Energy+Environmental Economics

BPA Lower Snake River Dams Power Replacement Study

Executive Summary

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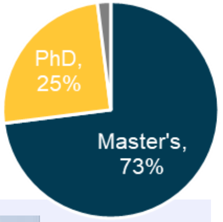
Who is E3?
Thought Leadership, Fact Based, Trusted.

100+ full-time consultants | 30 years of deep expertise | Engineering, Economics, Mathematics, Public Policy…




San Francisco

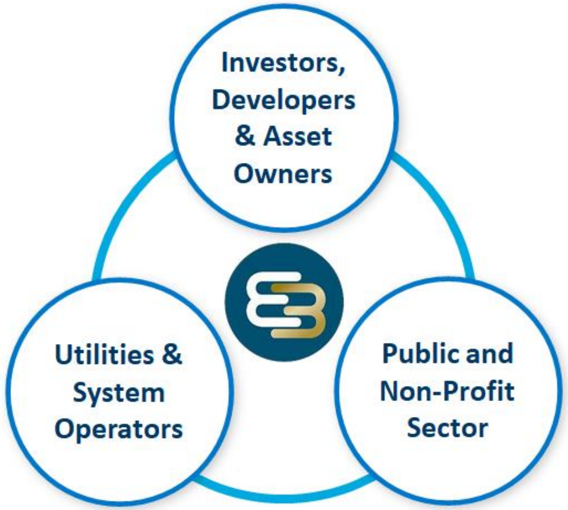

New York


Boston


Calgary

E3 Clients

300+ projects per year across our diverse client base



Recent Examples of E3 Projects

Buy-side diligence support on several successful investments in electric utilities (~$10B in total)

Acquisition support for investment in a residential demand response company (~$100M)

Supporting investment in several stand-alone storage platforms and individual assets across North America (10+ GW | ~$1B)

Acquisition support for several portfolios and individual gas-fired and renewable generation assets (20+ GW | ~$2B)

United Nations Deep Decarbonization Pathways Project

California: 100% clean energy planning and carbon market design for California agencies

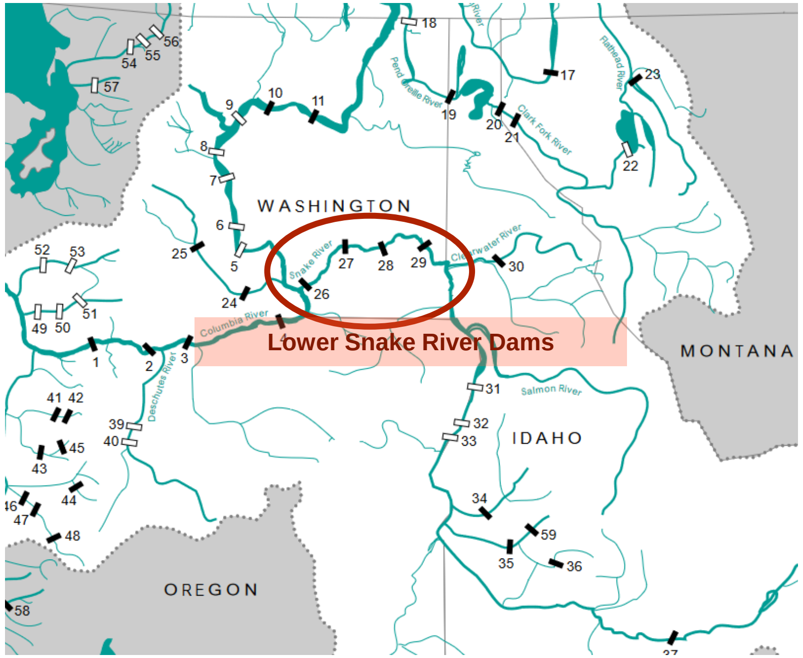
Net Zero New England study with Energy Futures Initiative

New York: NYSERDA 100% clean energy planning

Pacific Northwest: 100% renewables and resource adequacy studies for multiple utilities

About this study

- BPA contracted with E3 to conduct an independent analysis of the electricity system value of the four lower Snake River (LSR) dams
- E3 utilized our RESOLVE optimal capacity expansion model to identify least-cost portfolios of electricity resources needed to replace the electric energy and grid services provided by the dams through 2045
- Replacement costs are considered within the context of the Northwest region's aggressive, long-run decarbonization goals



Key Study Questions:

- What **additional resources** would be needed to replace the power services provided by the LSR Dams through 2045?
- What is the **net cost to** BPA ratepayers?
- How do costs and resource needs change under **different types of clean energy futures**?
- How much does replacing the dams rely on **emerging, not-yet-commercialized technologies**?

What would it take to replace the output of the four lower Snake River dams?

+ **What energy services are lost if the dams are breached?**
  - **3,483 MW of total capacity***, including approximately **2,300 MW of firm peaking** capability to avoid power shortages during extreme cold weather events
  - **~900** annual average MW of low-cost, zero-carbon energy** (enough energy to support ~450,000 households or 1.7x the City of Portland) as well as **operational flexibility** services
+ **How much would it cost to replace the power benefits of the four lower Snake River dams in E3's study with breaching in 2032?**
  - In E3's **baseline scenario**, total net present value (NPV)*** replacement costs would be ~**$12 billion**
  - In a **deep decarbonization scenario** with higher loads and zero emissions electricity by 2045, NPV costs range from **$11.2-19.6 billion** with at least one emerging technology
    - Reaching deep decarbonization **absent breakthroughs in not-yet-commercialized emerging technologies**, NPV costs could increase to **$42-77 billion**
+ **What are the long-term rate impacts to ~2 million public power households in 2045?**
  - Public power costs increase by **8-18% or ~$100-230 per year across most scenarios**
    - Costs increase by **34-65% or ~$450-850 per year** under deep decarbonization scenario **absent emerging technology breakthroughs**
+ **What resources are needed to replace the dams?**
  - A combination of **renewable generation** (wind), **"clean firm" resources** (such as dual fuel natural gas + hydrogen plants, advanced nuclear, or gas with carbon capture and storage)**, and energy efficiency**
  - Battery storage cannot cost-effectively replace hydro capacity in the Northwest due to charging limitations during energy shortfall events
+ **What is the timeline necessary to add the resources that would be required?**
  - E3 estimates that adding additional renewable energy and firm capacity additions would take approximately 5-7 years after congressional approval to breach the dams and possibly up to 10-20 years if additional new large-scale transmission was required. E3 assumed transmission would be built as needed for renewable additions.

Plant	Total Capacity (MW)
Lower Granite	930
Little Goose	930
Lower Monumental	930
Ice Harbor	693

Total = 3,483 MW

* Hydro traditionally operates above nameplate and closer to overload capacity (~15% above nameplate) and FERC uses these peak generation values in hydro licensing. Historical peak generation was 3,431 MW.
** E3's RESOLVE model uses 2001, 2005, and 2011 hydro years, which resulted in ~700 aMW of lower Snake River dams generation, making it a conservative estimate of the dams' GHG-free energy value
*** NPV calculated over a 50-year period following the date of breaching, using a 3% discount rate based on the approximate public power cost of capital.

Study Approach

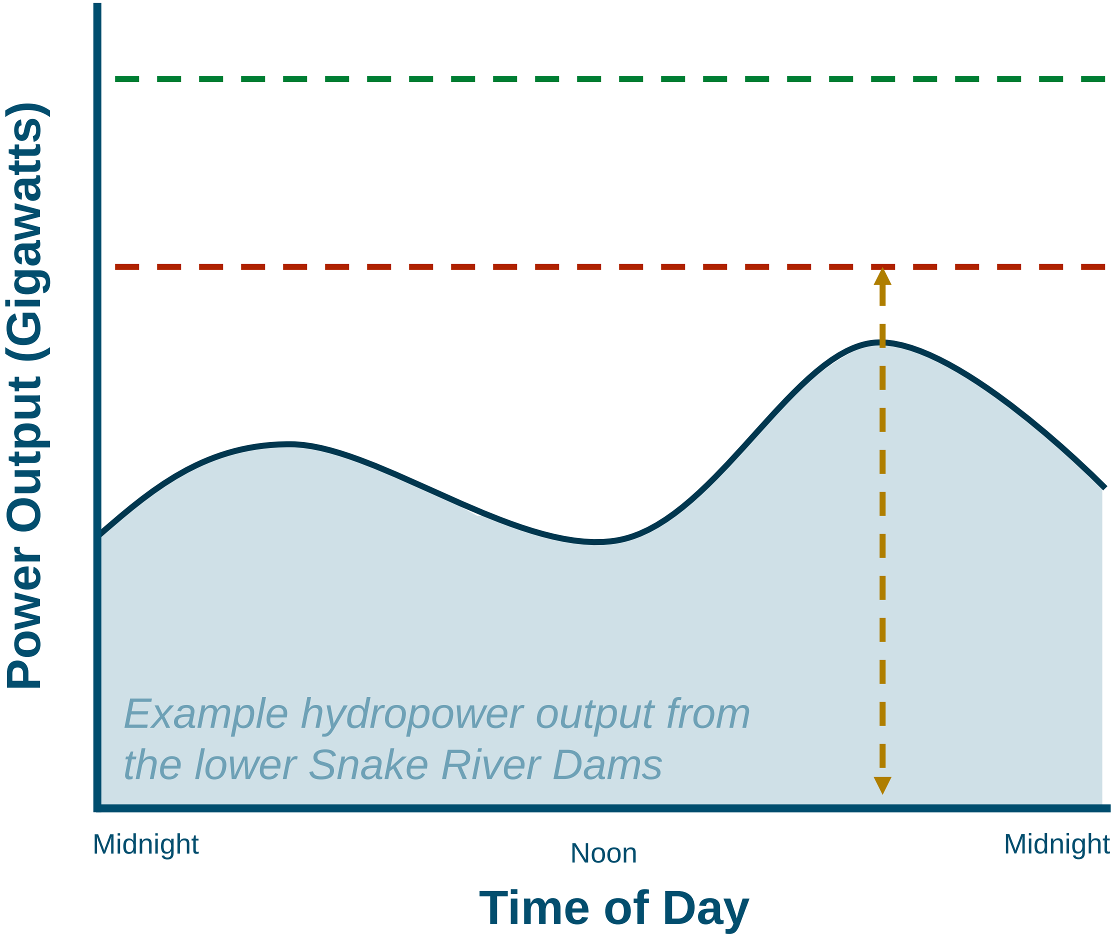
What grid services do the lower Snake River dams provide?

Little Goose

Lower Granite

Lower Monumental

Ice Harbor



Total "Capacity"
Maximum instantaneous power output the four dams
LSR Dams = 3.5 GW*

"Firm Capacity"
Sustained peaking output (+ reserves) during reliability strained conditions
(e.g. cold January during a drought year)
LSR Dams = 2.3 GW**

Annual (Carbon-free) Energy
Sum of hourly power produced across the year, subject to seasonal water availability
LSR Dams = 0.9 average GW***

Operational Flexibility
The ability to change power output to support a reliable grid, subject to water availability and operational constraints
LSR Dams provide short-term reserves + multi-hour ramping / renewable integration capabilities

E3's modeling selects the least-cost portfolio of resources to replace these services

Transmission Grid Reliability Services
Services to reliably operate the transmission grid
(e.g., voltage, frequency support, blackstart, etc.)
LSR Dams can provide, but not the focus of this study

Some of these services may be provided by modeled replacement resources, other may require additional investments

* Hydro traditionally operates above nameplate and closer to overload capacity (~15% above nameplate) and FERC uses these peak generation values in hydro licensing. Historical peak generation was 3,431 MW.
** Firm capacity assumed in this study is consistent with the ~65% Northwest hydro capacity value assumed by PNUCC (the Pacific Northwest Utilities Conference Committee).
*** Average GW means that on average across an average year the plant generated at ~0.9 GW, though its hourly output may be above or below that amount. LSR output was adjusted to reflect increased spill requirements of the EIS. However, E3's RESOLVE model uses 2001, 2005, and 2011 hydro years, which resulted in ~0.7 aMW of lower Snake River dams generation, making it a conservative estimate of the dams' GHG-free energy value.

What's the focus in this study compared to the CRSO EIS?

The study uses an optimization model to determine the least-cost replacement resources for the four lower Snake River dams subject to A) policy and B) reliability constraints

+ **Least-cost optimization: includes updated resource pricing and new emerging technologies**
+ **Policy: E3's modeling considers the effects of regional policies such as Washington's Clean Energy Transformation Act (CETA) and Oregon's 100% clean electricity standard**
  - Aggressive clean energy laws drive coal power plant retirements, price carbon emissions, and require long-term **carbon emissions reductions** by 2045
  - Study includes significant **electrification** that increases demand for electricity to support carbon-reduction in other sectors such as transportation, buildings, and industry, consistent with Washington's Energy Strategy
+ **Reliability: E3's modeling captures the need for the Northwest system to meet peak load during extreme weather and low hydro conditions (known as "resource adequacy").**
  - Captures the abilities and limits of different technologies to serve load during reliability challenging conditions
    - E.g. during extended cold-weather periods with high load, low hydropower availability, and low wind and solar production
  - Resources with high energy production costs may be selected for reliability needs but then run sparsely only during extreme conditions (e.g. natural gas + hydrogen combustion turbines)
+ **LSR operations: incorporates preferred alternative operations selected in the EIS**
  - Increases spill from the dams, lowering available annual energy and changing operational flexibility

Policy landscape: Washington, Oregon, California

+ **The study includes the impacts from clean energy policies in the Pacific states**

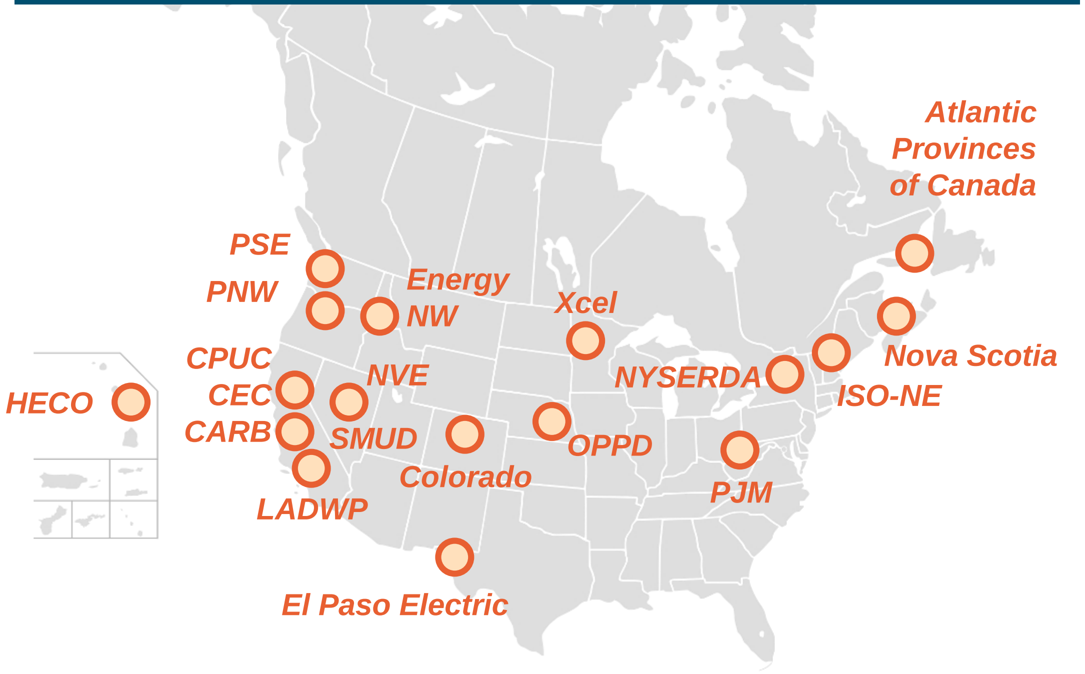
	RPS or Clean Energy Standard?	Coal Prohibition?	Cap-and-Trade?	New Natural Gas?	Economy-Wide Carbon Reduction?
WA	✓ Carbon neutral by 2030, 100% carbon free electricity by 2045	✓ Eliminate by 2025	✓ Cap-and-invest program established in 2021, SCC in utility planning	✓	✓ 95% GHG emission reduction below 1990 levels and achieve net zero emissions by 2050
OR	✓ 50% RPS by 2040, 100% GHG emission reduction by 2040, relative to 2010 levels	✓ Eliminate by 2030	✓ Climate Protection Plan adopted by DEQ in 2021 (power sector not included)	✕ HB 2021 bans expansion or construction of power plants that burn fossil fuels	✓ 90% GHG emission reduction from fossil fuel usage relative to 2022 baseline
CA	✓ 60% RPS by 2030, 100% clean energy by 2045	✓ Coal-fired electricity generation already phased out	✓	✕ CPUC IRP did not allow in recent procurement order	✓ 40% GHG emission reduction below 1990 levels by 2030 and 80% by 2050

Study uses E3's Northwest RESOLVE Model

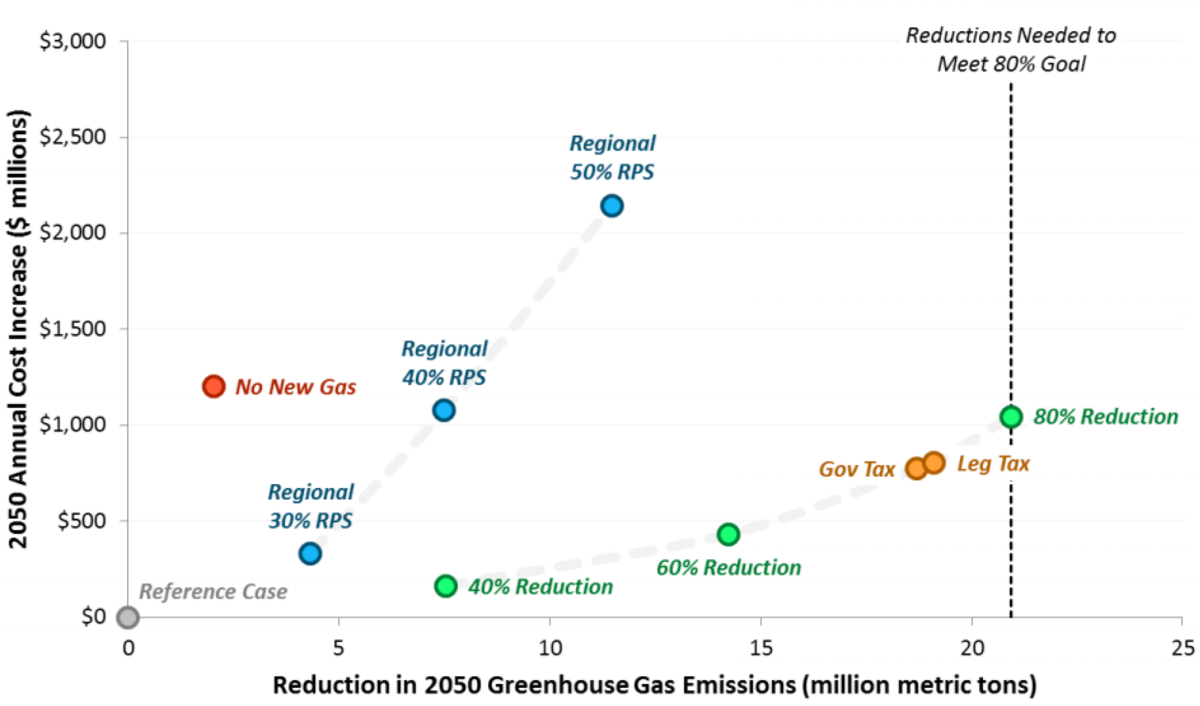
+ **E3 has used RESOLVE across North America to tackle complex policy and planning questions**
  - RESOLVE develops optimal portfolios of **zero-carbon resources** to meet policy and reliability goals

+ **E3 has used RESOLVE in several prior Pacific Northwest studies**
  - PNW Low-Carbon Scenario Analysis (PGP, 2017)
  - PNW Zero-Emitting Resources Study (ENW, 2021)

RESOLVE Case Studies



Pacific Northwest Low-Carbon Scenarios



Modeling approach involves a three-step process

1. ***With the lower Snake River dams*, optimize long-term resource needs and operations for the Pacific Northwest**
   - Produces necessary resource additions and total system costs and emissions

2. ***Remove the lower Snake River dam generating capacity, then re-optimize* long-term resource needs and operations for the Pacific Northwest**
   - Produces a second set of resource additions and total system costs and emissions
   - All scenarios breach the dams in 2032, except for one scenario in 2024

3. ***Calculate additional resources and investment + operational costs* required to replace the dams**
   - Calculated as the difference between steps 1 and 2 above

Key modeling assumptions

Element	Study Approach	Impact on Dams Replacement Needs
Study Years	• 2025 through 2045*, including fuel price forecasts and declining renewable + storage costs	Considers long-term needs
Clean Energy Policy Scenarios	• Aggressive OR+WA legislation reflected, including coal retirements + carbon pricing** • Two electric emissions scenarios considered: 1. **100% clean retail sales** (~65-85% carbon reduction***) 2. **Zero-emissions** (100% carbon reduction)	Clean energy policy requires long-term **replacement of LSR dams with GHG-free energy**
Load Growth Scenarios	• Two load scenarios: 1. **Baseline** (per NWPCC 8th Power Plan) 2. **High electrification** load growth (to support economy-wide decarbonization) • Significant quantities of energy efficiency are embedded in all scenarios	Higher load scenarios **increase the value of LSR dams energy + firm capacity**
Reliability Needs	• Modeling ensures reliability needs during extreme conditions (e.g. high loads + low hydro) • Captures ability (and limits) of renewables, battery storage, and demand response to support system reliability	Reliability needs require **replacement of LSR dams firm capacity contributions**

Technologies Modeled, including "Emerging" Technologies	• Broad range of dam replacement technology options considered:
	  • **Baseline technologies**: solar, wind, battery + pumped storage, energy efficiency, demand response, dual fuel natural gas + hydrogen combustion plants
	  • **Sensitivities** include Emerging Technologies and Limited Technologies (No New Combustion) scenarios
	• Resource costs developed by E3 using NREL 2021 ATB, Lazard Cost of Storage v.7, NuScale Power (for small modular reactor costs)
		Technology available for LSR dams replacement determines replacement cost

Distributed Energy Resource Options	• Energy efficiency, demand response, and customer solar embedded into modeling inputs • Additional energy efficiency and demand response can be selected	**Demand resource can help replace LSR dams**, though low-cost supply is limited

* 20-years of end effects are also considered in RESOLVE (2045-2065) and LSR Dam replacement costs were calculated based on 50-years (e.g. 2032-2082)

** The carbon price assumed drives the region to >100% CES by 2045, so a scenario without a carbon price was modeled to understand the LSR dam replacement impacts of a binding CES target.

*** A 100% clean retail sales target allows emissions for electric generation beyond that needed to serve "retail sales", i.e. losses during transmission to retail loads and exported energy.

Scenarios

+ Scenario 1: 100% Clean Retail Sales

- Northwest resources produce enough clean energy to meet **100% of retail electricity sales** on an annual average basis
- Some gas generation is retained for reliability, but carbon emissions are reduced **85% below 1990 levels**
- **Business-as-usual** load growth

+ Scenario 2: Deep Decarbonization

- **Zero carbon emissions** by 2045
- **High electrification** of buildings, transportation, and industry to reduce carbon emissions in other sectors
- **Emerging technologies** become available to provide firm, carbon-free power

Emerging Technologies

Technology	S1 100% Clean	S2a Deep Decarb Baseline	S2b Deep Decarb Emerging Tech.	S2c Deep Decarb No New Combustion
Mature technologies (solar, wind, battery + pumped storage, energy efficiency, demand response)	Available	Available	Available	Available
Hydrogen (existing natural gas retrofits)	Available	Available	Available	Available
Hydrogen (new dual fuel natural gas + hydrogen)	Available	Available	Available	Not available
Nuclear (small modular reactors)	Not available	Not available	Available	Not available
Natural Gas w/ Carbon Capture and Storage	Not available	Not available	Available	Not available
Offshore Wind (floating)	Not available	Not available	Available	Available

Available
Not available

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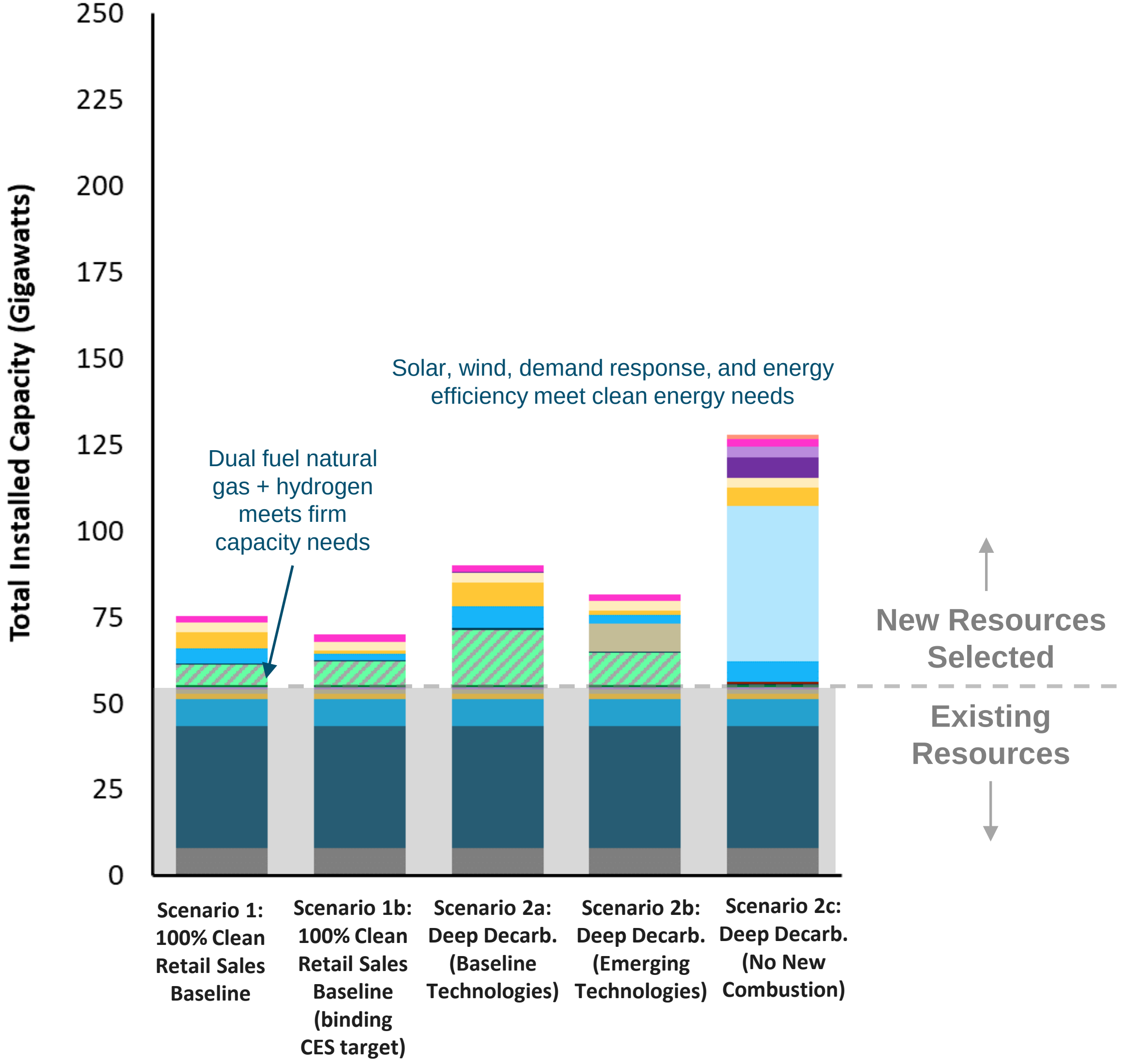
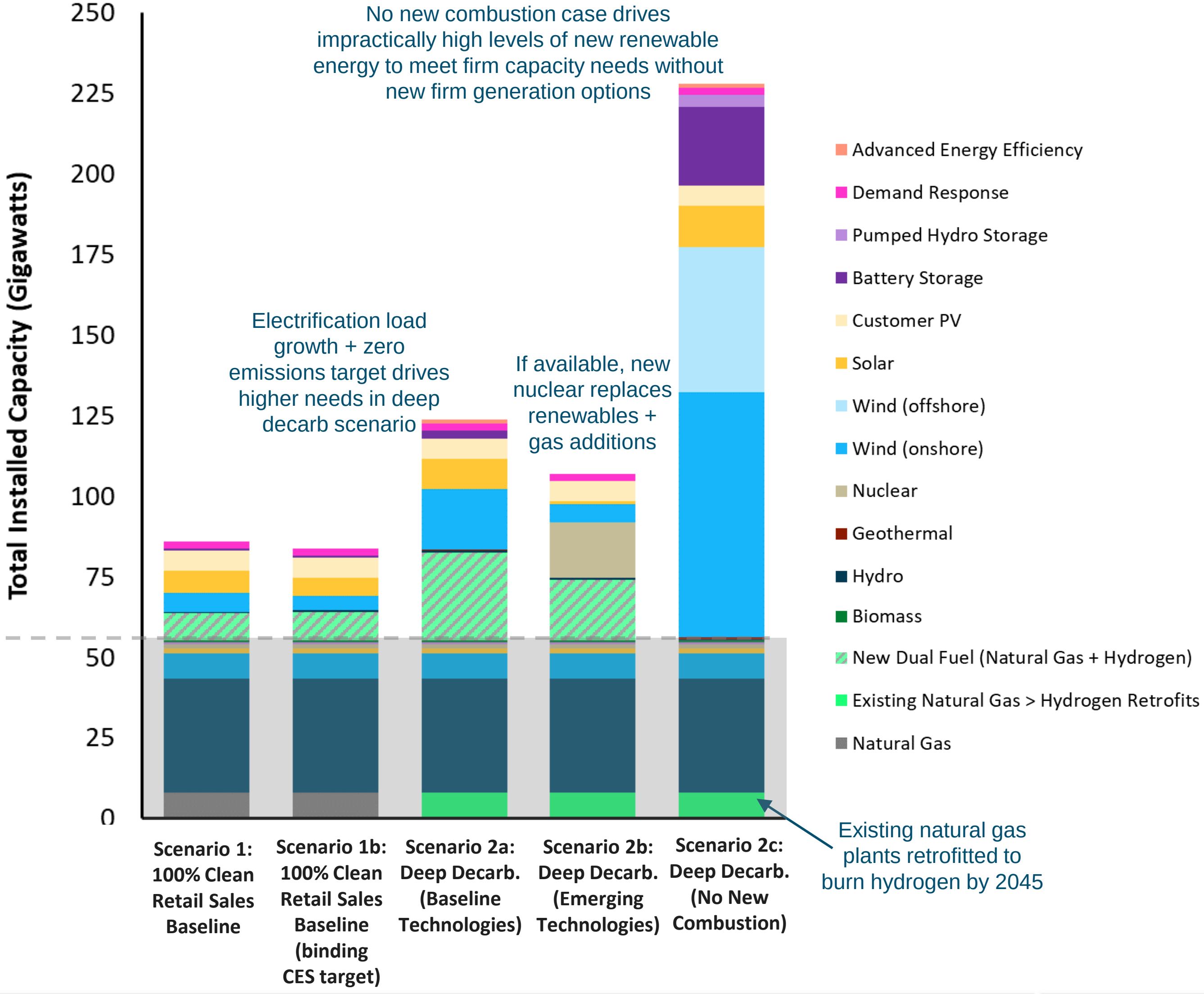
Northwest Resource Needs in Scenarios With the Lower Snake River Dams

Even without breaching the dams, all scenarios show large levels of new resource additions

2035 Northwest Resource Mix



2045 Northwest Resource Mix



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Replacing the Power from the Lower Snake River Dams

Replacement resources selected to replace the lower Snake River dams

- **RESOLVE selects an optimal portfolio of replacement resources including additional advanced energy efficiency, wind, solar, green hydrogen, and/or advanced nuclear**
- **Firm capacity is mostly replaced with ~2 GW of dual fuel natural gas + hydrogen turbines**
  - These turbines may initially burn natural gas when needed during reliability challenged periods, but would transition to hydrogen by 2045 to reach zero-emissions
- **If advanced nuclear is available, it replaces renewables and some of the gas plants**
- **The "no new combustion" scenario requires impractically large (~12 GW) buildout of renewable energy to replace the dams' firm capacity contributions and GHG-free energy**
  - A range of costs was developed for this scenario based on the assumed transmission needs for renewable additions

Scenario	Replacement Resources Selected, Cumulative by 2045 (GW*)
Scenario 1: 100% Clean Retail Sales	+ 2.1 GW dual fuel NG/H2 CCGT + 0.5 GW wind
Scenario 1b: 100% Clean Retail Sales (binding CES target)**	+ 1.8 GW dual fuel NG/H2 CCGT + 1.3 GW solar + 1.2 GW wind
Scenario 2a: Deep Decarb. (Baseline Technologies)	+ 2.0 GW dual fuel NG/H2 CCGT + 0.3 GW li-ion battery + 0.4 GW wind + 0.05 GW advanced energy efficiency + additional H2 generation***
Scenario 2b: Deep Decarb. (Emerging Technologies)	+ 1.5 GW dual fuel NG/H2 CCGT + 0.7 GW nuclear SMR
Scenario 2c: Deep Decarb. *(No New Combustion)*	+ 10.6 GW wind + 1.4 GW solar

* 1 GW = 1,000 MW
** In scenario 1b, the 100% CES target is binding in 2045, causing the need to fully replace the GHG-free energy output of the LSR dams. In scenario 1, the high carbon price assumed drives the region higher than the 100% CES target, making it a non-binding constraint in the model.
*** Replacing LSR dams GHG-free energy at least-cost leads RESOLVE to generate an additional 1.2 TWh of hydrogen generation during low renewable conditions (or 0.14 average GW).

Total costs for replacing the lower Snake River dams

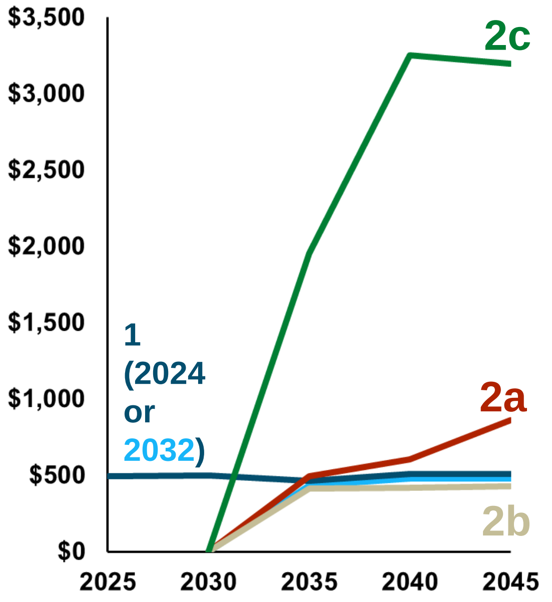
+ Costs are expected to fall on Bonneville Power Administration's public power customers

- Costs could **increase public power retail costs** by 8-18%, or up to 34-65% absent emerging technologies
- Costs could **raise annual residential electricity bills** by up to $100-230/year, or up to $450-850/yr absent emerging technologies

	Total Costs (real 2022 $)	Annual Cost Increase (real 2022 $)			Incremental Public Power Costs [% increase vs. ~8.5 cents/kWh NW average retail rates]
	Net Present Value in year of breaching	2025	2035	2045	2045
Scenario 1: 100% Clean Retail Sales	$12.4 billion	n/a	$434 million	$478 million	0.8 cents/kWh [+9%]
Scenario 1: 100% Clean Retail Sales (2024 dam breaching)	$12.8 billion	$495 million	$466 million	$509 million	0.8 cents/kWh [+9%]
Scenario 1b: 100% Clean Retail Sales (binding CES target)	$12.0 billion	n/a	$445 million	$473 million	0.8 cents/kWh [+9%]
Scenario 2a: Deep Decarb. (Baseline Technologies)	$19.6 billion	n/a	$496 million	$860 million	1.5 cents/kWh [+18%]
Scenario 2b: Deep Decarb. (Emerging Technologies)	$11.2 billion	n/a	$415 million	$428 million	0.7 cents/kWh [+8%]
Scenario 2c: Deep Decarb. *(No New Combustion)*	*$42 – 77 billion*	n/a	*$1,045 – 1,953 million*	*$1,711 – 3,199 million*	*2.9 – 5.5 cents/kWh [+34 – 65%]*

Deep decarbonization without emerging technologies drives very high costs

Cost differences driven primarily by 2045 carbon policy and availability of emerging technologies



Costs increase over time as loads grow and carbon policy becomes more stringent

- Cost increases account for replacement energy, capacity, and reserves as well as avoided LSR capital + expense, but do not include any costs for breaching the dams, which would be an additional cost.
- NPV and annual cost increase are shown for the Northwest Region as a whole, but the incremental costs are calculated relative to the BPA Tier I annual sales for public power customers. NPV calculated over a 50-year period following the date of breaching, using a 3% discount rate based on the public power cost of capital.
- % increase versus average retail rates assumes ~8.5 cents/kWh retail rates (estimated from OR and WA average retail rates). This does not include additional rate increases driven by higher loads or clean energy needs that increase regional rates as shown in the earlier 2045 incremental cost chart.
- Annual residential customer cost impact assumes 1,280 kWh/month for average residential customers in Oregon and Washington (current ~1,000 kWh/month average + 28% from electrification load growth).
- New federal tax credits for hydrogen plants/fuels or ITC/PTC extension for renewables would provide a cost reduction to public power customers from taxpayers
- Lower end of range for scenario 2c assumes limited transmission build out (based on replacement resource additions' marginal ELCC instead of delivering the full nameplate capacity), annual cost plot shows only high end of range

Cost of generation for lower Snake River dams replacement resources (using common utility metric of $/MWh)

+ **The lower Snake River dams provide a low-cost source of GHG-free energy and firm capacity**
+ **Even in a best-case scenario, replacement power would cost several times as much as the lower Snake River dams costs**
  - This is driven by both energy replacement as well as replacement of firm capacity and operational flexibility
+ **Compared to ~$13-17/MWh for the lower Snake River dams, replacement resources cost between $77-139/MWh**
  - Replacement costs rise to ~$275-500/MWh in a deep decarbonization scenario absent emerging technology

Incremental LSR Dam Replacement Resource Costs

Lower Snake River Dams All-in Generation Costs (2022 $/MWh)
$13/MWh w/o LSRCP*
$17/MWh w/ LSRCP*

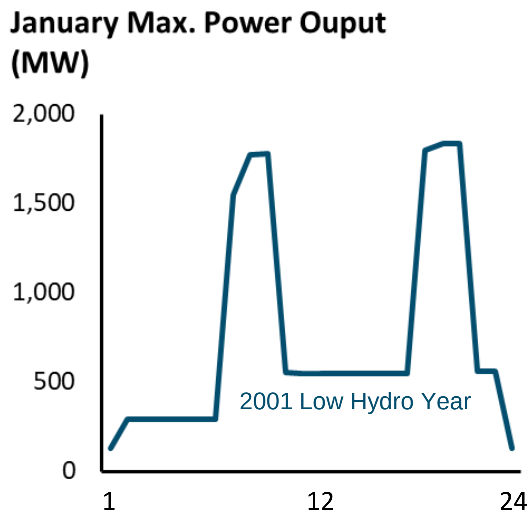
Scenario	2045 Costs to replace LSR Generation** (real 2022 $/MWh)
Scenario 1: 100% Clean Retail Sales	$77/MWh
Scenario 1: 100% Clean Retail Sales (2024 dam breaching)	$82/MWh
Scenario 1b: 100% Clean Retail Sales (binding CES target)	$77/MWh
Scenario 2a: Deep Decarb. (Baseline Technologies)	$139/MWh
Scenario 2b: Deep Decarb. (Emerging Technologies)	$69/MWh
Scenario 2c: Deep Decarb. *(No New Combustion)*	$277 – 517/MWh

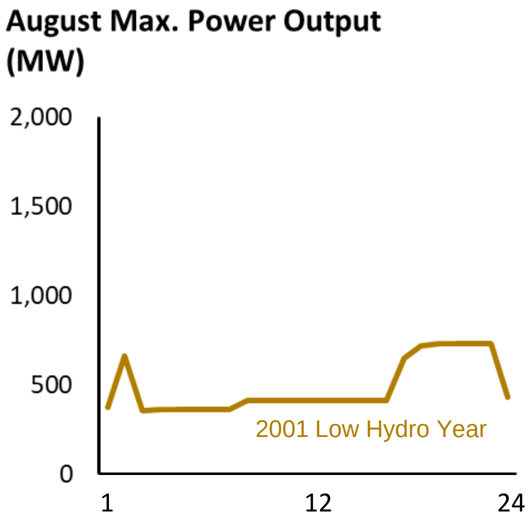
* BPA directly funds the annual operations and maintenance of the Lower Snake River Compensation Plan (LSRCP) fish hatcheries and satellite facilities. Congress authorized the LSRCP as part of the Water Resources Development Act of 1976 (90 Stat.2917) to offset fish and wildlife losses caused by construction and operation of the four lower Snake River projects.

** Replacement $/MWh costs are calculated as CoreNW revenue requirement increase with LSR dams breached divided by the annual MWh of the LSR dams assumed in E3's modeling (~700 aMW). These costs includes replacement of the LSR dam energy, capacity, and reserve provision. A significant portion of the costs is capacity costs to replace the dams' RA capacity contributions.

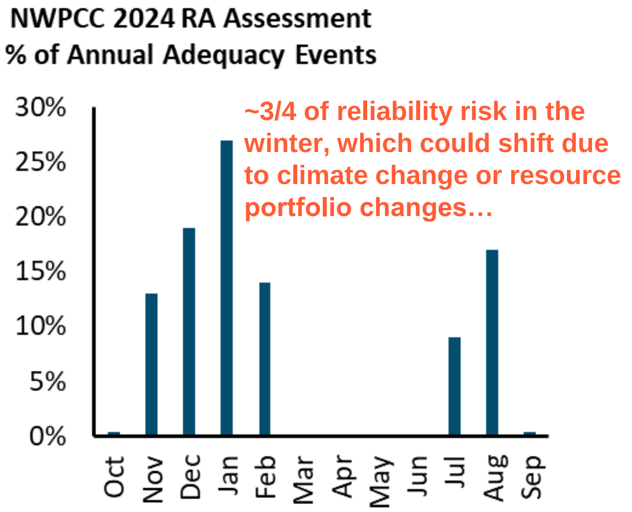
Firm capacity value of the lower Snake River dams

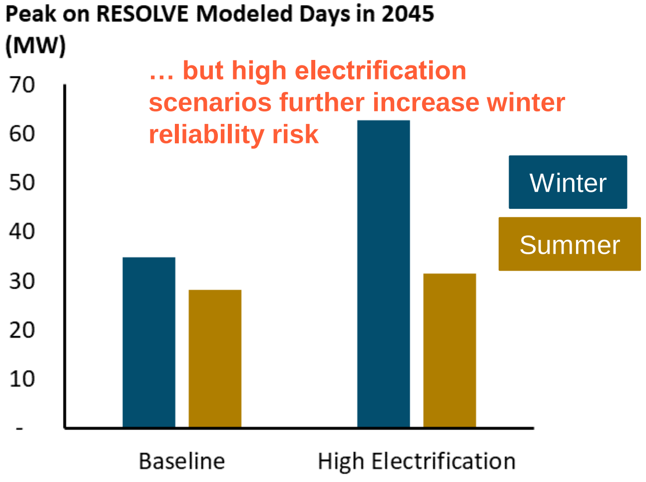
+ **The firm capacity value is a significant driver of replacements costs**
+ **PNUCC 2021 estimate of NW hydro sustained peaking capacity was used for the lower Snake River dams' firm capacity value (65% or 2.3 GW)**
+ **E3 also analyzed modeled hourly LSR dam output during the 2001 low hydro year (using BPA data post EIS spill requirements)**
  - Suggests a winter firm capacity value of ~56-60%
+ **E3 predicts a continued concentration of risk in the winter in deep decarbonization scenarios with high space heating electrification**
  - However, in a system with higher summer reliability risk, the LSR firm capacity value would be lower
  - E3 estimates the impact of a lower firm capacity value for S1 and S2a scenarios to be:
    - 1.5 GW firm capacity value (43%) → ~9-20% lower NPV replacement cost
    - 1.0 GW firm capacity value (29%) → ~14-33% lower NPV replacement cost





Assuming the Northwest remains winter reliability challenged, LSR Dams could have contributed ~56-60% of total capacity or 1.9-2.1 GW* in the 2001 low hydro year





* Includes 100-250 MW reserve provision on top of maximum power output

Key conclusions

1. **Replacing the four lower Snake River dams comes at a substantial cost, even assuming emerging technologies are available**
   - Require 2,300 – 4,300 MW of replacement resources
   - An annual cost of $415 million – $860 million by 2045*
   - Total net present value replacement cost of $11.2 – 19.6 billion based on 3% discounting over a 50-year time horizon following the date of breaching
   - Increase in costs for public power customers of $100 – 230 per household per year (an 8 – 18% increase) by 2045
2. **The biggest cost drivers for replacement resources are the need to replace the lost firm capacity and the need to replace the lost zero-carbon energy**
3. **Replacement resources become more costly over time due to increasingly stringent clean energy standards and electrification-driven load growth**
4. **Emerging technologies such as hydrogen, advanced nuclear, and carbon capture can limit the cost of replacement resources to meet a zero emissions electric system, but the pace of their commercialization is highly uncertain**
   - Replacing the dams in deep decarbonization scenarios without any emerging technologies requires impractical levels of renewable additions at a very high cost ($42-77 billion NPV cost)

* Replacement resource costs are calculated assuming project financing per E3's pro forma calculator, rather than assuming upfront congressional appropriation

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Thank you

Questions, please contact:

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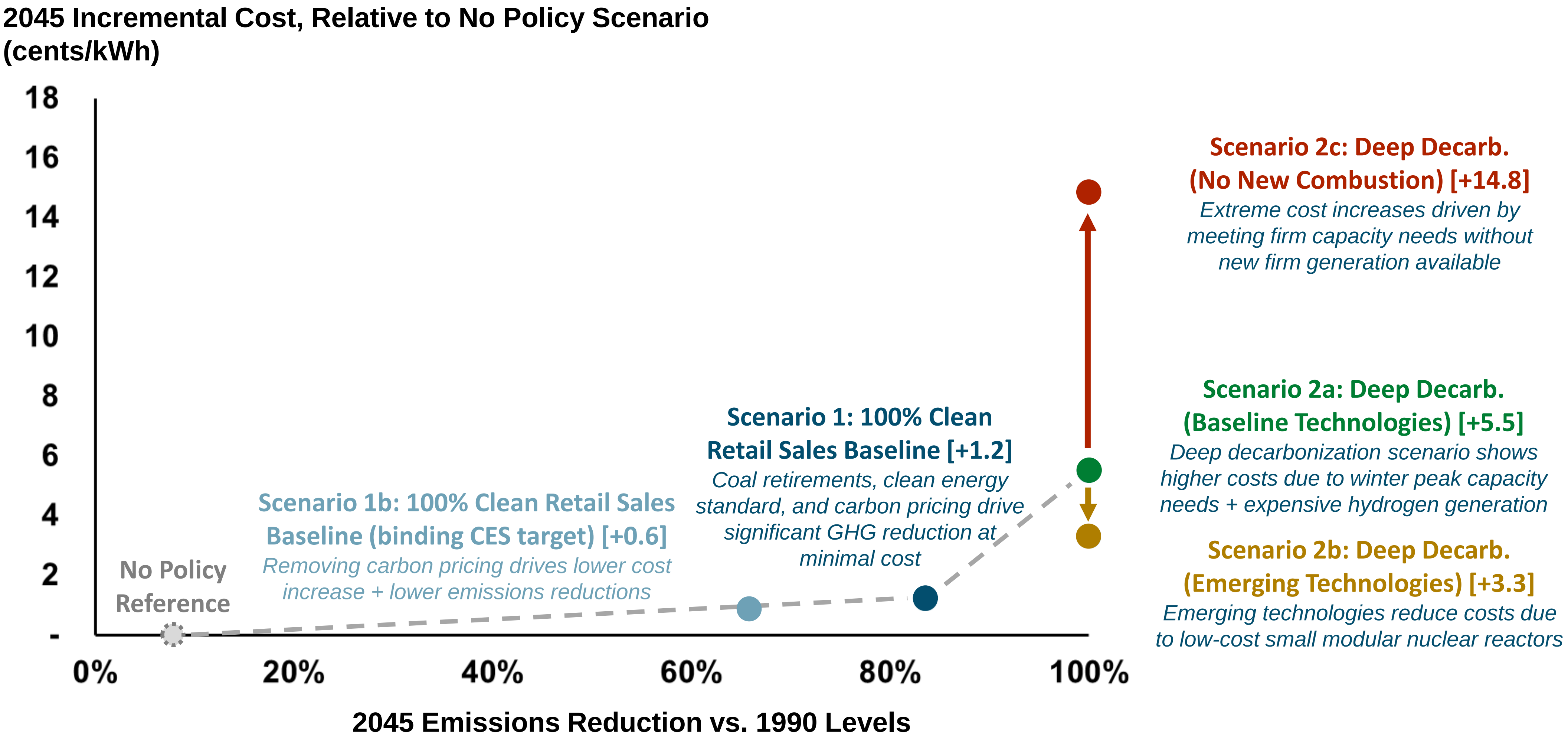
Appendix A: Additional Modeling Results

Significant carbon reductions are possible, but the cost of reaching zero emissions depends on technologies available



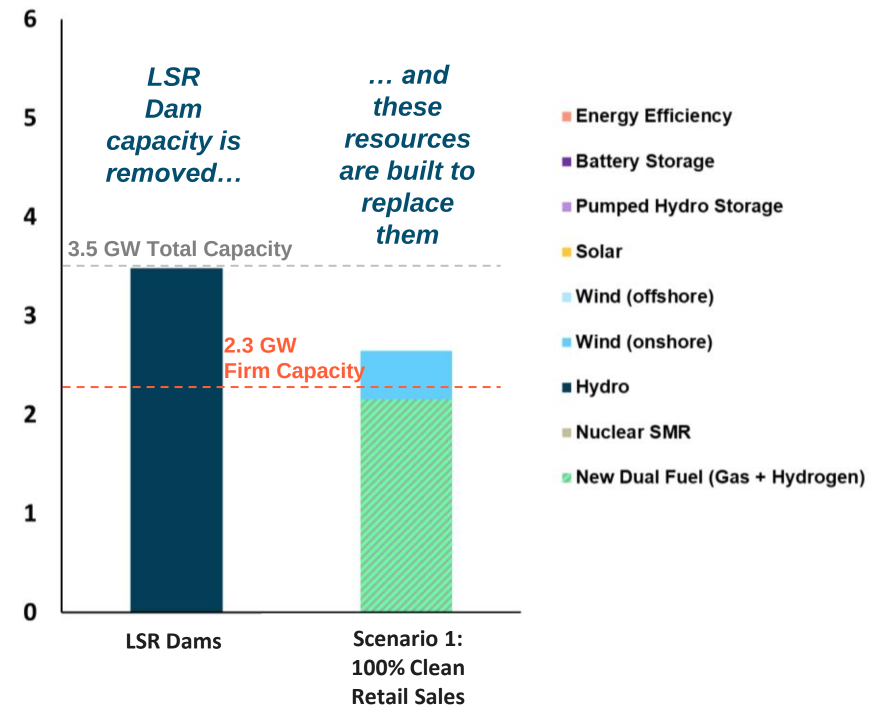
NOTES:
- 2020 average retail rates for OR and WA were 8-9 cents/kWh; 1990 electric emissions were ~33 MMT
- High electrification scenarios would avoid natural gas infrastructure costs, which would offset some of the electric peaking infrastructure cost increase

Replacing the Lower Snake River Dams
Scenario 1: 100% Clean Retail Sales

- Capacity replaced with 2.2 GW of dual fuel natural gas + hydrogen turbines and 0.5 GW wind
- Wind and imports provide the most energy replacement, but gas plant is needed for meeting extreme weather peak load events to avoid power shortages
- 2045 GHG emissions increase ~11% as not all LSR generation needs to be replaced to still meet 100% clean retail sales target

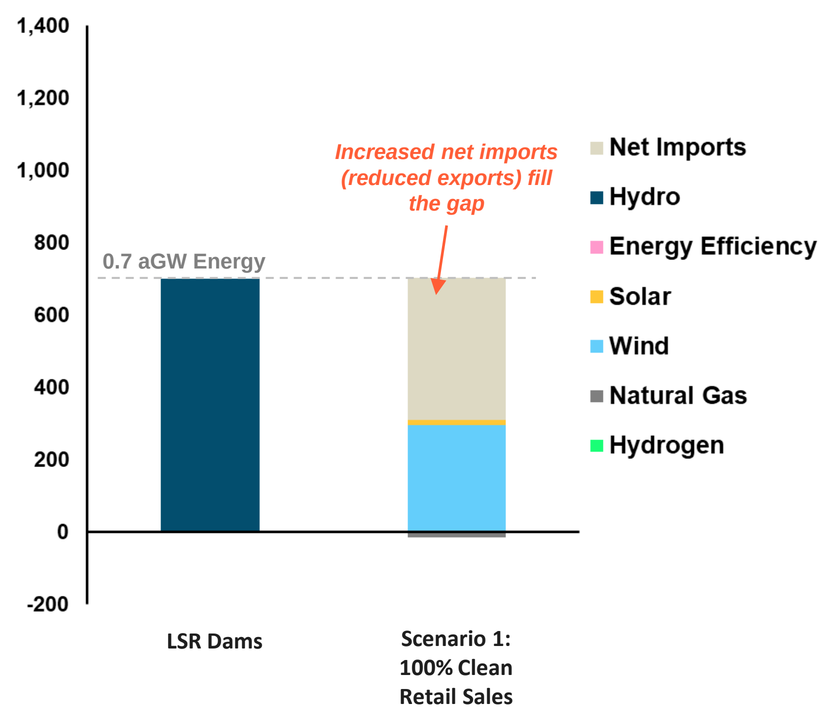
Additional Resources Built to Replace LSR Dams (2045)

2045 Capacity
(GW)



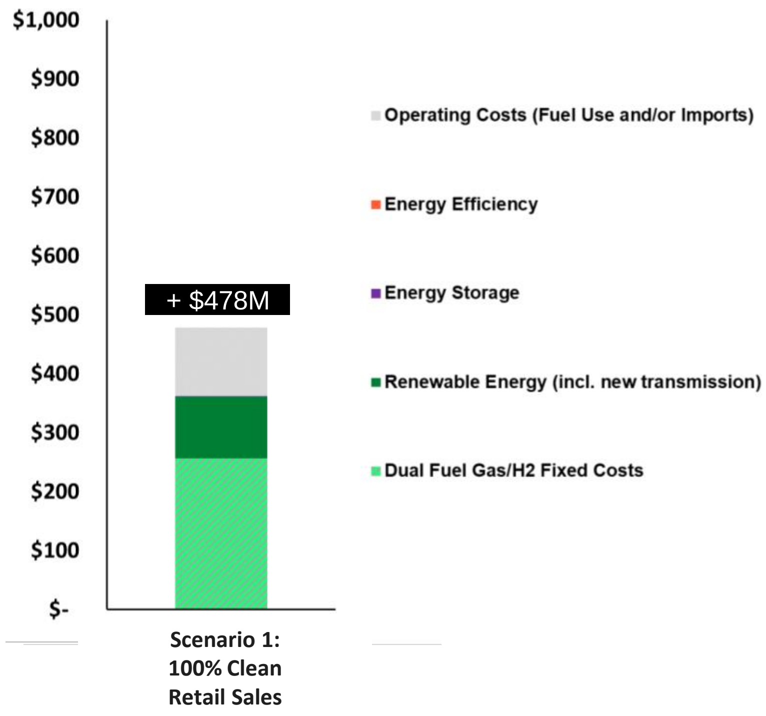
Additional Generation to Replace LSR Dams (2045)

2045 Generation
(Annual GWh)



Additional Cost (2045)

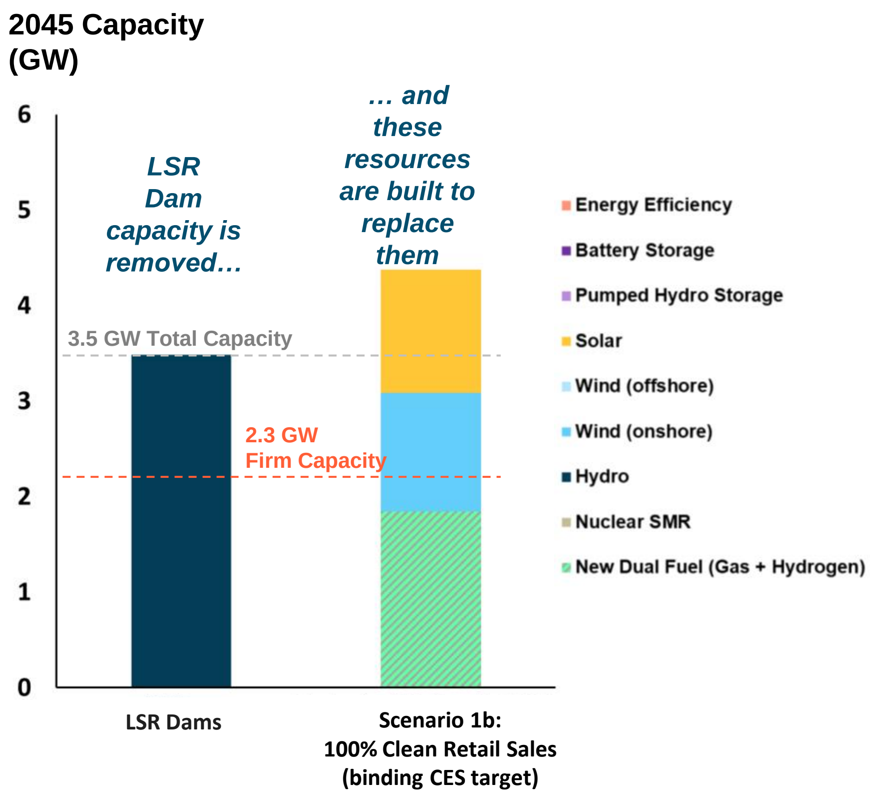
2045 Annual Cost Increase
($ million)



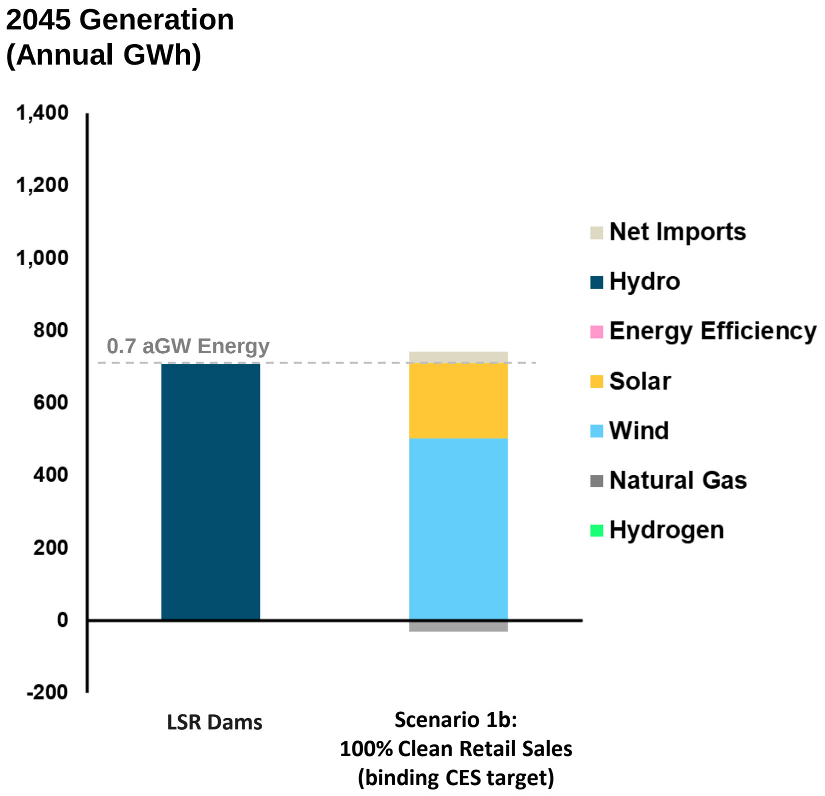
Replacing the Lower Snake River Dams
Scenario 1b: 100% Clean Retail Sales (binding CES target)

- Capacity replaced with 1.8 GW of dual fuel natural gas + hydrogen turbines, 1.3 GW solar, and 1.2 GW wind
- Wind and solar provide the energy replacement, but gas plant is needed for meeting extreme weather peak load events to avoid power shortages

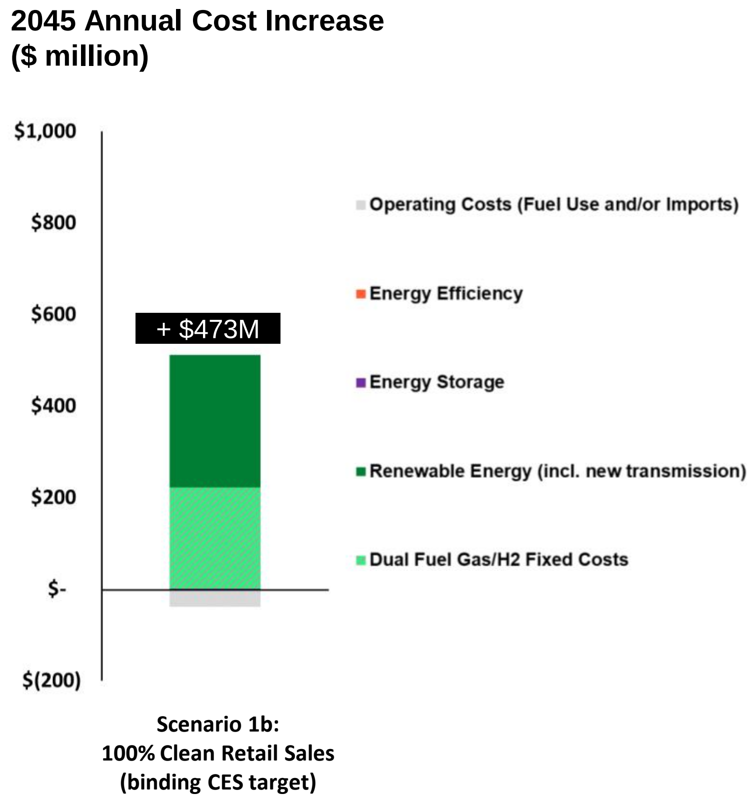
Additional Resources Built to Replace LSR Dams (2045)



Additional Generation to Replace LSR Dams (2045)



Additional Cost (2045)

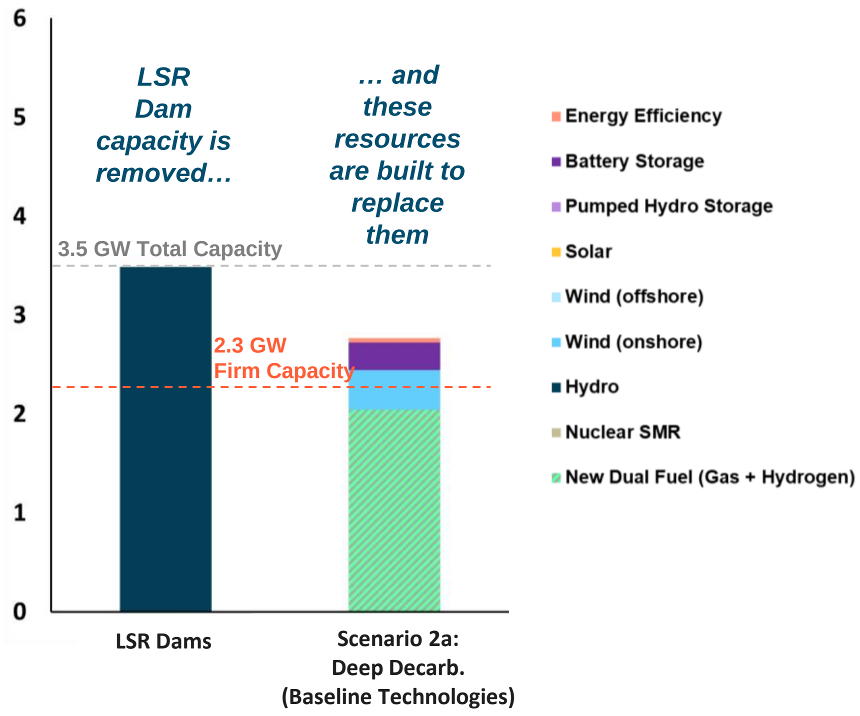


Replacing the Lower Snake River Dams
Scenario 2a: Deep Decarbonization (Baseline Technologies)

- Scenario includes electric load increases for transportation and other sectors
- In 2045, hydrogen generation is a key replacement resource and is assumed to be available, though not commercially available today
- This scenario would cost $860 million dollars per year in 2045, driven by high hydrogen fuel costs (~$40/MMbtu)

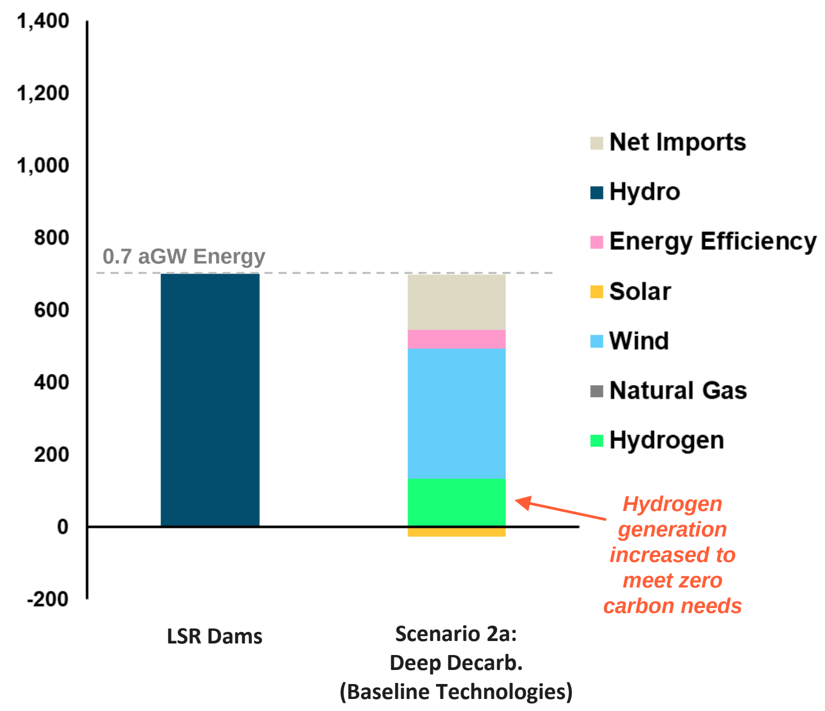
Additional Resources Built to Replace LSR Dams (2045)

2045 Capacity (GW)



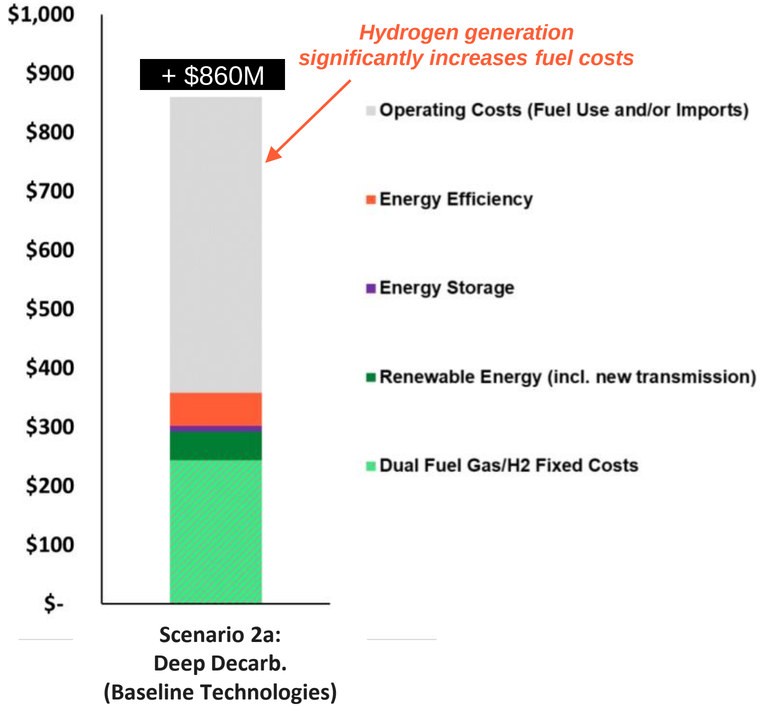
Additional Generation to Replace LSR Dams (2045)

2045 Generation (Annual GWh)



Additional Cost (2045)

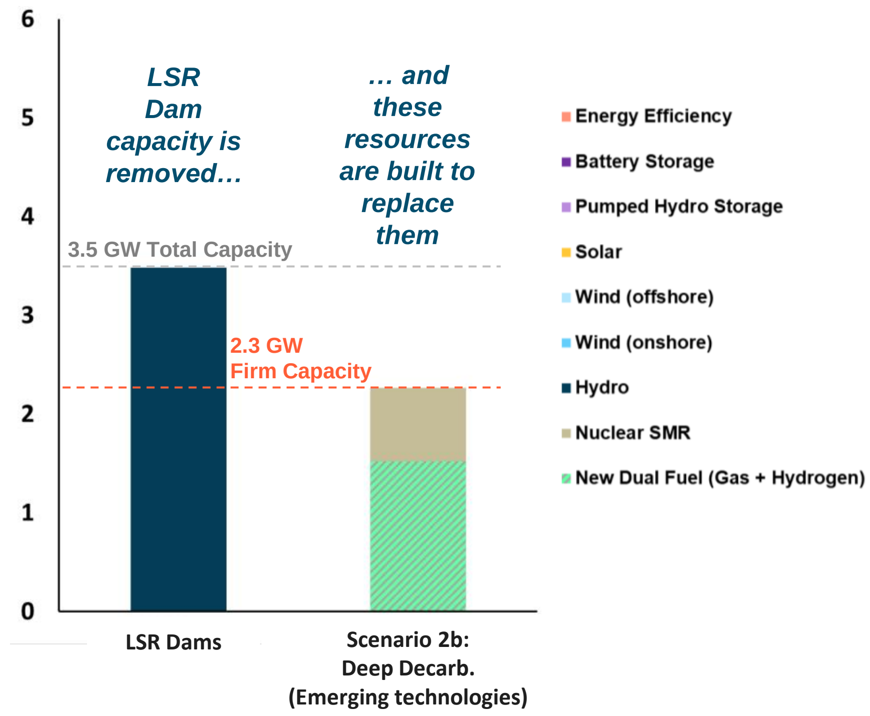
2045 Annual Cost Increase ($ million)



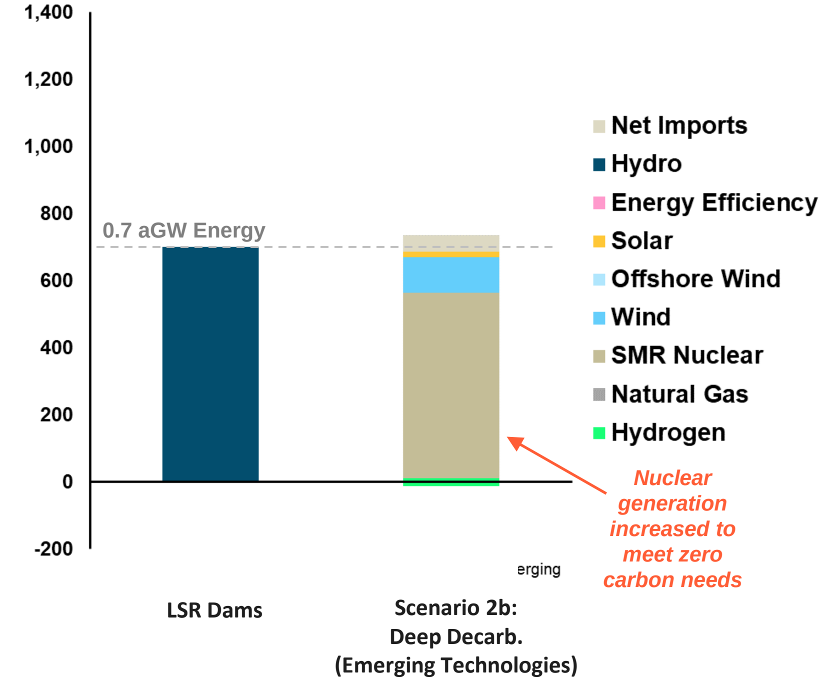
Replacing the Lower Snake River Dams
Scenario 2b: Deep Decarbonization (Emerging Technologies)

Additional Resources Built to Replace LSR Dams (2045)	Additional Generation to Replace LSR Dams (2045)	Additional Cost (2045)

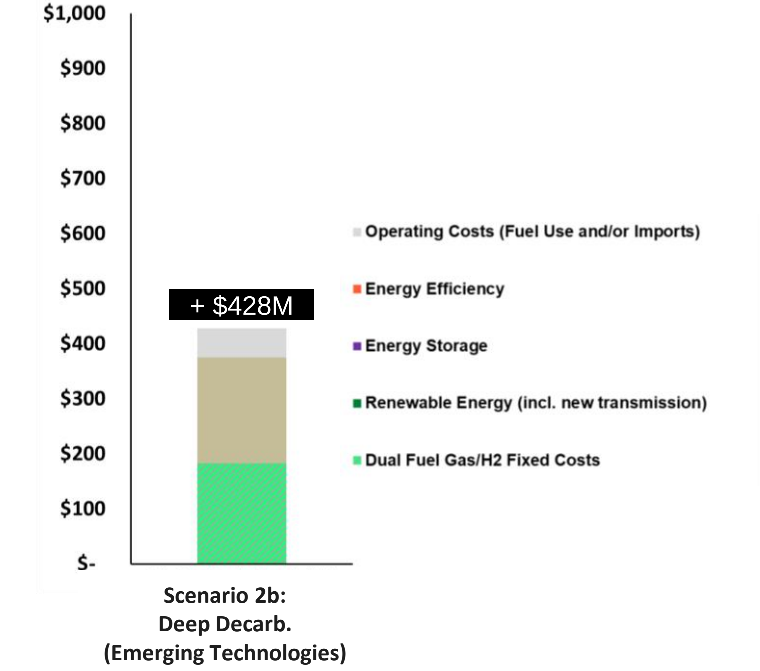
2045 Capacity (GW)



2045 Generation (Annual GWh)

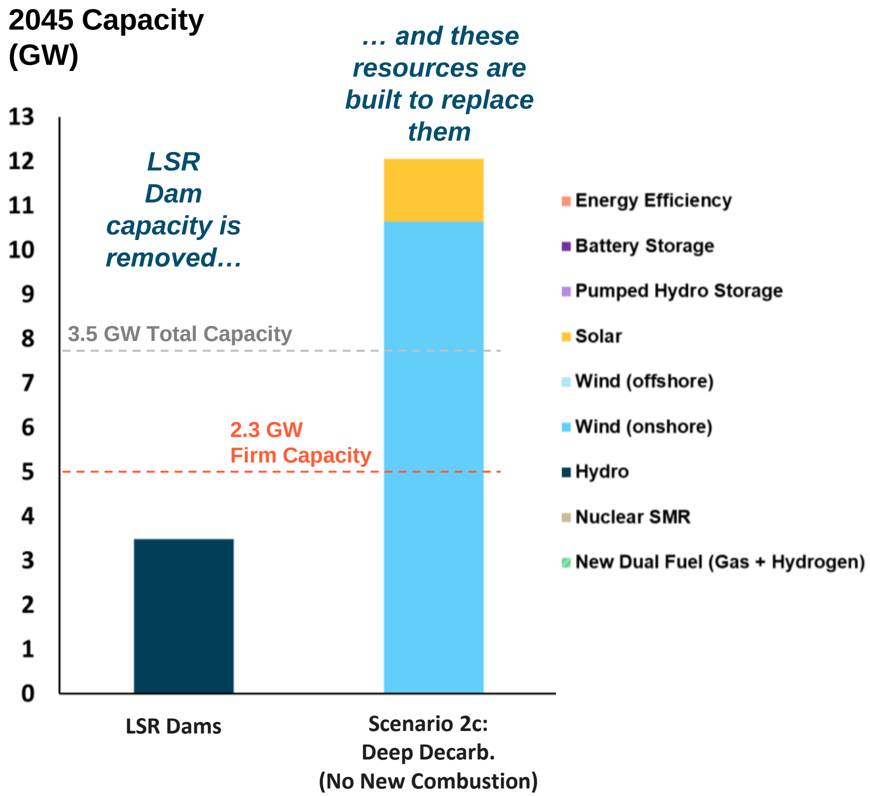


2045 Annual Cost Increase ($ million)

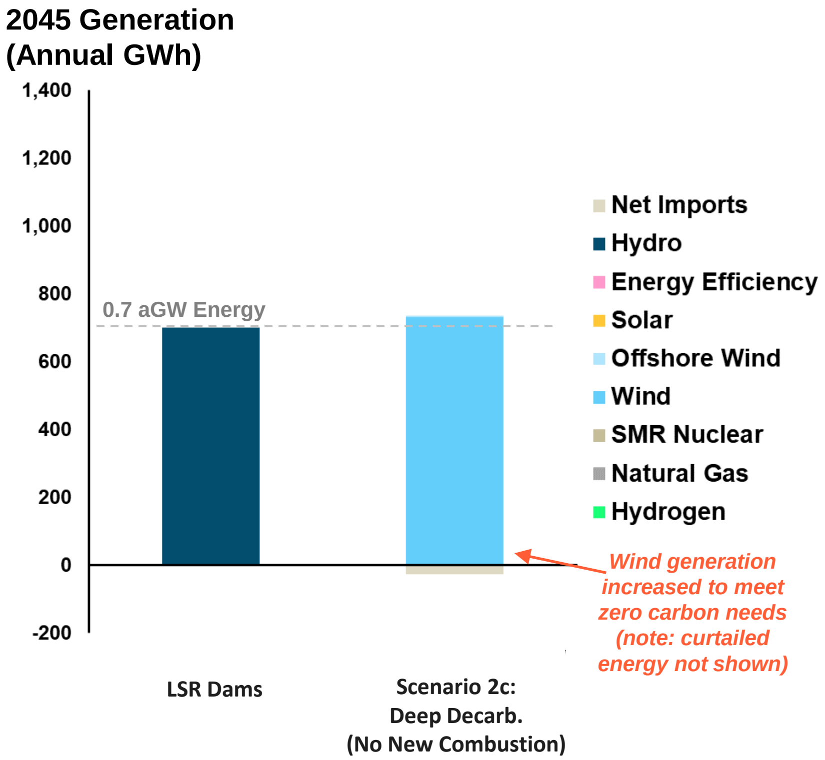


Replacing the Lower Snake River Dams
Scenario 2c: Deep Decarbonization (No New Combustion)

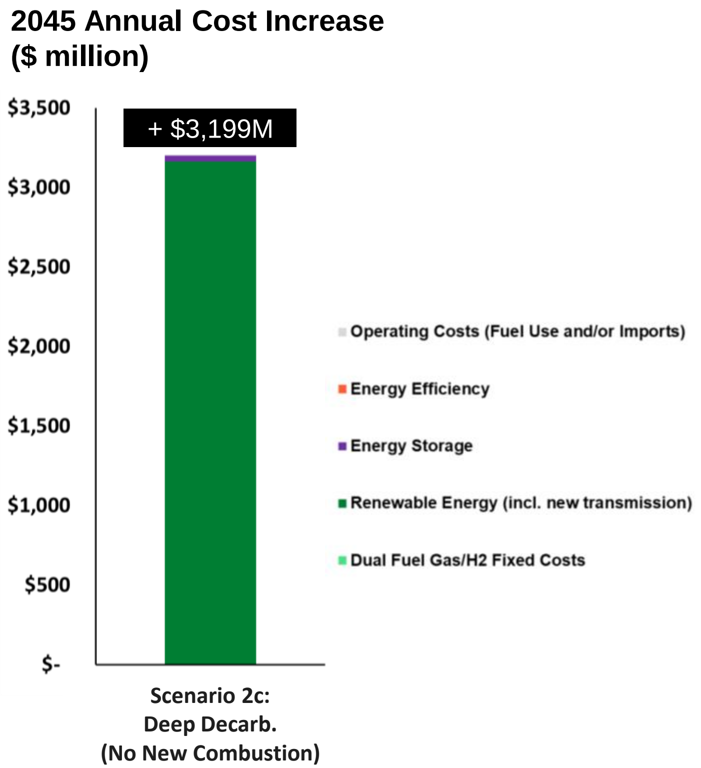
Additional Resources Built to Replace LSR Dams (2045)



Additional Generation to Replace LSR Dams (2045)



Additional Cost (2045)



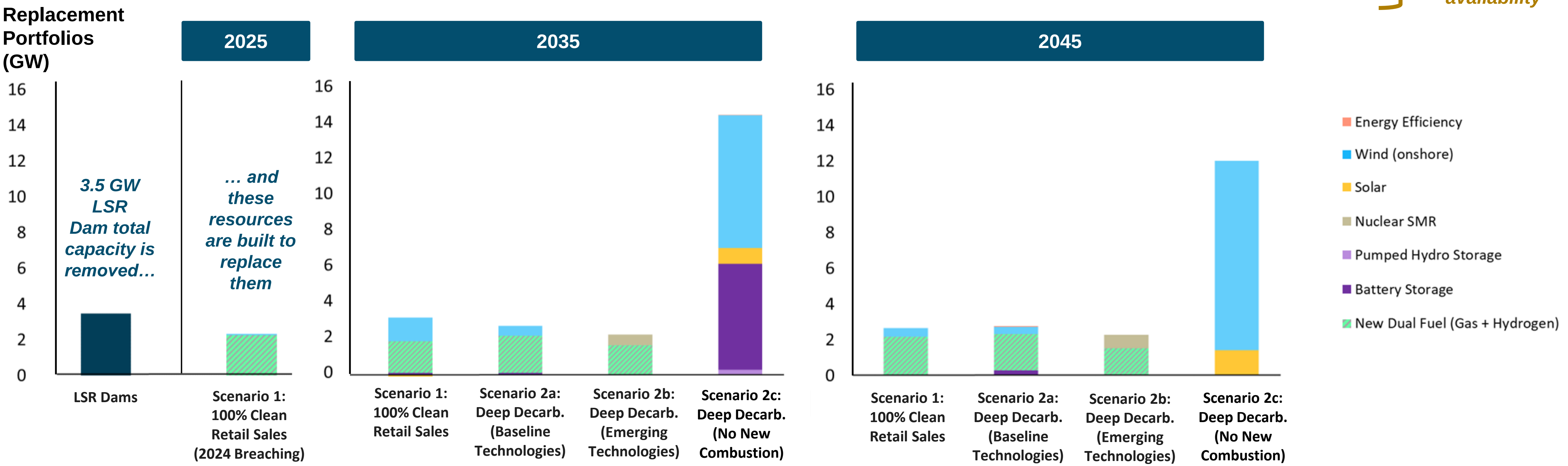
- Note: in the cost summary, a range of costs was developed for this scenario based on the assumed transmission needs for renewable additions
- High end assumes 100% of nameplate, low end assumes 25% of nameplate (approx. marginal ELCC of renewable additions)
- Low end represents a higher ratio of renewable capacity to transmission capacity, recognizing that much of the additional energy added by 2045 would be curtailed due to over-supply

Replacing the Lower Snake River Dams Capacity Across All Scenarios

- Scenario 1 (100% Clean Retail Sales, 2032 LSR Dams breaching): shown in previous slide
- **Scenario 1 (100% Clean Retail Sales, 2024 LSR Dams breaching): similar to scenario 1, but with dual fuel natural gas + hydrogen turbine replacement in 2025**
- Scenario 2a (Deep Decarbonization, Baseline Technologies): shown in previous slide
- **Scenario 2b (Deep Decarbonization, Emerging Technologies): small modular nuclear reactors replace LSR capacity and energy, instead of additional wind power**
- **Scenario 2c (Deep Decarbonization, No New Combustion): very high replacement need as wind and solar alone struggle to replace LSR dam firm capacity and zero-carbon energy output**

Limited load growth, carbon emissions remain in 2045

High load growth, carbon emissions eliminated by 2045… sensitive to emerging technology availability



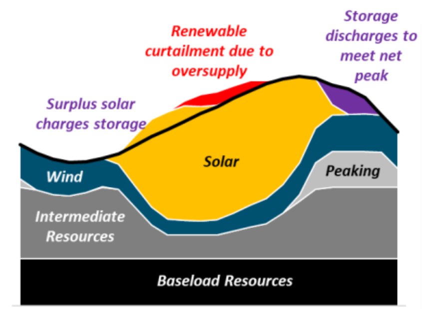
Appendix B: Additional Modeling Inputs

RESOLVE optimizes investments to meet clean energy targets reliably

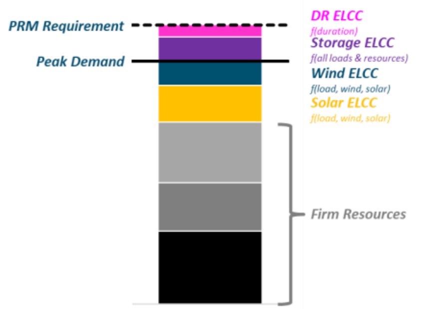
RESOLVE is an optimal capacity expansion model specifically designed to identify least-cost plans to meet reliability needs and achieve compliance with regulatory and policy requirements

- Linear optimization model explicitly tailored to study challenges to arise at high penetrations of variable renewables and energy storage
- 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

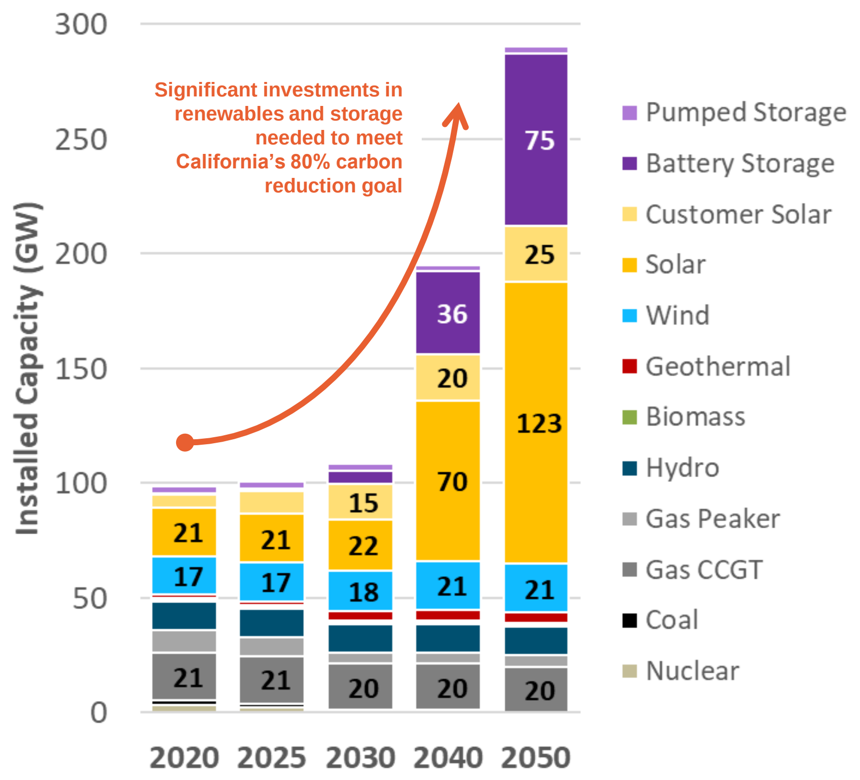
Operational module simulates hourly system operations for a sample of representative days



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



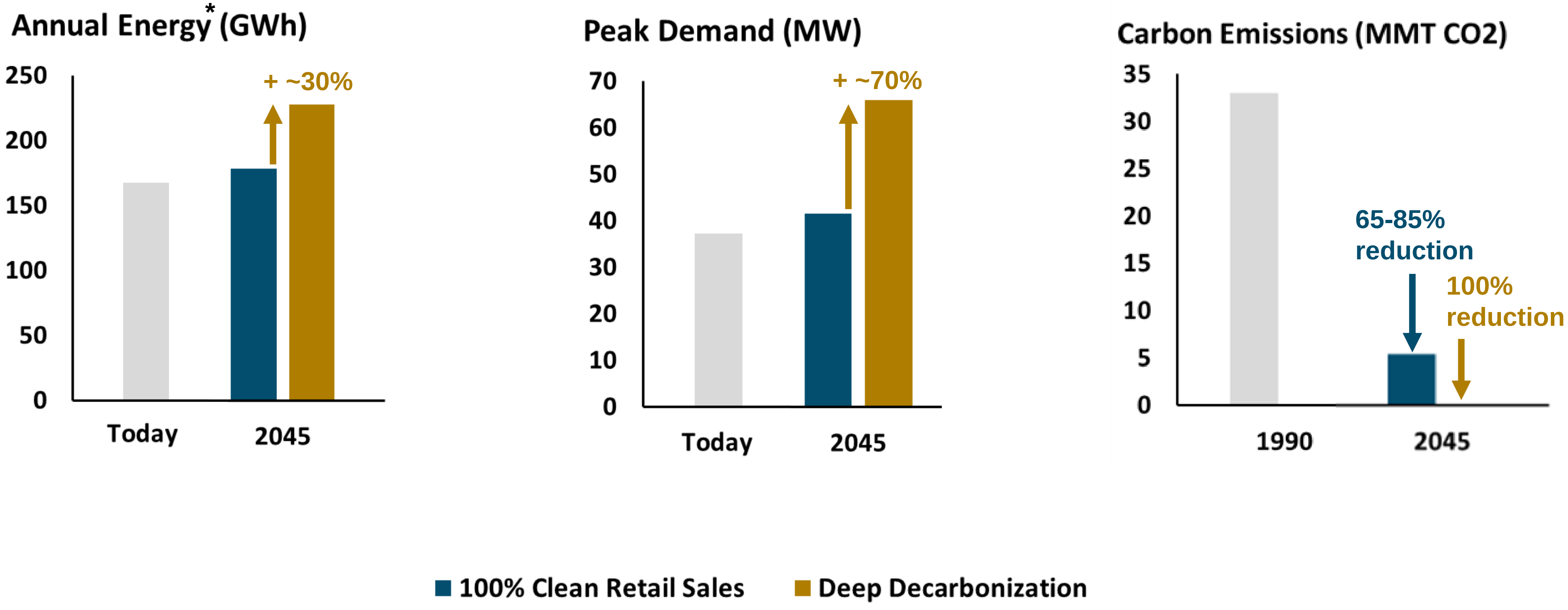
Least-cost plan cooptimizes investments and operations to meet clean energy policy targets, selecting from a diverse set of potential resources including wind, solar, storage, DSM, and natural gas



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

Load growth and carbon emissions in two clean energy scenarios modeled

Increases in Electricity Use and Declines in Carbon Emissions

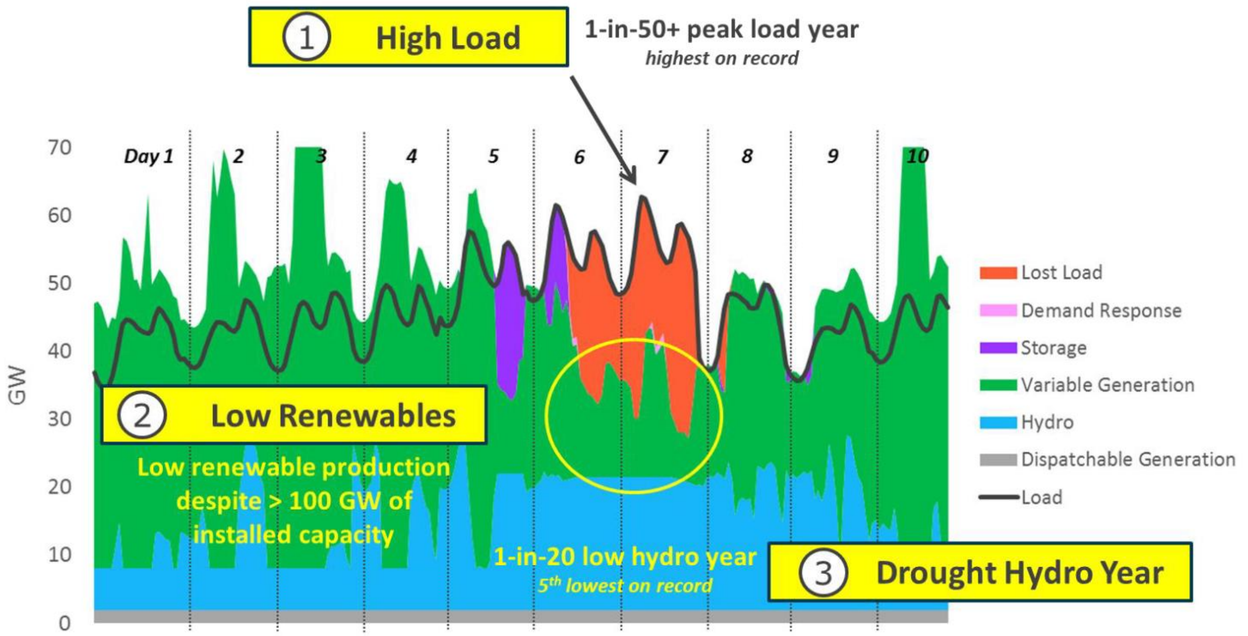


* Load based on 2021 NWPCC Power Plan, shown as retail sales (after assumed growth in customer PV and energy efficiency)

Resource Adequacy Resource Options

- **RESOLVE resource adequacy constraint requires capacity to meet peak demand + a 15% planning reserve margin**
  - Planning reserve margin (PRM) constraint is "installed capacity" (ICAP) based for firm resources, peaking capacity for hydro, ELCC for other non-firm resources
- **The nature of the Northwest reliability risk limits the ability of battery storage to provide reliable capacity contributions**
  - Storage and hydro show "antagonistic" interactions, which limit energy storage reliability value in "energy-limited" conditions where energy storage resources are unable to charge (with low hydro and renewable output) and run out of discharge (during extended energy shortfall events)

Key Drivers of Future Pacific Northwest Reliability Events

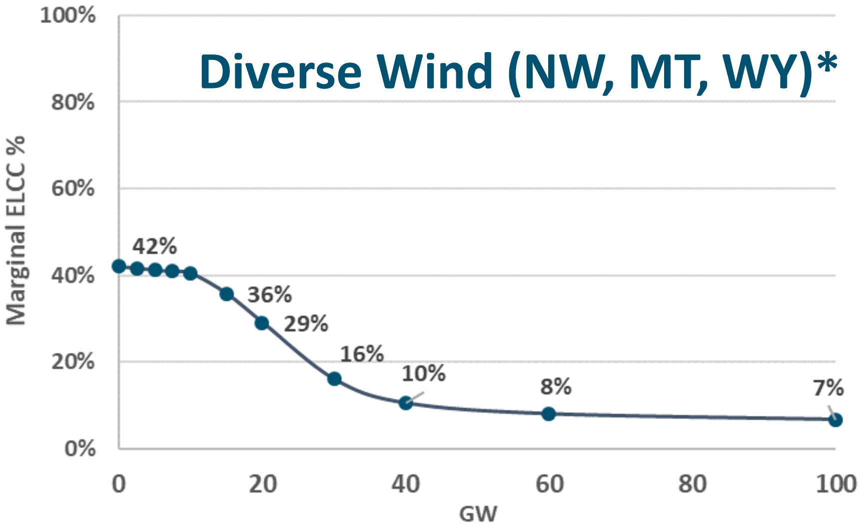


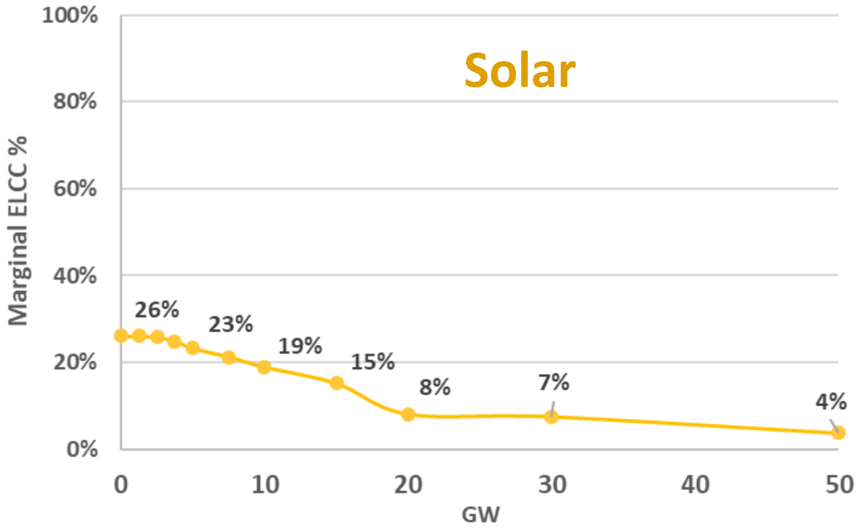
Sample week in 2050 in a 100% GHG reduction scenario, from E3, *Resource Adequacy in the Pacific Northwest,* 2019.

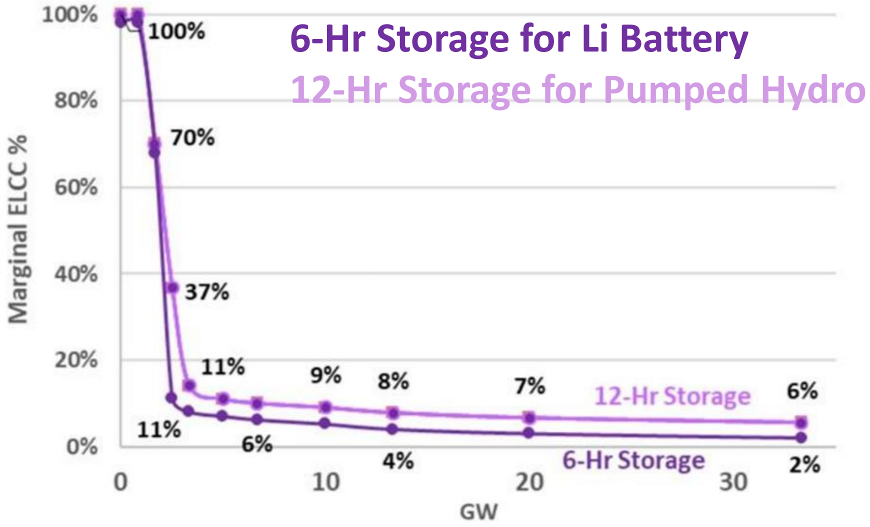
Resource	RA Capacity Contributions
Hydro	65%, based on sustained winter peaking capacity in critical water year conditions (per BPA/PNUCC)… WRAP method is still evolving
Battery storage	Sharply declining ELCCs*
Pumped storage	Sharply declining ELCCs*
Solar	Declining ELCCs
Wind	Declining ELCCs
Demand Response	Declining ELCCs
Energy Efficiency	Limited potential vs. cost
Small Hydro	Limited potential
Geothermal	Limited potential
Natural gas to H2 retrofits	Clean firm, but not fully commercialized
New dual fuel natural gas + H2 plants	Clean firm, but not fully commercialized
New H2 only plants	Clean firm, but not fully commercialized
Gas w/ 90-100% carbon capture + storage	Clean firm, but not fully commercialized
Nuclear Small Modular Reactors	Clean firm, but not fully commercialized

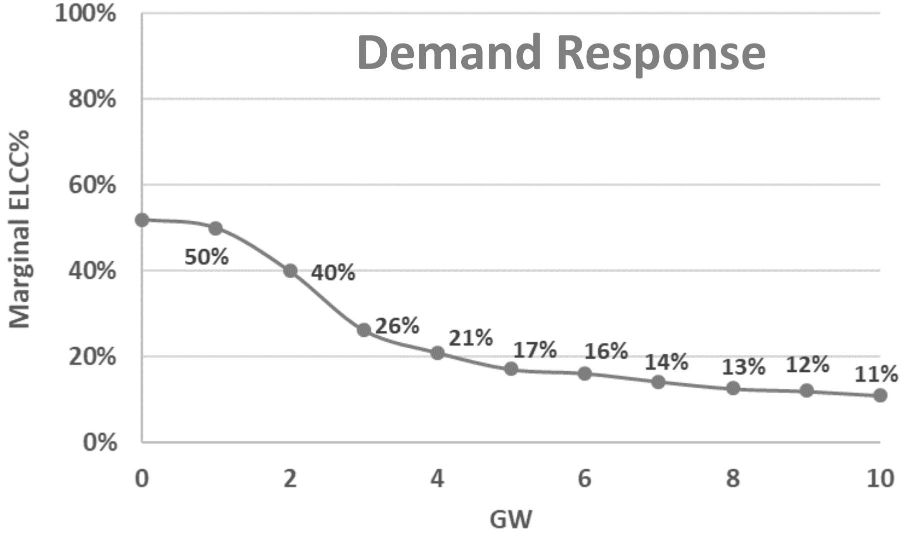
* E3 performed a sensitivity with battery ELCCs that do not decline so sharply. This sensitivity did change the LSR dam replacement resources and costs.

Incorporating Declining Capacity Contributions of Renewables, Storage, and DR









- A reliable electric system requires enough capacity to meet peak loads and contingencies
- This study incorporates information from E3's 2019 report *Resource Adequacy in the Northwest* about the effective capacity contribution of renewables, storage, and DR at various penetration levels

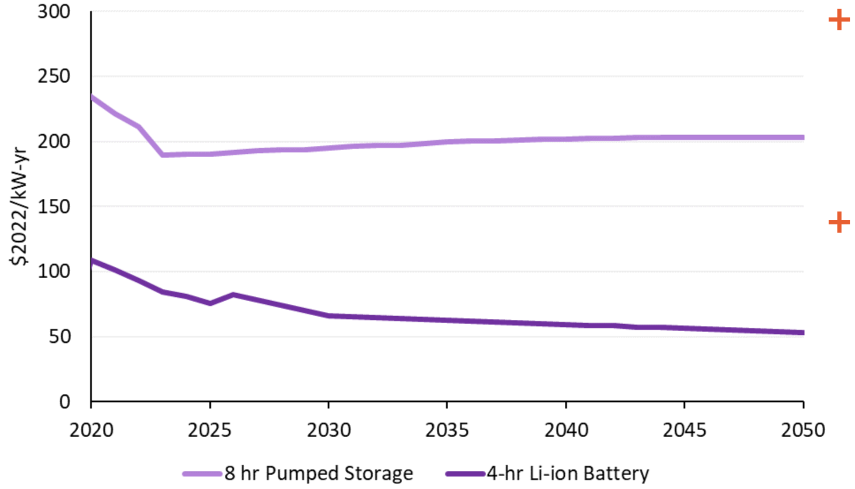
* The offshore wind sensitivity in this study assumed the same ELCC curve as modeled for diverse on-shore wind resources in the Resource Adequacy in the Northwest report.

ELCC = Effective Load Carrying Capability = firm contribution to system peak load

New Resource Options

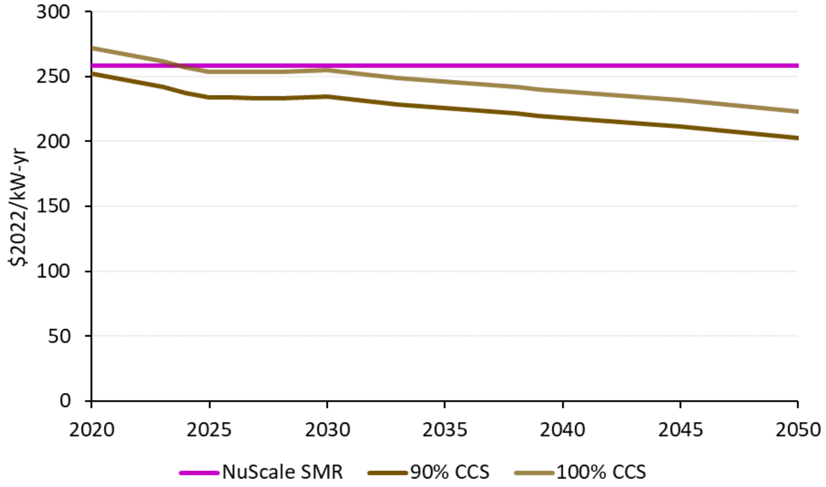
All-in Fixed Costs

Storage Options



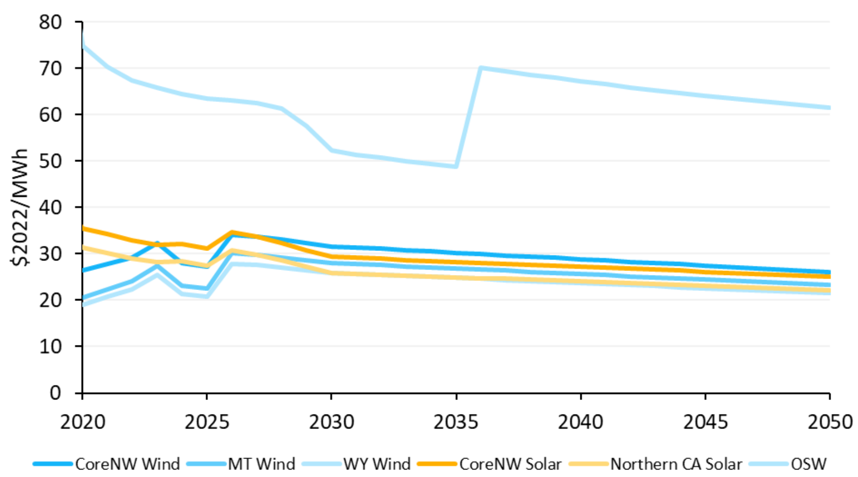
- Battery Storage costs derived from E3's inhouse and Lazard LCOS 7.0 (Oct 2021)
- Pumped storage is from Lazard's last published PHS costs (LCOS 4.0). Assumes CAPEX and FO&M are flat + financing cost trends same for battery storage.

Firm Low Carbon Options



- CCS costs derived from E3's inhouse "Emerging Tech" ProForma
- SMR costs are derived from the vendor NuScale, for an "nth of a kind" installation of the technology they are developing

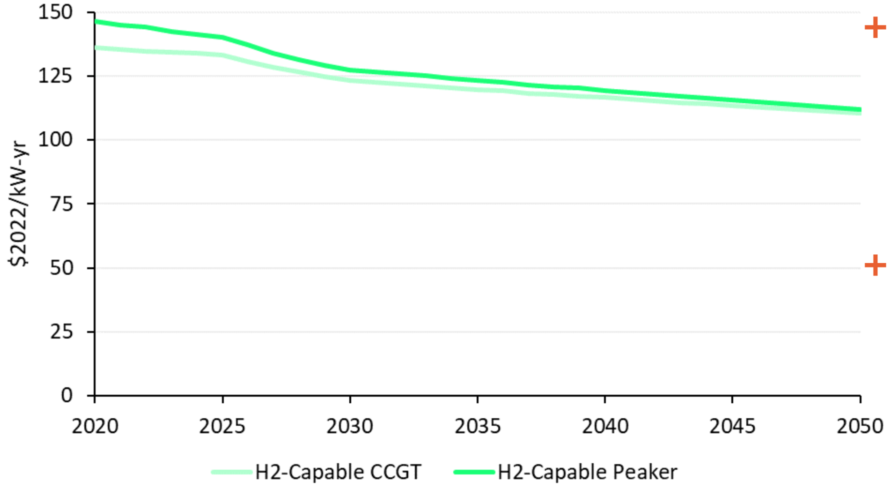
Renewable Options



Renewable costs derived from E3's in house Pro Forma which integrates NREL ATB 2021

Costs shown here do not include the cost of upgraded or new Transmission lines

Gas Options

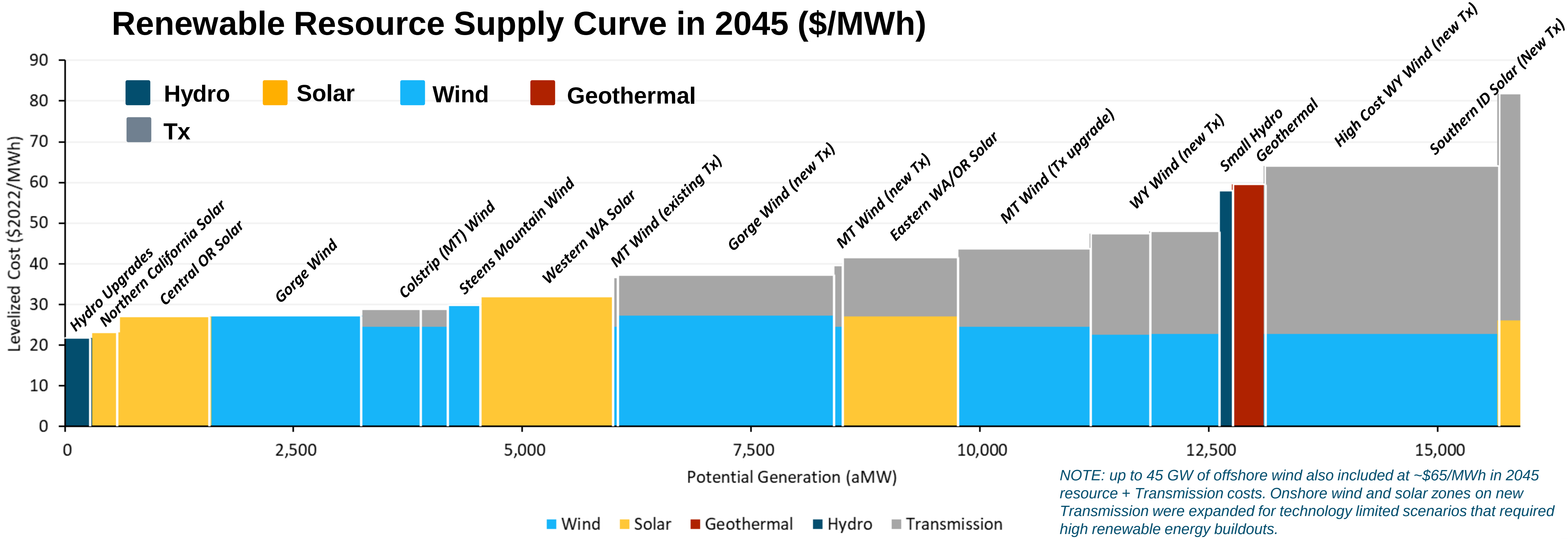


- CCGT and peaker costs are derived from E3's inhouse ProForma which integrates NREL ATB 2021
- New Hydrogen or upgrades include a ~10% additional cost that converges by 2050

NOTE: only dual fuel natural gas + H2-enabled new resources modeled, given NW policy constraints

New Resource Options
Renewables

- The following supply curves integrate Transmission costs that RESOLVE sees
- The "no new combustion" scenario required increases in the supply of wind on new transmission (Northwest, MT+WY, and offshore) to enable a feasible solution



NOTE: up to 45 GW of offshore wind also included at ~$65/MWh in 2045 resource + Transmission costs. Onshore wind and solar zones on new Transmission were expanded for technology limited scenarios that required high renewable energy buildouts.

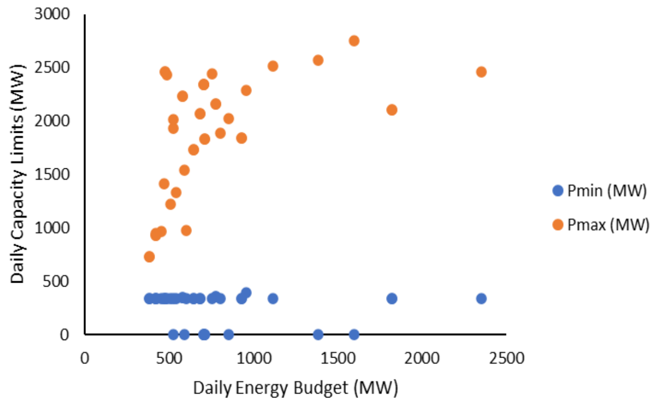
Hydro Operating Data

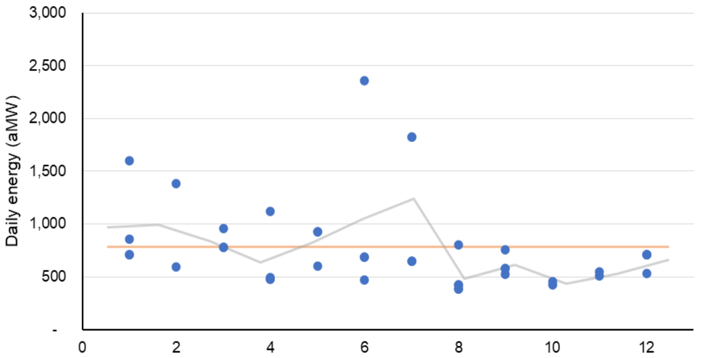
+ **Key RESOLVE inputs (for each representative RESOLVE day)**
  - Max generation MW
  - Min generation MW
  - Daily MWh hydro budget
  - Ramp
+ **Hydro operating data is parameterized using representative conditions for 3 low/mid/high historical years (2001, 2005, 2011)**
  - Lower Snake River and lower Columbia River dams were adjusted per BPA hydro modeling w/ latest fish spill constraints
+ **Hydro firm capacity contribution is assumed to be 65% of total MW, per PNUCC methodology (based on BPA 10-hr sustaining peaking capacity)**

LSR Hydro

Ramp Rates

Hydro Resource	1-hr	2-hr	3-hr	4-hr
LSR_Hydro	36%	43%	45%	48%





Non-LSR NW Hydro

Ramp Rates

Hydro Resource	1-hr	2-hr	3-hr	4-hr
CoreNW_Hydro	14%	23%	30%	34%