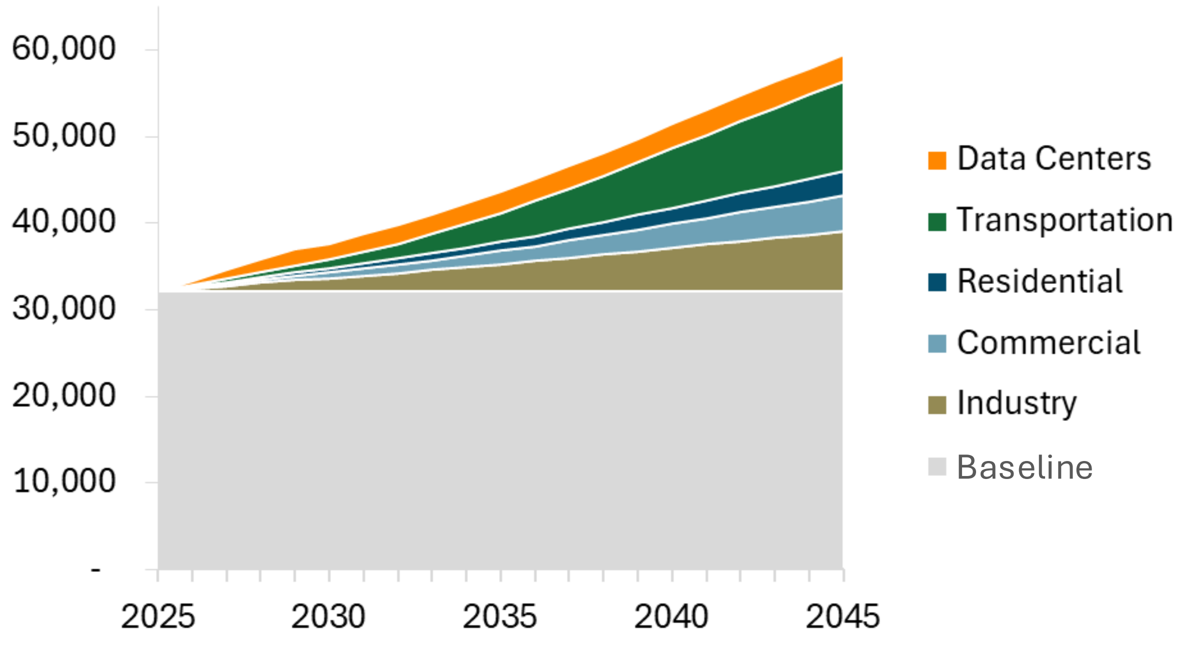
Regional Load Forecasts
Incremental Load Growth by Sector

Reference Loads
Incremental Load Growth by Sector over Baseline (aMW)



Annual Load by Sector aMW	2025	2030	2035	2040	2045
Baseline	31,916	31,916	31,916	31,916	31,916
Industry	-	681	900	1,129	1,367
Commercial	-	762	1,663	2,748	3,943
Residential	-	558	1,176	1,814	2,449
Transportation	-	895	2,273	3,787	5,129
Data Centers	-	1,862	2,438	2,800	3,105

High Loads
Incremental Load Growth by Sector over Baseline (aMW)

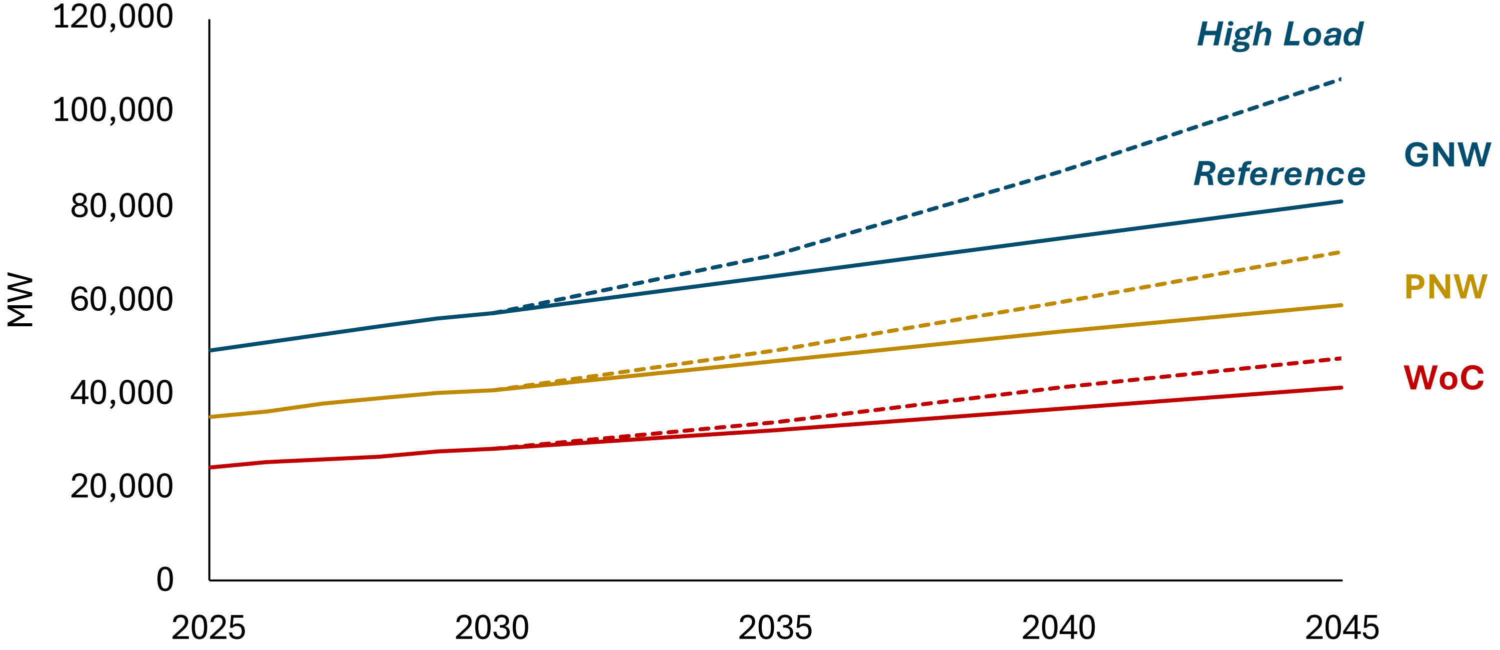


Annual Load by Sector aMW	2025	2030	2035	2040	2045
Industry	-	1,545	3,139	5,064	6,950
Commercial	-	681	1,548	2,754	4,125
Residential	-	446	1,024	1,850	2,818
Transportation	-	990	3,383	6,850	10,386
Data Centers	-	1,864	2,441	2,800	3,103

Regional Load Forecasts
Growth in Total Resource Need

Total Resource Need

All Regions and Scenarios, MW



- Through 2035, EV adoption and new data centers contribute the most to growth in reliability needs
- **Reference**: After 2035, residential space heating also drives some reliability need
- **High Load**: After 2035, accelerated electrification across both buildings and transportation drive growth in reliability need

	2025	2030	2035	2040	2045	
GNW	49.2 (+0)	57.2 (+8.0)	69.0 (+19.8)	84.9 (+35.7)	103.0 (+53.8)	High Load Total Resource Need GW (+ GW Increase Relative to 2025)
PNW	35.3 (+0)	40.8 (+5.5)	48.6 (+13.6)	58.0 (+22.7)	67.1 (+31.8)	High Load Total Resource Need GW (+GW Increase Relative to 2025)
WoC	24.5 (+0)	28.0 (+3.5)	33.4 (+8.9)	39.8 (+15.3)	45.7 (+21.2)	High Load Total Resource Need GW (+GW Increase Relative to 2025)

Candidate Resources

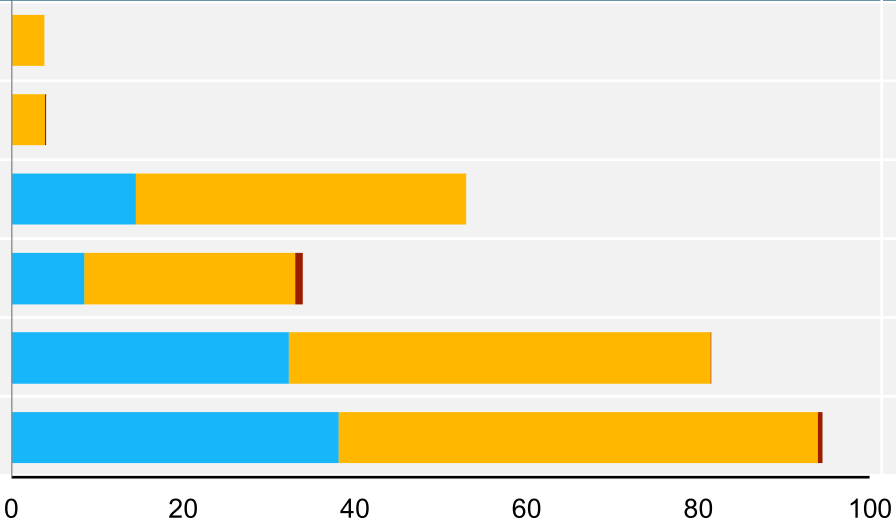
Mature and Emerging Technology Resource Options Studied

	Scenario	RA contributions	Additional considerations
Mature	Solar	Low and declining ELCCs	Variable energy resource
	Onshore wind	Declining ELCCs	Variable energy resource
	Natural gas	Firm	Carbon emitting, requires pipeline infrastructure
	Short-duration storage (4-8 hr li-ion)	Declining ELCCs	ELCC saturation impacted by hydro fleet interactions
	Long duration storage (10-12 hr pumped hydro)	Declining ELCCs	ELCC saturation impacted by hydro fleet interactions
	Geothermal	Limited potential	High cost per kWh and limited PacNW sites
	Energy efficiency (embedded in load forecast)	High, but takes time to scale	Can reduce new load but cannot serve existing load
	Demand response	Declining ELCCs	Duration and use limited
Emerging	Natural gas to clean CT retrofits (H2, RNG, etc.)	Firm	High enabling infrastructure costs + long timelines
	New clean CTs (H2, RNG, etc.)	Firm	High enabling infrastructure costs + long timelines
	Gas w/ 100% carbon capture and storage	Firm	High enabling infrastructure costs + long timelines
	Nuclear small modular reactors	Firm	Uncertain costs + long timelines
	Enhanced geothermal	Firm	Uncertain costs and potential
	Multi-day storage (100 hr)	Slower declining ELCCs	Uncertain costs, high round-trip energy losses

- *Emerging technologies face cost uncertainty, unclear commercialization timelines, and/or high enabling infrastructure needs*

Candidate Resources
Renewable Resource Potential

+ **The total resource potential, resource quality, and development costs of each renewable technology type are differentiated both between RESOLVE zones and within each zone**[1]



Renewable Resource Potential by Zone Nameplate GW	Candidate Wind CF %	Candidate Solar CF %
PNW NW	N/A	18%
PNW SW	37% - 40%	24%
PNW NE	N/A	23%
PNW SE	34% - 36%	26%
Inland NW	42% - 47%	23%
Central West	35% - 52%	24% - 29%

1. Zonal resource potential derived from by WestTEC PLEXOS capacity expansion study, which developed land use screens from Wu et al (2023). Screens remove legally protected, administratively protected, and high conservation value areas. Each zone includes tranches of wind and solar resources with distinct generation profiles, capacity factors, and interconnection costs

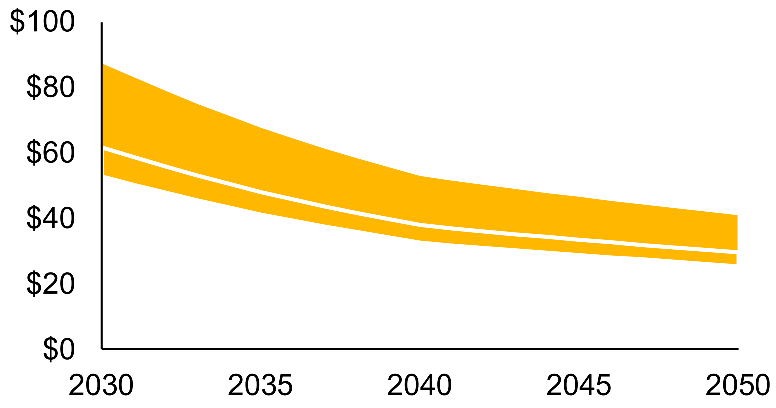
Candidate Resources

Renewable and Storage Resource Costs

+ **Levelized candidate resource costs developed in RECOST, E3's in-house discounted cash flow model**
+ **Cost trajectories reflect market and policy outlook today, including sunsetting of tax credits and supply chain bottlenecks**
  - Supply chain bottleneck costs remain high in 2030, decline over across the decade
  - Solar and wind do not receive ITC/PTC, battery storage receives ITC until 2040

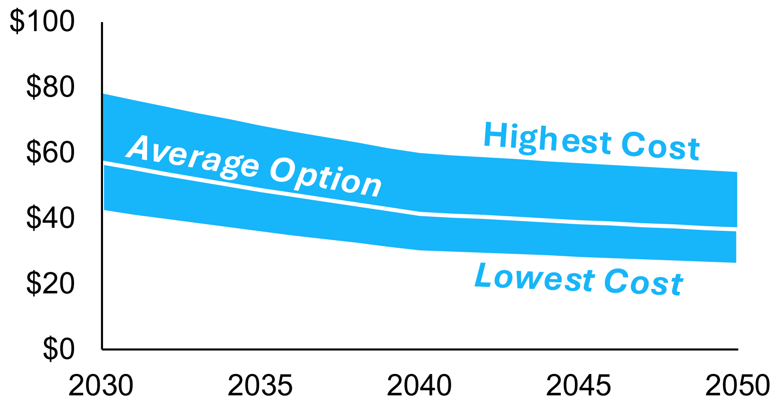
Candidate Solar

LCOE 2024$/MWh



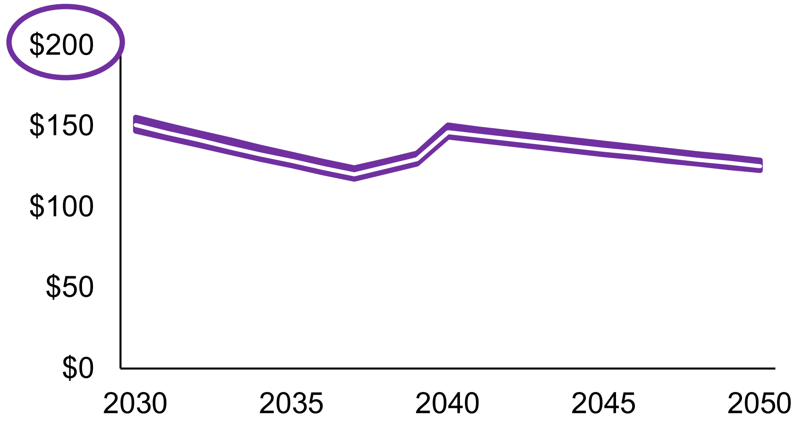
Candidate Wind

LCOE 2024$/MWh



Candidate 4-hr Battery Storage

Levelized Fixed Cost 2024$/kW-year

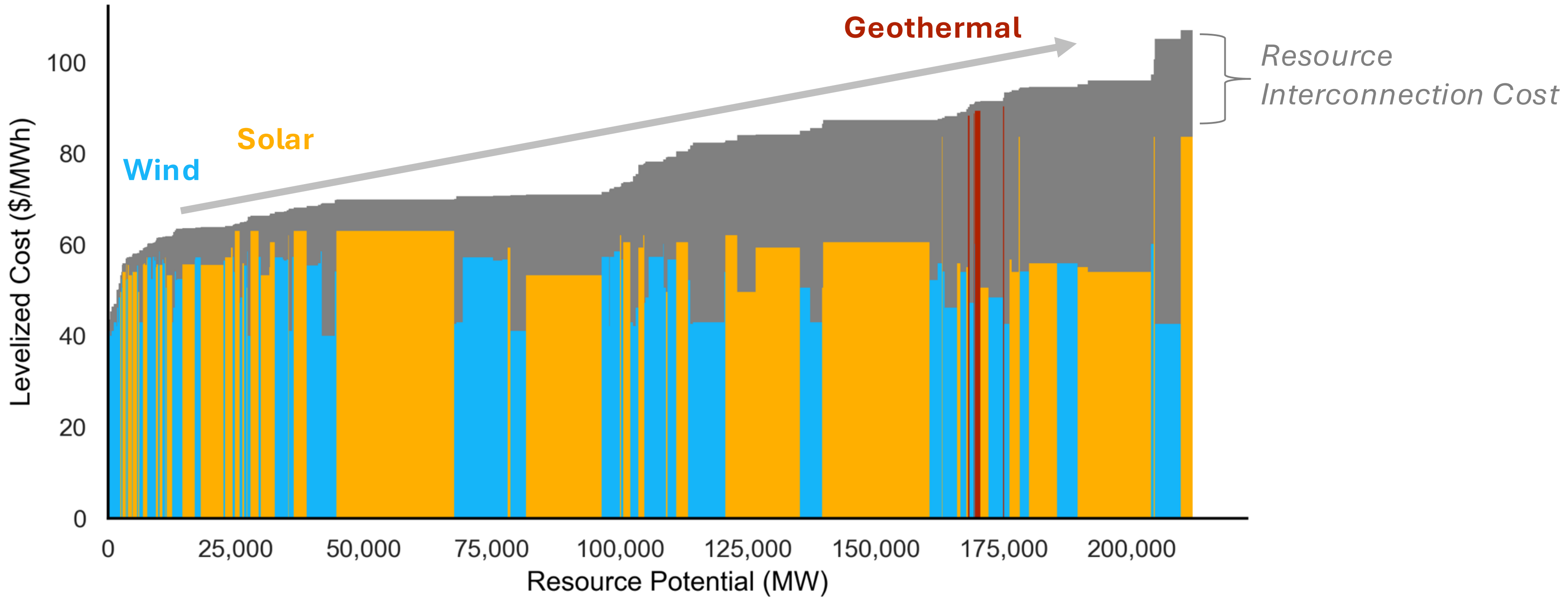


Candidate Resources
Renewable Resource Supply Curve

- Greater Northwest renewable supply curve combines cost of resource development and interconnection
- Resources in each region face rising tiers of interconnection costs once grid-proximate resources are selected

Greater Northwest **Renewable Supply Curve**

Levelized Cost of Energy and Interconnection Costs 2024$/MWh | 2030



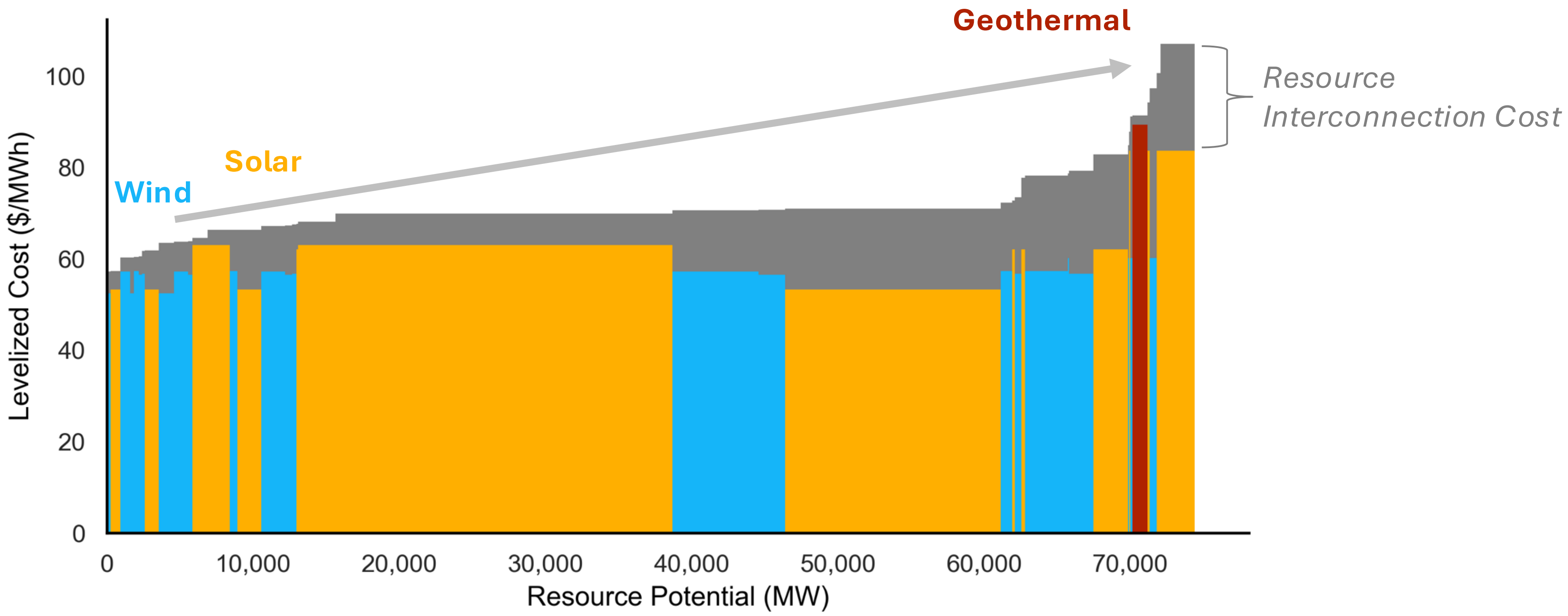
Candidate Resources

Renewable Resource Supply Curve

+ The Pacific Northwest has solar potential of varied quality across Washington and Oregon
+ All wind resource potential is located East of the Cascades

Pacific Northwest **Renewable Supply Curve**

Levelized Cost of Energy and Interconnection Costs 2024$/MWh | 2030

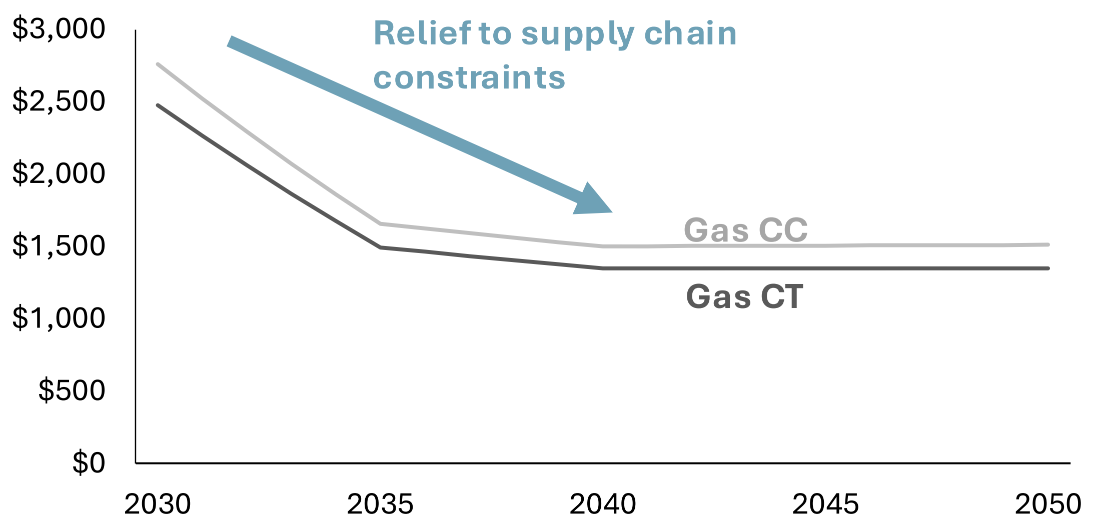


Firm Resources – New Gas Generation

+ **New Gas Generation is available to RESOLVE starting in 2030**
  - Elevated plant capital costs in 2030: $2,800/kW for Combined Cycle, $2,500/kW for Combustion Turbine
  - Costs decline throughout 2030's as supply chain constraints & order backlog are relieved
  - Firm gas delivery contract costs for new pipeline capacity are included within capital costs of new gas plants in the Greater Northwest region[1]

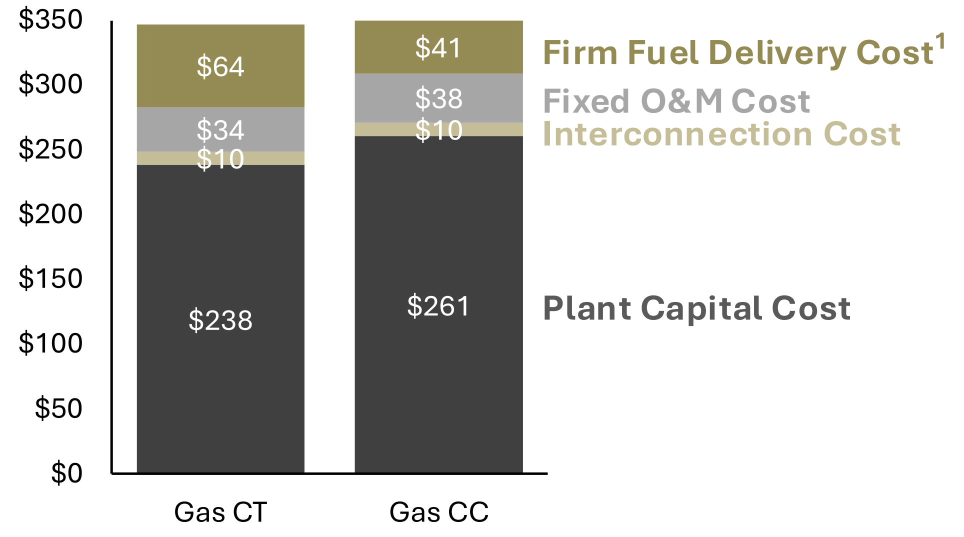
Gas Plant Capital Cost Trajectory

2024$/kW by Commercial Operating Date (COD)



Gas Annualized Fixed Cost Components

2024$/kW-year for 2030 COD



1. Firm fuel delivery cost is estimated gas delivery contract cost of new pipeline in Greater Northwest region. New plants are assumed to hold firm delivery contract to generate at full plant capacity throughout winter season, with $1.10/Dth/day incremental cost above non-firm delivery on existing pipelines.

Candidate Resources

If available, emerging technologies can provide “clean firm” capacity

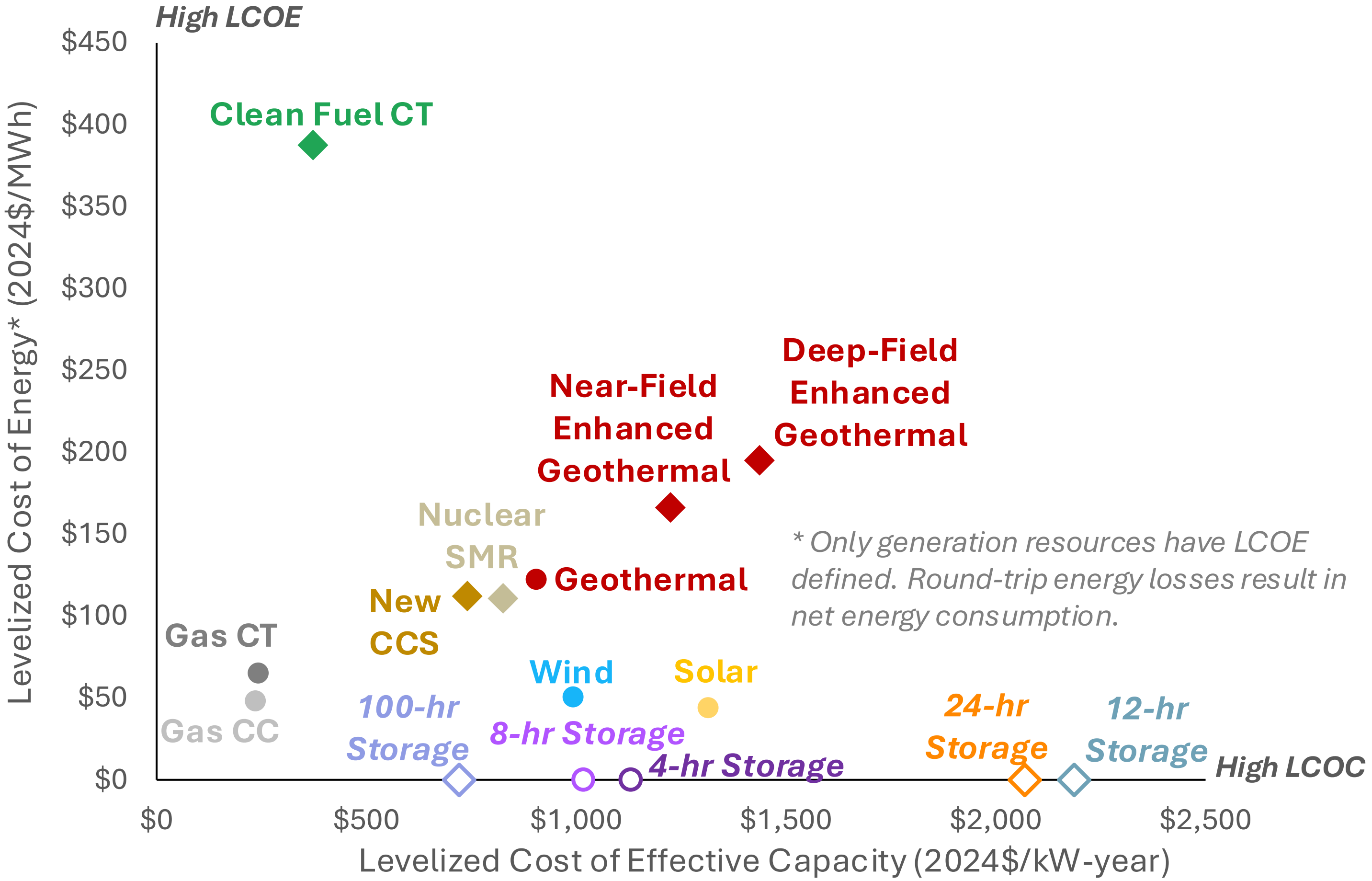
+ **Emerging technology cost and commercialization trajectories remain unknown**
  - Modeled to be available at scale by 2040
+ **By providing “clean firm” capacity, emerging technologies may be able to reduce the costs and increase the feasibility to achieve up to 100% decarbonization of the NW system**

Roles	Emerging Candidate Options	Capacity Provision	Energy Provision
Long-duration Energy Storage	12-hr Storage (eg. Vanadium Flow)	**Subject to ELCC declines**	**None**
	24-hr Storage (eg. Vanadium Flow, Thermal)		
	100-hr Storage (eg. Iron-Air)		
Clean Firm Baseload	Near-Field Enhanced Geothermal	**Firm**	**High** Likely to operate at moderate to high capacity factor
	Deep-Field Enhanced Geothermal		
	Nuclear SMR		
	New CCS		
Clean Combustion	Carbon-neutral fuels (eg. RNG, Green H2)	**Firm**	**Low** Likely to operate at low capacity factor due to high variable cost

Candidate Resources

Emerging Technology Options

Greater Northwest Resource Cost Comparison, 2045



1. Figures show average costs of grid-proximate resources in Greater Northwest. Remote solar and wind resources are 30-60% more expensive due to interconnection costs.
2. Levelized Cost of Energy based on maximum potential generation of each resource type. Levelized Cost of Capacity based on estimated Greater Northwest resource marginal ELCCs in 2045: 93-95% for thermal, 8% for solar, 18% for wind, 12% for 4-hr Li-ion, 80% for 100-hr Iron-Air Battery. LCOC does not reflect energy arbitrage value of storage which is impacted by duration and round-trip efficiency losses.

+ Emerging Technologies are made available at scale after 2040

- Energy storage resources do not provide any energy value, but can be competitive capacity options long-term in cases with large renewable buildout
- Emerging new firm baseload generation can provide both energy and capacity at competitive costs
- Converting combustion turbines to run on clean fuels becomes the cheapest clean capacity resource but are expensive to run for energy

+ Low Cost sensitivity has 30% lower capital costs for Emerging Technologies

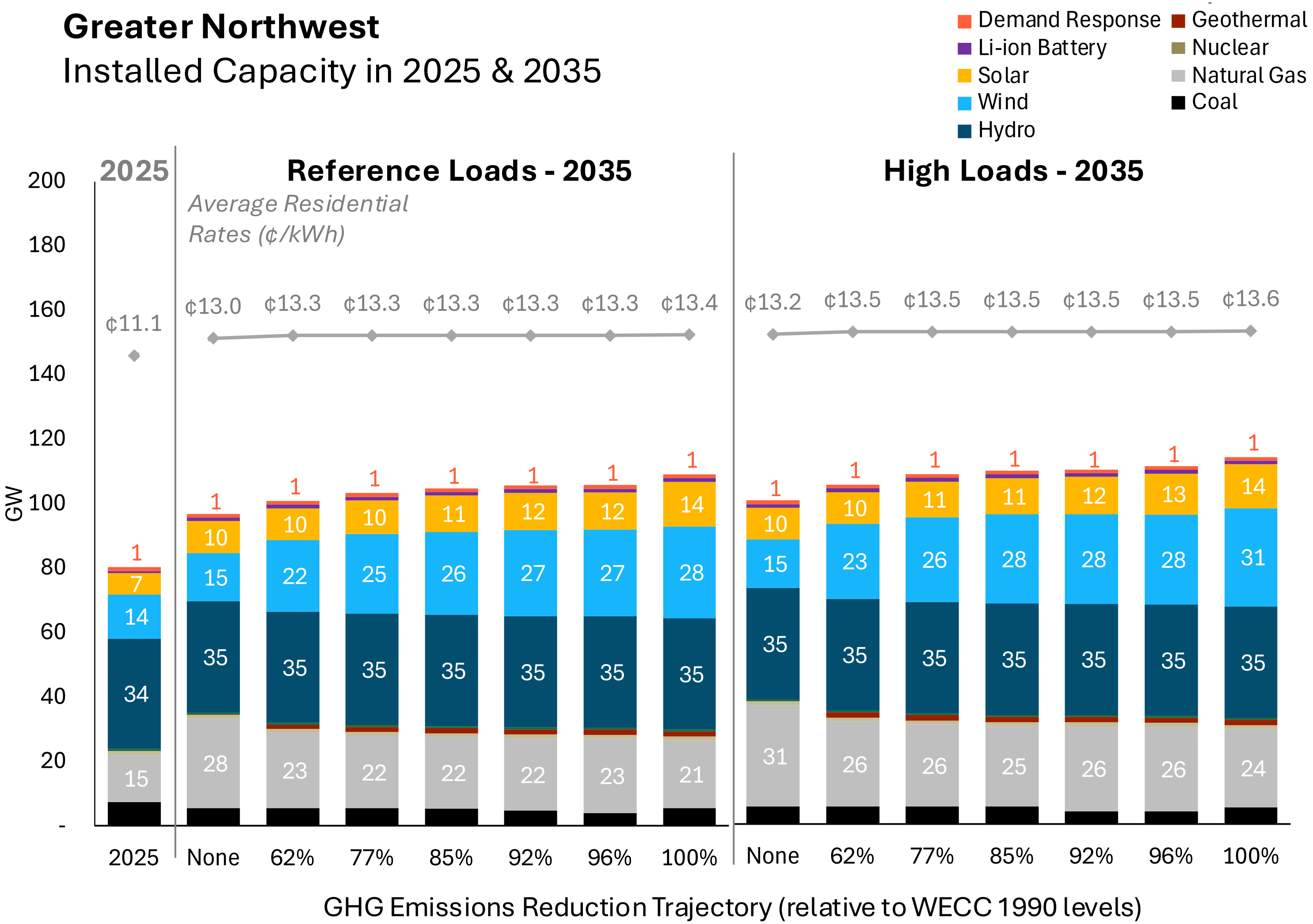
Detailed Portfolio Analysis Scenarios and Results

Portfolio optimization scenarios consider GHG policy, loads, and technology availability

Policy Scenario	Load Scenario	Technology Scenario
No GHG Policy	Reference High Loads	Mature Technologies
62% GHG Reduction (below 1990 levels)	Reference High Loads	Mature Technologies
85% GHG Reduction	Reference High Loads	Mature Technologies
92% GHG Reduction	Reference High Loads	Mature Technologies
96% GHG Reduction (Current Policy Targets)	Reference	Mature Technologies Mature Technologies (No New Gas)
	High Loads	Mature Technologies Mature Technologies (No New Gas) Emerging Technologies (Long-Duration Storage) Emerging Technologies (Clean Baseload) Emerging Technologies (Clean Fuels) Emerging Technologies (No Combustion) Emerging Technologies (All) Emerging Technologies (All, Low Cost)
100% GHG Reduction	High Loads	Mature Technologies Emerging Technologies (Long-Duration Storage) Emerging Technologies (Clean Baseload) Emerging Technologies (Clean Fuels) Emerging Technologies (No Combustion) Emerging Technologies (All)

2035 Portfolio: Wind and solar scale to support clean energy policies, natural gas selected as least-cost RA resource

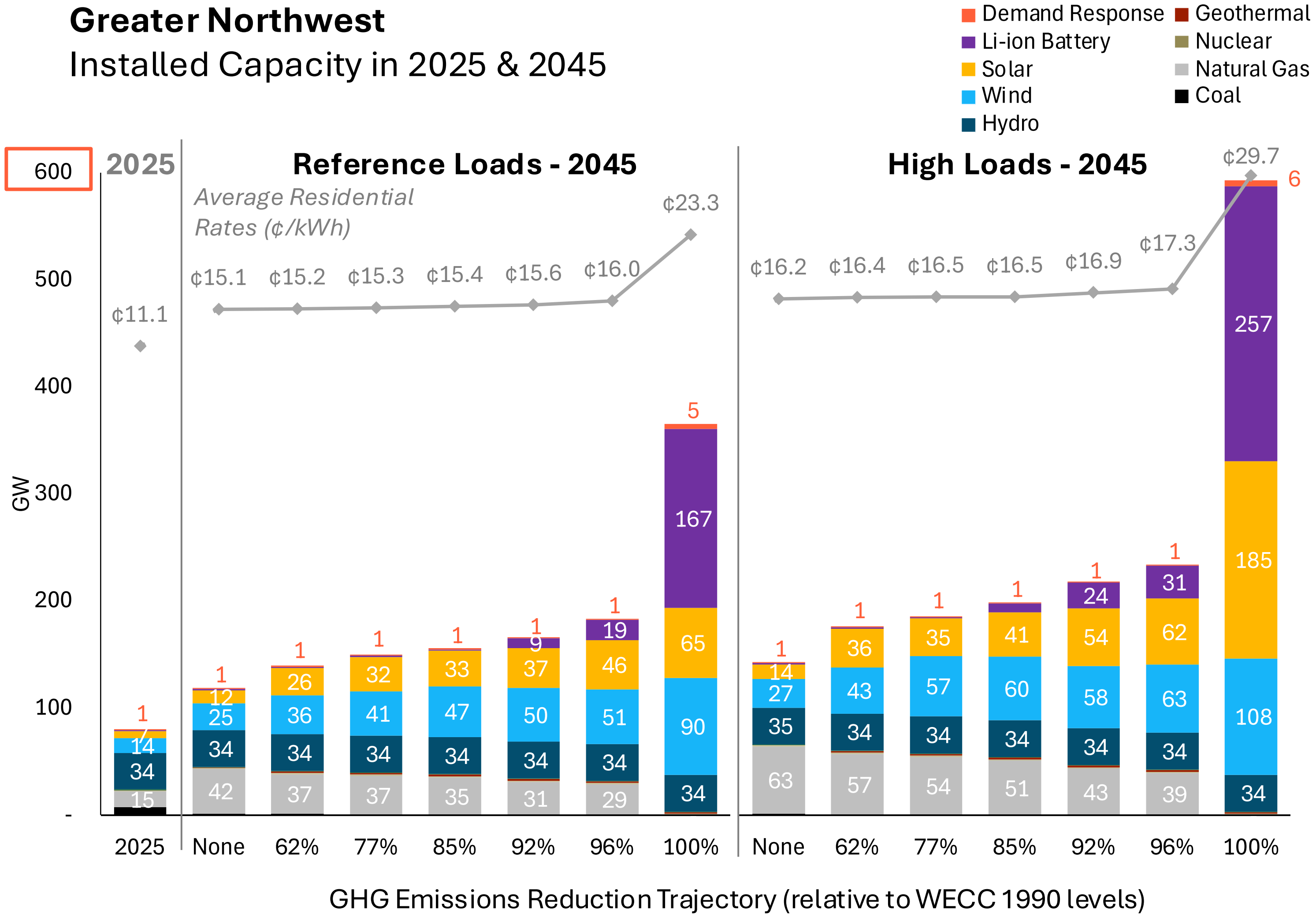
Greater Northwest
Installed Capacity in 2025 & 2035



- **To meet GHG reduction targets, all existing coal is retired by 2045**
- **Renewables are added by 2035 to meet growing loads on the path to 2045 96% GHG Reduction decarbonization goals**
  - 13-26 GW Wind
  - 3-13 GW Solar
- **For growing resource adequacy need, 6-16 GW natural gas are selected [1]**
  - Renewables added for clean energy policies partially reduce the need for natural gas to the extent they generate during low hydro winter periods
- **Without new gas, costs and resource needs increase significantly**
  - Up to 77 GW storage and 4 GW DR are selected although ELCCs continue to be low

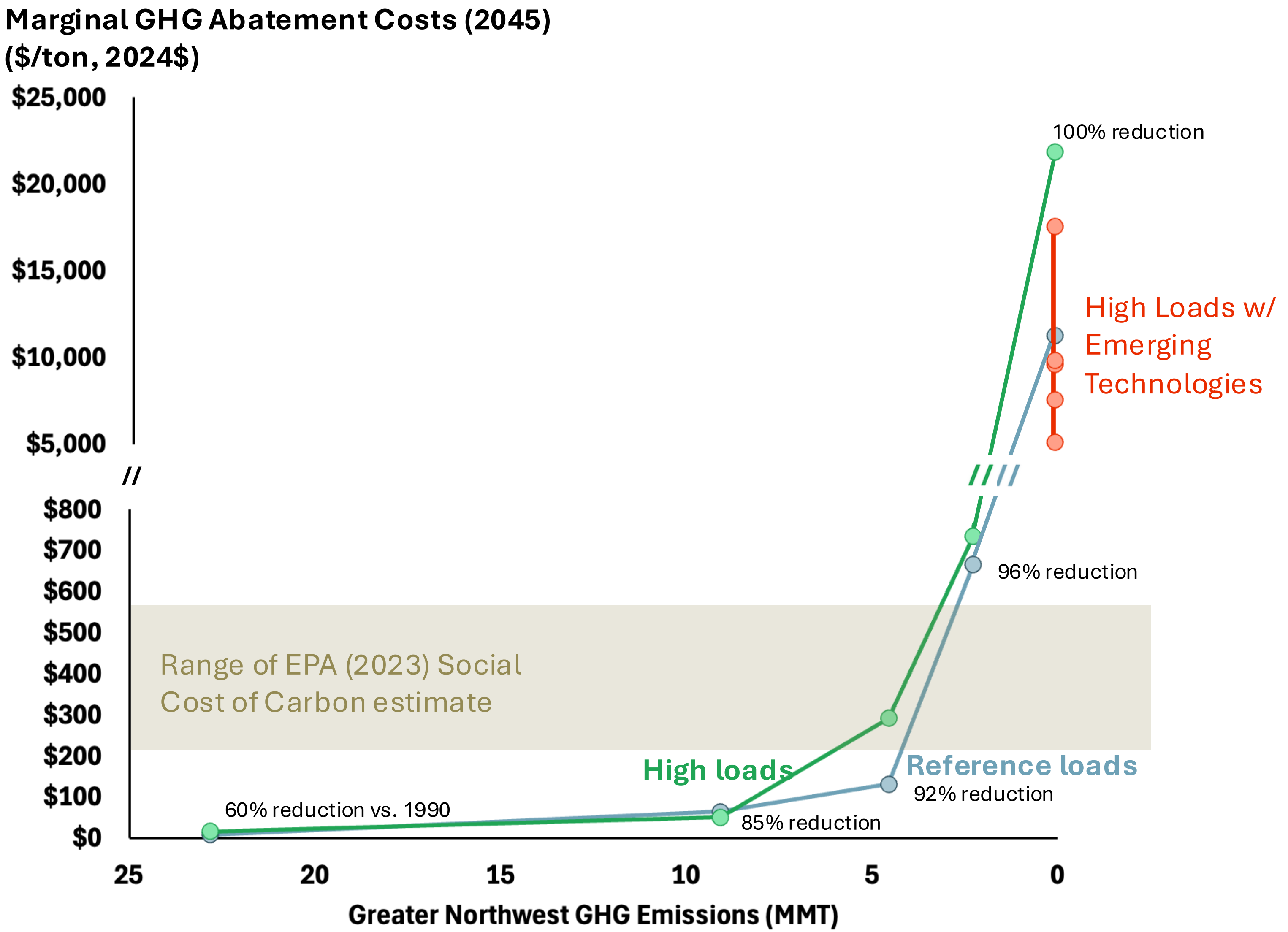
2045 Portfolio: Further load growth dramatically increases need for both new clean energy production and firm capacity

Greater Northwest
Installed Capacity in 2025 & 2045



- **Meeting 96% GHG Reduction targets in 2045 with mature technologies requires significant scale up of renewables**
  - 37-49 GW Wind
  - 39-54 GW Solar
- **If natural gas allowed to support RA needs, reaching 96% GHG reduction costs ~1 cents/kWh above a no policy case**
- **For growing resource adequacy need, up to 24 GW natural gas are selected even in the 96% GHG reduction scenario**
  - Disallowing no gas in 2045 with 100% GHG reduction requires >250 GW of Battery Storage build out to meet the system reliability requirements
  - Meeting increased reliability needs without new gas requires >170 GW of Battery Storage by 2045

GHG reductions up to ~90-95% below 1990 levels can be achieved at or below the social cost of carbon

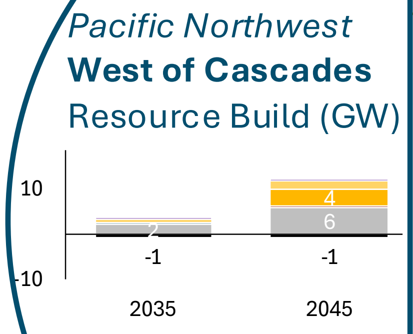


- Social cost of carbon data source: EPA November 2023, https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf

To meet subregional RA needs, new resources are distributed across the Greater Northwest and new interregional transmission is selected

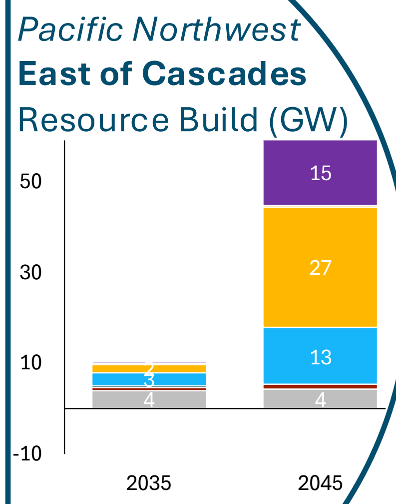
96% GHG Reduction - High Load Scenario

- Demand Response
- Li-ion Battery
- Solar
- Wind
- Hydro
- Geothermal
- Nuclear
- Natural Gas
- Coal



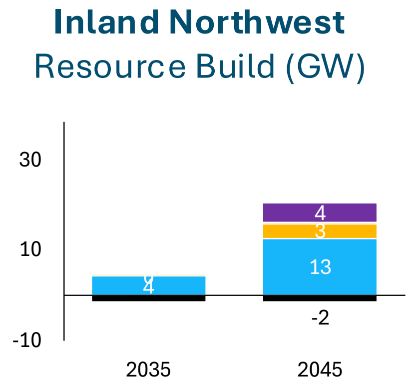
East to West Cascades
Tx Interface (MW)

2025	19,250
2035	**21,400 (+2,150)**
2045	**27,890 (+8,640)**



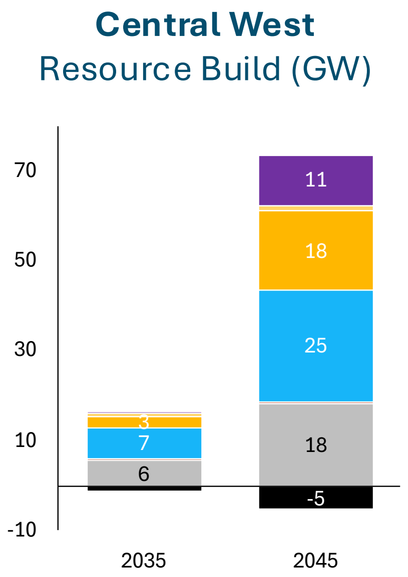
Inland Northwest into Pacific Northwest
Tx Interface (MW)

2025	2,200
2035	**2,800 (+1,600)**
2045	**5,189 (+1,989)**



Central West into Pacific Northwest
Tx Interface (MW)

2025	2,400
2035	**3,400 (+1,000)**
2045	**3,719 (+1,319)**



The West of Cascades subregion requires over 4 GW of new firm capacity by 2035 and 17 GW by 2045

Met by ~8 GW local resources and ~9 GW transmission expansion

The Pacific Northwest subregion requires over 11 GW of new firm capacity by 2035 and 31 GW by 2045

Met by ~28 GW local resources and ~3 GW transmission expansion, which also helps deliver MT+WY wind

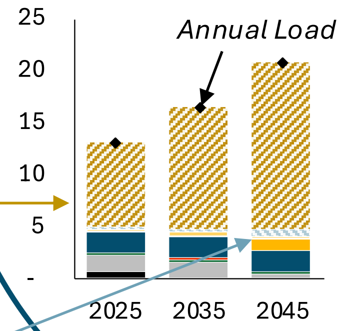
- Results show RESOLVE's optimal solution to meet local needs, but those needs could be plausibly met by different combinations of local resources and transmission upgrades.

As load grows the most West of Cascades, generation grows primarily on the East side and on the rest of the study region

96% GHG Reduction - High Load Scenario

- Demand Response
- Li-ion Battery
- Solar
- Wind
- Hydro
- Geothermal
- Nuclear
- Natural Gas
- Coal

Pacific Northwest
West of Cascades
Annual Energy (aGW)



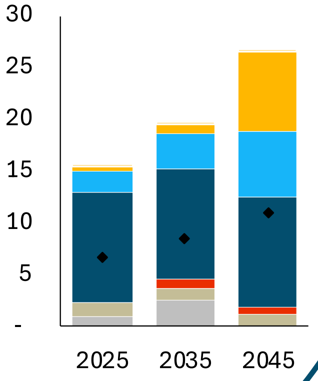
Net Imports from East of Cascades

Net Imports from External Zones (CA, BC)

East to West Cascades
Tx Interface (aGW)

2025	8.2	←
2035	**10.2**	←
2045	**16.2**	←

Pacific Northwest
East of Cascades
Annual Energy (aGW)



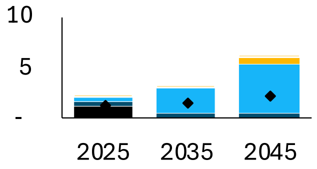
Inland Northwest into Pacific Northwest
Tx Interface (aGW)

2025	0.3	←
2035	**1.2**	←
2045	**1.9**	←

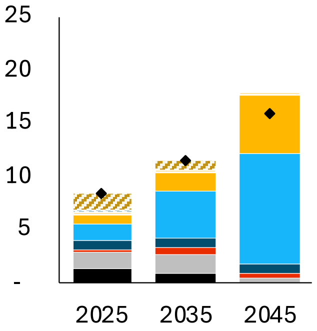
Central West into Pacific Northwest
Tx Interface (aGW)

2025	*-0.9*	→
2035	*-0.4*	→
2045	*-0.1*	→

Inland Northwest
Annual Energy (aGW)



Central West
Annual Energy (aGW)



The West of Cascades subregion requires over 10 aGW of net imports by 2035 and 16 aGW by 2045
Annual Loads of 21 aGW in 2045 are met by less than 5 aGW of local generation

The Pacific Northwest subregion shifts from a net exporter today to a net importer in 2035 and 2045
Direction of flows throughout the year vary substantially based on hydro availability and wind generation levels

- RESOLVE also models loads and resources in external regions, which also trade energy with the Greater Northwest region

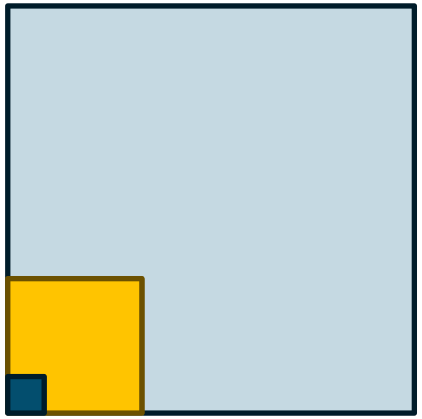
Renewable Land Use

Land Use Impact

96% GHG Reduction, Reference Load

- Each point on the map indicates 200 MW
- Sites not to scale or indicative of future resource siting locations

Technology	Nameplate MW	Direct land use (acres)	Direct + indirect land use (acres)	Total land use (acres)
Wind ▲	50,790	38,094	4,279,069	4,317,163
Solar ● (utility-scale)	41,470	373,225	n/a	373,225
Total	**92,260**	**411,319**	**4,279,069**	**4,690,388**



Wind (total project area) = ~85 acres/MW

Solar (direct) = ~9 acres/MW

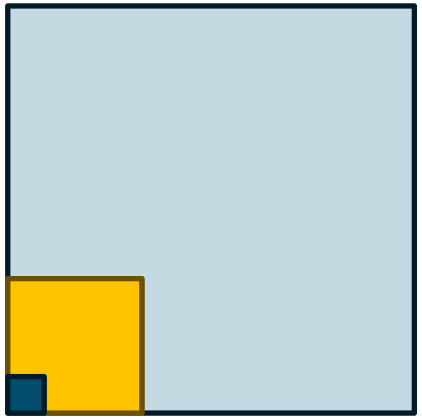
Wind (permanent direct) = ~0.75 acres/MW

Land Use Impact

96% GHG Reduction, High Load

- Each point on the map indicates 200 MW
- Sites not to scale or indicative of future resource siting locations

Technology	Nameplate MW	Direct land use (acres)	Direct + indirect land use (acres)	Total land use (acres)
Wind ▲	63,485	47,615	5,348,612	5,396,227
Solar ● (utility-scale)	56,899	512,083	n/a	512,083
Total	**120,384**	**559,698**	**5,348,612**	**5,908,310**



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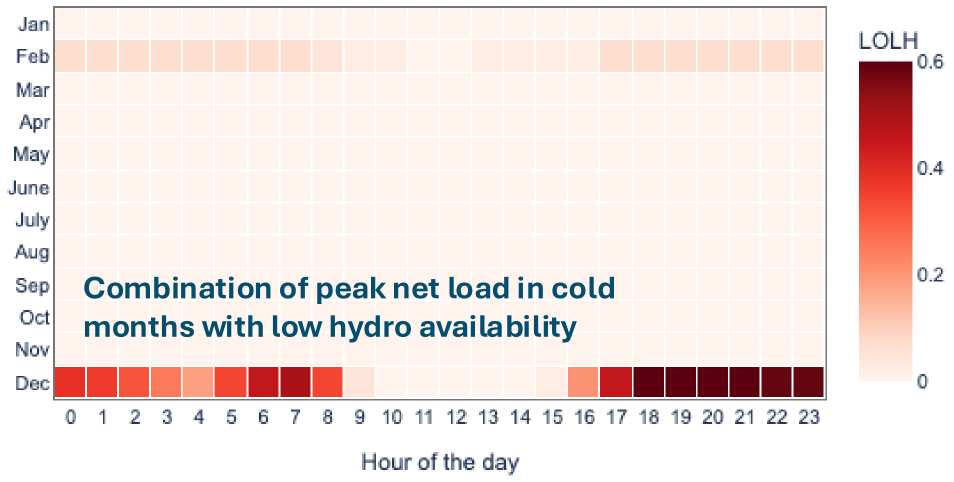
Long-term (2045) System Reliability Dynamics

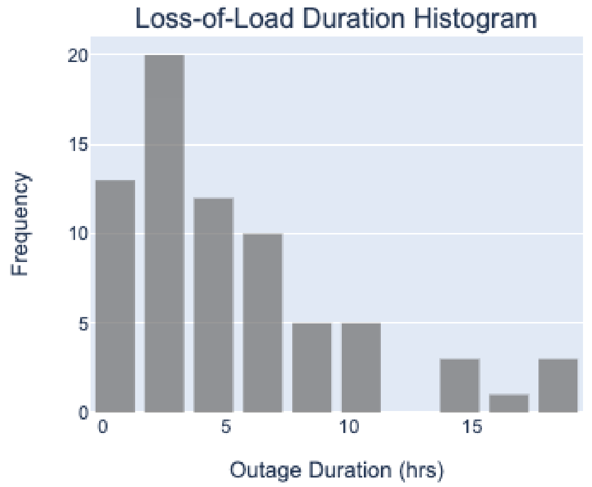
Long-term Reliability Risk in the Northwest
High Loads Scenario under 96% GHG Reduction

- **By 2045, only about 27% of the region's energy comes from hydro, reducing the impact of year-to-year variability, though not eliminating it**
- **Under 96% GHG reduction, as much as 70% of generation could come from wind + solar**
  - Water variability will continue to be critical for resource adequacy in the region, while renewable variability becomes increasingly important
- **Most simulated shortfall events occur during the cold winter months during high net load *hours* when loads peak and renewables are low**
- **Simulated reliability events mostly last less than 12 hours, shorter than the extended duration events modeled for the 2025 system**

Average Loss-of-Load Hours (LOLH) by Month x Hour

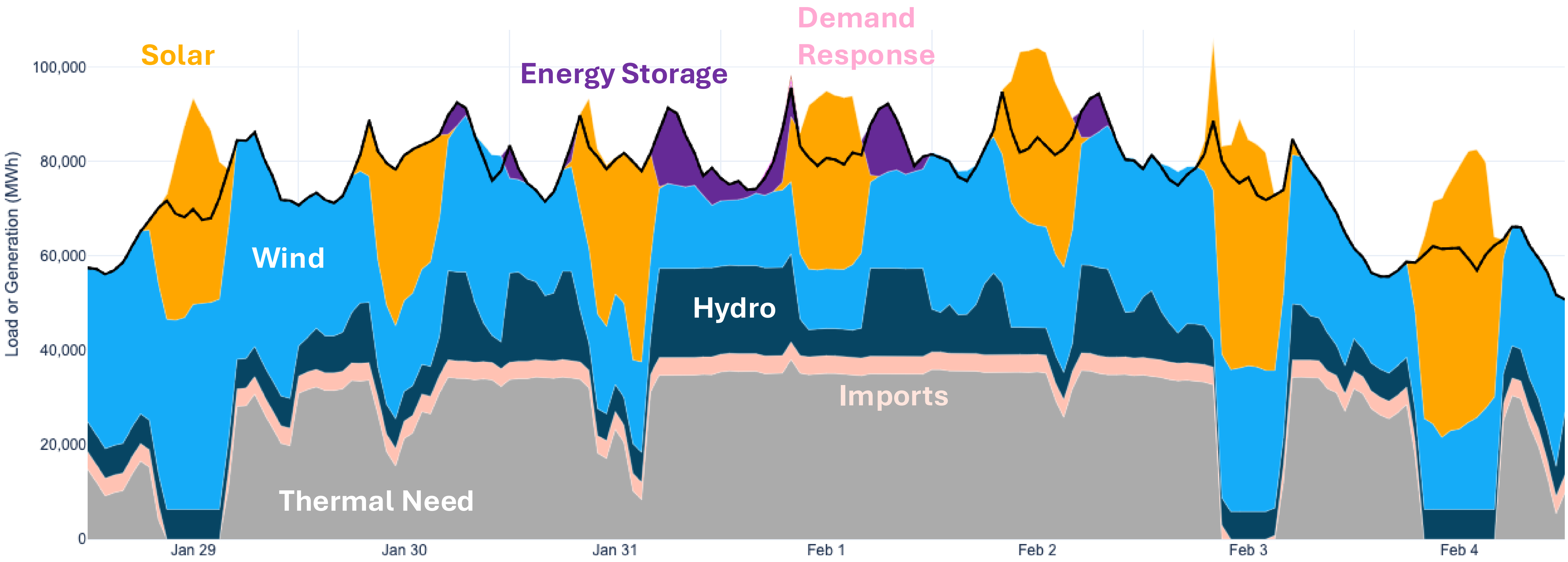


Distribution of Loss-of-Load Events



Resource availability example: February 2045 (High Loads, 96% GHG Reduction) simulated under 1996 load + 1993 hydro conditions

Greater Northwest in 2045, RECAP simulation of high load, low hydro, but high renewables winter week



Resource availability example: February 2045 (High Loads, 96% GHG Reduction) simulated under 1990 load + 2001 hydro conditions

Greater Northwest in 2045, RECAP simulation of shorter-duration reliability risk