ENERGY
STRATEGIES

Lower Snake River Dam Replacement Study

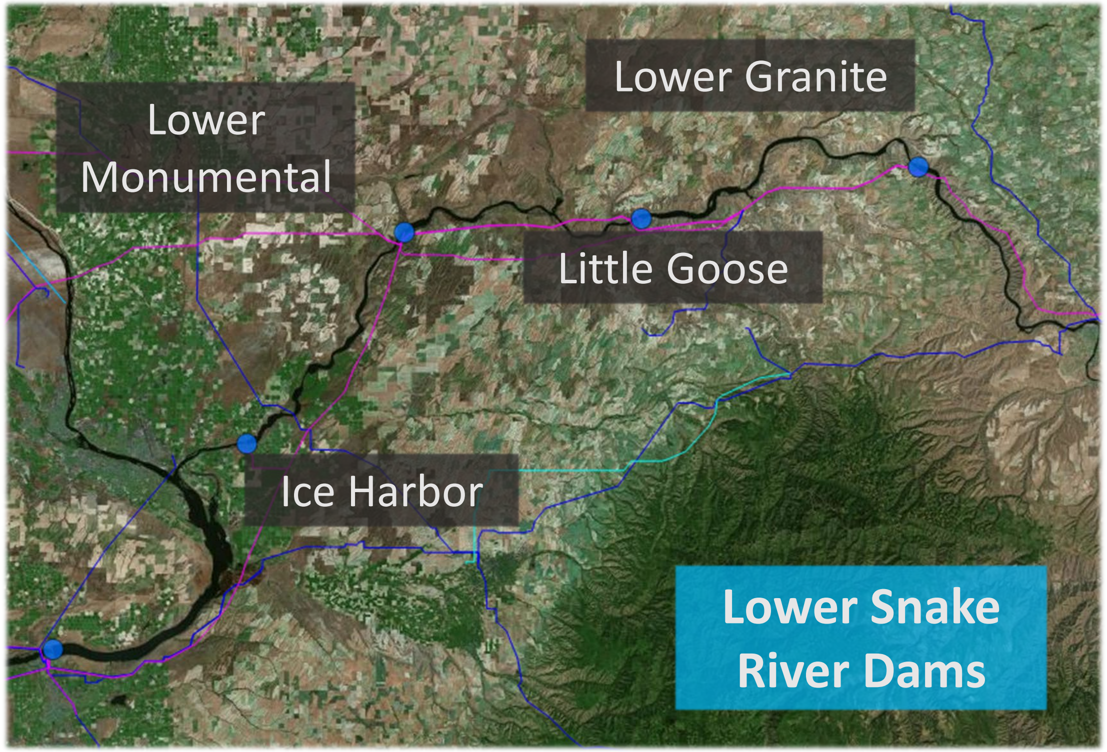
A study investigating the cost and feasibility of optimized clean-energy replacement portfolios

May 18th, 2022

Study Motivation

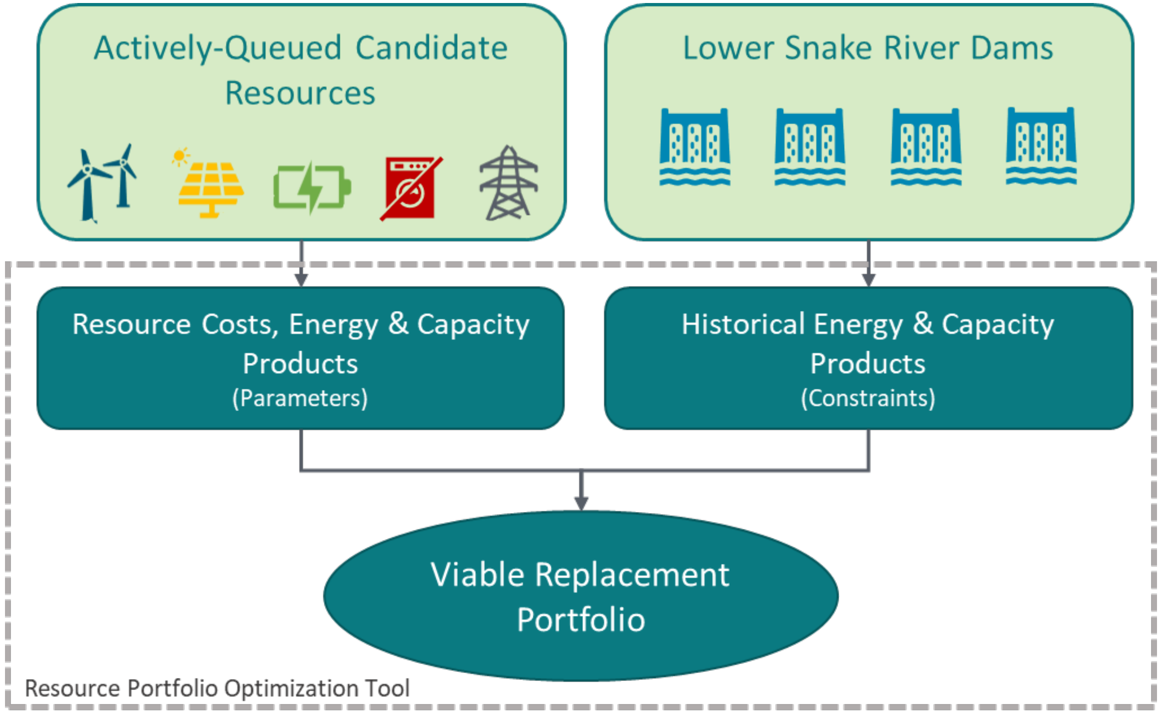
- **The potential removal of the Lower Snake River (LSR) Dams is a central topic of debate in the Pacific Northwest**
  - As it relates to the LSR dams' energy value, proponents for retaining the dams argue that they provide a carbon-free, flexible, and reliable source of power that supports the stable operation of the regional transmission grid
  - Advocates for dam removal cite high O&M costs, relatively low energy value of LSR dam output, and the prevalence of low-cost carbon-free replacement resources
- **In 2018, Energy Strategies published the Lower Snake River Dams Power Replacement Study commissioned by the NW Energy Coalition**
  - The study evaluated the cost, feasibility, & regional reliability implications of replacing the LSR Dams with a variety of clean energy portfolios and demonstrated that:
    - The LSR dams could be replaced with a portfolio of market-ready resources
    - Replacement would require minimal high-voltage transmission upgrades as transmission reliability was not compromised based on powerflow reliability analysis
- **This new study complements this prior work by identifying an optimal set of *specific* investments required to replace the LSR dams in the late-2020 timeframe, subject to market supply constraints**
  - The objective of this study is to identify least-cost clean energy replacement energy portfolios that meet or exceed energy attributes historically provided by the dams
  - Study focuses on a “one-to-one” replacement strategy, as well as alternative replacement objectives where monthly energy “needs” of the region are prioritized over what the dams have provided the region historically, allowing for a consideration of tradeoffs

LSR Dam	Year in Service	Nameplate Capacity (MW)
Ice Harbor	1961	603
Lower Monumental	1969	810
Little Goose	1970	810
Lower Granite	1975	810



Study Overview

- **Study methodology uses an in-house resource planning optimization tool to identify least-cost replacement portfolios that meet or exceed the following grid products provided by the LSR dams:**
  - ❖ Monthly Energy (MWh/month)
  - ❖ Energy Value ($M/year)
  - ❖ Capacity Value (MW)
- **Study compiled these parameters for the LSR dams and actively-queued, market-ready resources**
  - ❖ Study based on data from 2006 to 2020
  - ❖ This timeframe aligns with current spill and fish management protocols



All results presented in 2020$

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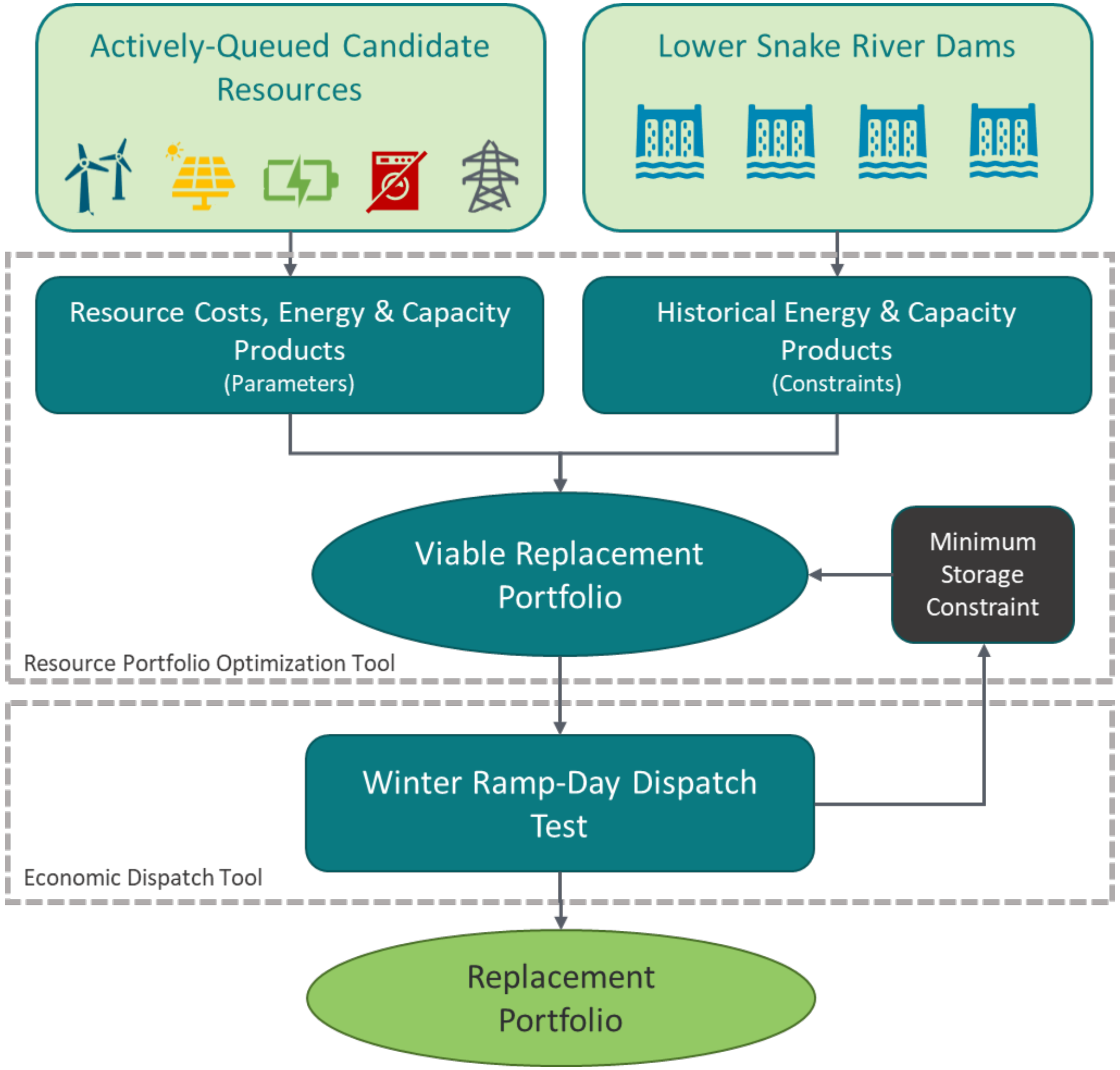
  - ❖ Study based on data from 2006 to 2020
  - ❖ This timeframe aligns with current spill and fish management protocols
- **After a viable portfolio is selected based on above criteria, the portfolio was dispatched against historical LSR dam production "high-ramp-days"**
  - ❖ Attempted to match historical dam production for top 10% of days in which the LSR dams provided morning or evening ramping (mainly occurring in winter months)
  - ❖ If portfolio was deficient, additional battery storage introduced into portfolio optimization tool to ensure the ramping objective was met



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Study Purpose: Summary

What the study IS:

- An effort to **characterize select energy attributes** of the dams based on 15+ years of historical operations.
- An exploration into the selection of **optimal blends of specific resources & investments** to create a portfolio that provides similar or greater energy attributes.
- An attempt to emulate aspects of utility **RFP evaluations** in which specific projects are selected into a portfolio, subject to market supply limitations.
- An effort to move beyond conceptual or generic replacement portfolios to the identification of a specific set of real-world projects in development.
- An independent assessment using a new **analytical framework** designed to address targeted energy issues surrounding dam replacement.

What the study is NOT:

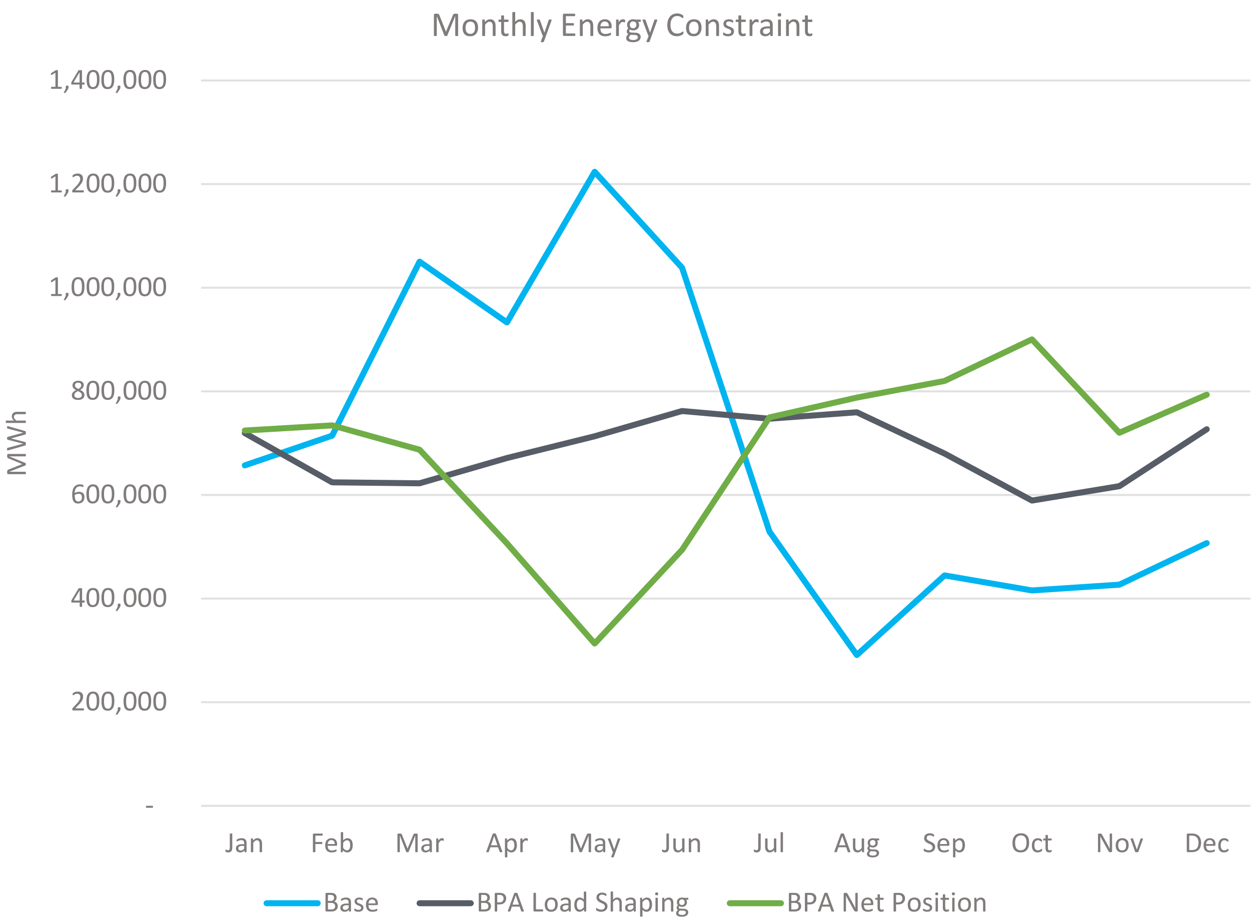
- A **regionally-focused planning study** considering dispatch, resource adequacy, and flexibility modeling in the context of the Pacific Northwest system *(see* Energy Strategies' 2018 study for detailed analysis of such issues*).*
- A consideration of **all replacement options**, alternatives, and their impacts. For example, energy efficiency was not considered as a replacement option, nor was any transmission reliability analysis performed as a part of this assessment, although both issues have been explored previously.
- Designed to capture the **full range of costs** and benefits associated with dam removal related to fisheries, transportation, irrigation, and recreation.
- A **policy position** on whether the dams should or should not be removed – the study is technically focused and does not seek to replicate prior work, instead it adopts a new approach to help better inform the region on the subject matter.

Sensitivities Consider Impact of Different Planning "Objectives"

- **Energy Strategies performed two sensitivity studies to investigate the ability of replacement portfolios to meet BPA system needs, as opposed to LSR historical output targets, alone**
  - Sensitivities assess a monthly energy constraint profile that highlights different planning objectives for the BPA system, but results in portfolios built to **obtain the same amount of total annual energy as the dams generated historically**
- **Base (LSR Dam Shape)**
  - Monthly energy profile is represented by the average monthly energy output of the dams, based on 2006 – 2021 production data
    - High energy output in late spring and early summer

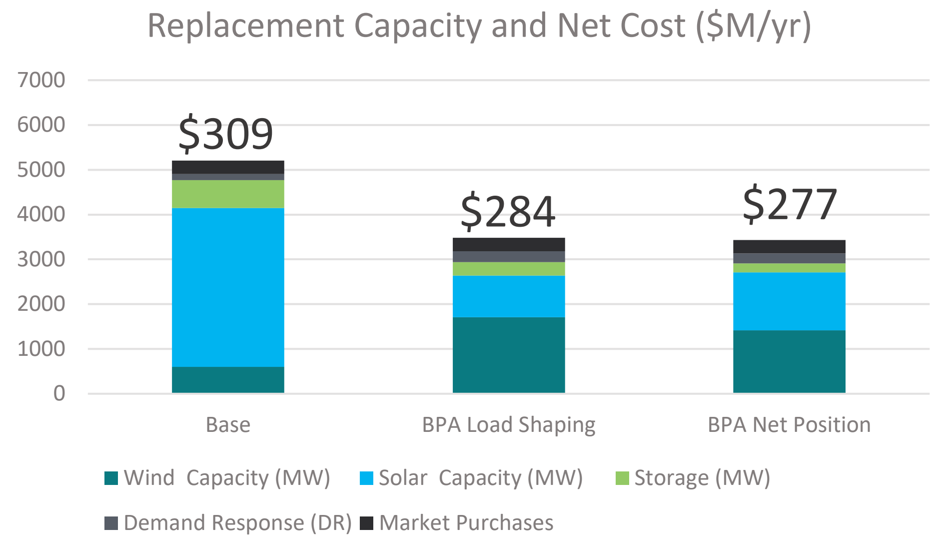
Sensitivities

- **BPA Load Shape Sensitivity**
  - Monthly energy profile developed based on BPA Gross Load per NWPCC's CanESM2 Medium 2030 climate scenario
    - Summer & Winter-peaking shape with smaller month-to-month variation
- **BPA Net Position Shape Sensitivity**
  - Monthly Energy profile developed based on BPA Net Position (Gross load – Hydro generation) in 2019
    - Late-summer peaking shape as this represents time when electrical load is high while hydro output is low

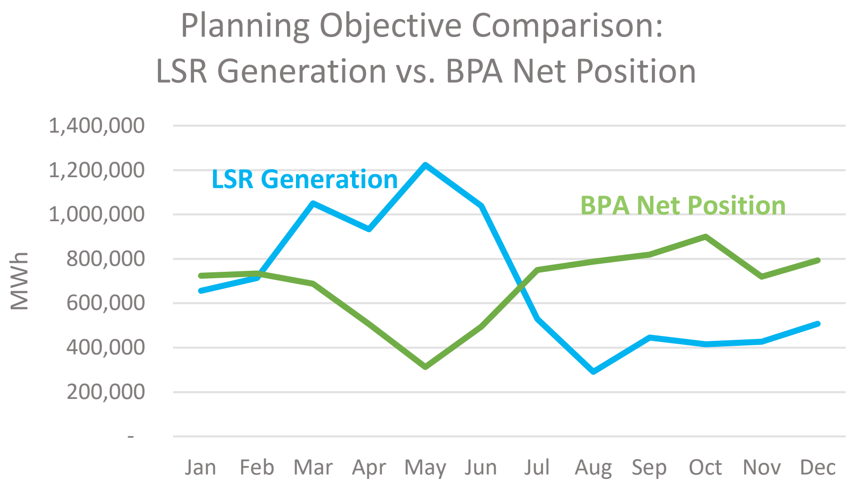


Key Takeaways from Study

- **A diverse resource portfolio made up of wind, solar, DR, storage, and market purchases, at a net annual cost of $277M, was able to sufficiently replace the energy, capacity value, and ramping provided historically by the LSR dams**
  - ❖ Replacement costs estimated in this study range from $309M - 277M/year
  - ❖ Study did not consider energy efficiency but doing so would likely help reduce replacement costs
  - ❖ "Base" study sought to replace monthly energy output from dams, while "BPA Load Shaping" and "BPA Net Position" sensitivities sought to replace annual energy provided by dams but in months in which the region was likely in need (versus when power was generated, historically)

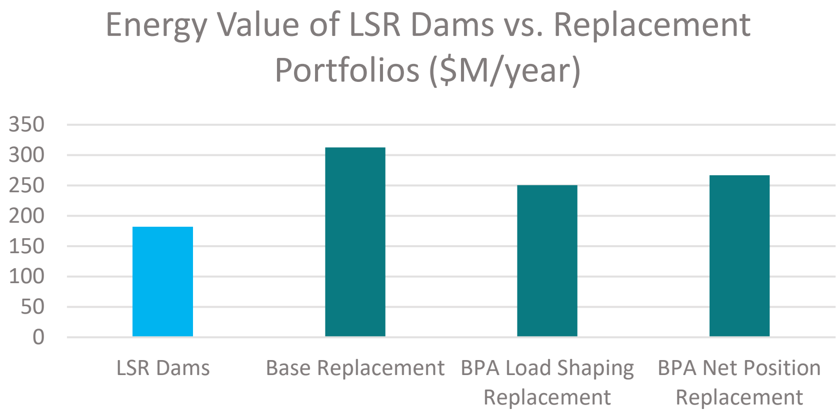


- **Replacing the dams on a one-for-one basis could cause an increase in annual replacement costs of *$32M/year* compared to scenarios that assume a planning objective based on what the region needs going forward**
  - ❖ Analysis suggests that cost-efficient replacement of the LSR dams requires a diverse set of replacement resources and a *regional planning objective* that does not simply replace energy services historically provided by the dams
  - ❖ When the planning objective is centered around replacing historical dam output, replacement portfolios are skewed towards solar resources, which drives up the cost of the portfolio as solar has limited to no ramping capability in the early morning winter hours

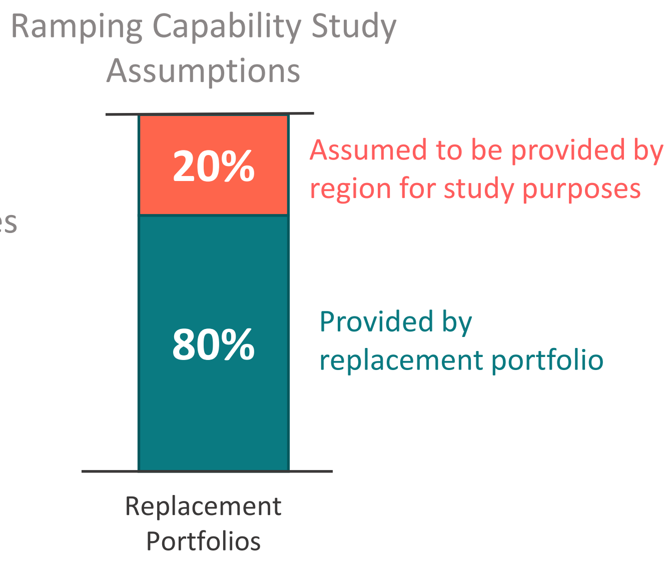


Key Takeaways from Study (continued)

- **The study indicates that replacement portfolios will generate power at times when the region needs it the most, resulting in $69M - $143M million per year of energy value above what the LSR dams provide for the same time period**
  - ❖ This result is heavily driven by the LSR dams generating most of their annual energy output during the spring runoff season when power prices are low and the region exports its excess energy



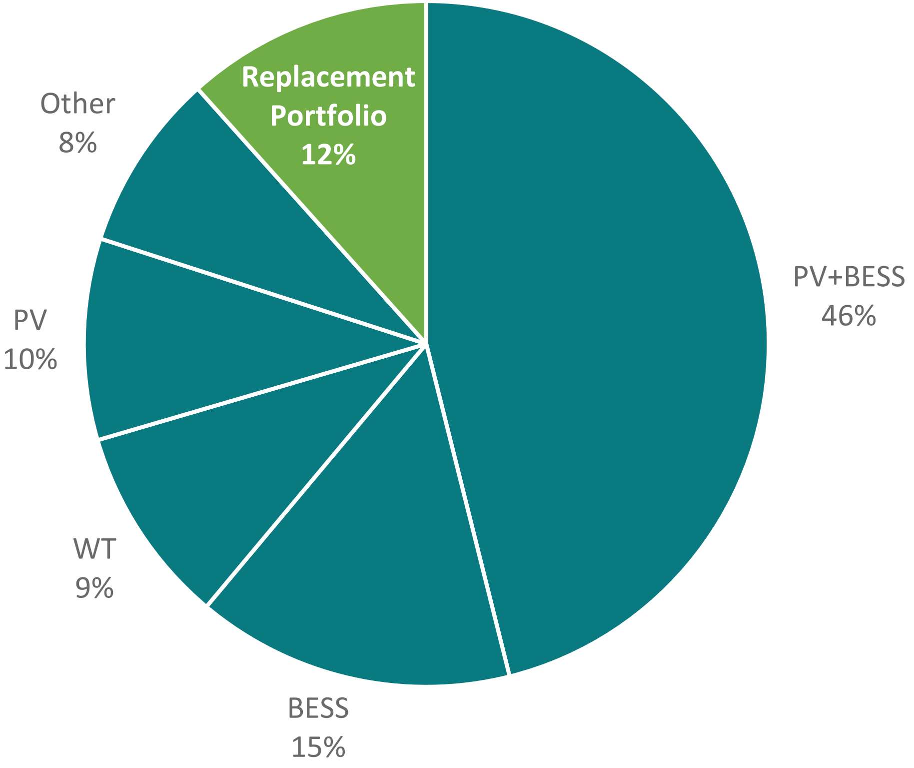
- **Study supports prior conclusions regarding the technical feasibility of replacing the energy, capacity, and ramping value provided by the LSR dams**
  - ❖ Ramping was the most difficult replacement criteria to evaluate in this study since the modeling framework did not account for the broader region's ability to provide some portion of ramping services
  - ❖ It was clear that a diverse mix, inclusive of storage, is the best route to providing maximum ramping capability within the replacement portfolio
  - ❖ Given potential for flexibility being supplied from elsewhere in the region, providing 100% of the historical ramping of the dams may not be necessary or cost effective, so the study sought to have replacement portfolios meet 80% of historical ramping service provided by LSR dams. We recommend regionally-focused analysis to confirm the reasonableness of this approach and provide more detail about regional ability to contribute to ramping capacity as a part of a replacement portfolio.



Key Takeaways from Study (continued)

- **Approximately 12% of the total candidate supply, including wind, solar, storage, DR, and market purchases, were selected into the portfolios in this study, indicating the region's status quo level of resource development is more than sufficient to replace the LSR dams in the late-2020/2030 timeframe**
  - ❖ It is well understood that development interest in the Northwest region is still growing, so even after this study's conservative assumption regarding the likely contracting of many resources in BPA's queue, the aggregate demand for LSR dam replacement is much less than the regional supply (which is likely to grow)

Relative Size of Replacement Portfolio vs. Candidate Resource Pool

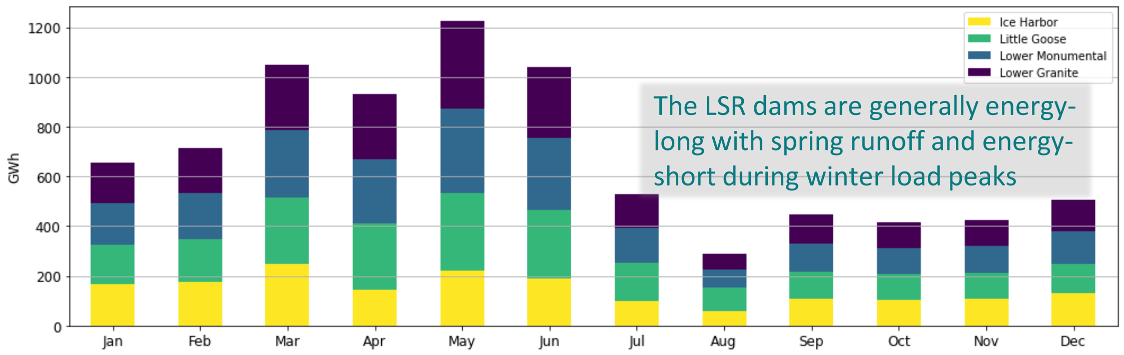


Overview of Study Assumptions and Methods

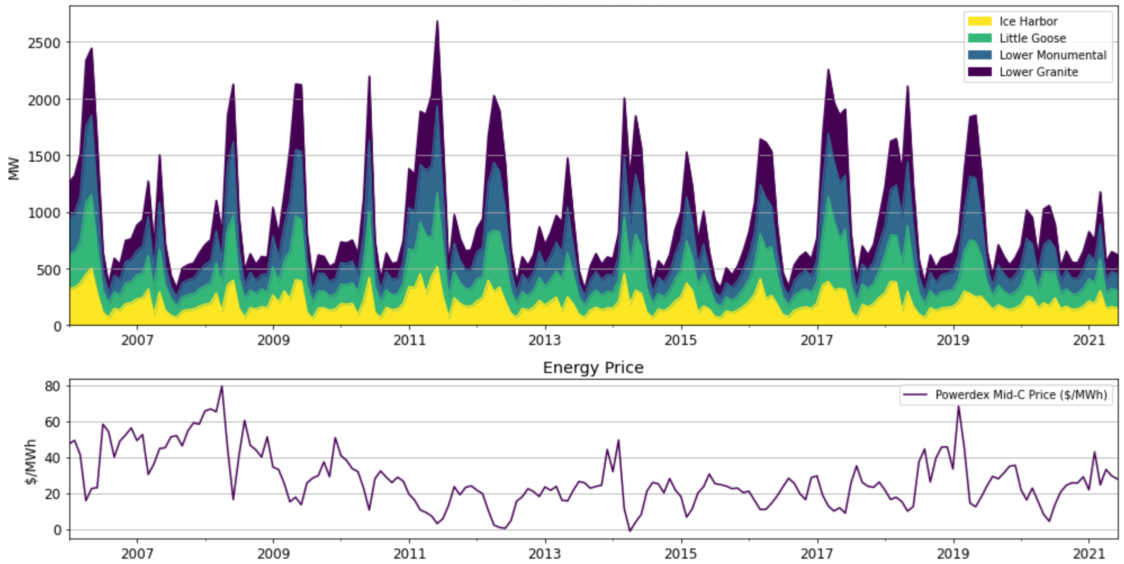
Historical Dam Data Used to Define Replacement Requirements

- **Analysis of historical operational data, energy prices, and prior study work was used to define constraints, or "requirements", of the replacement portfolio**
- **A monthly energy constraint was calculated based on 15 years of dam production**
  - Hourly production data of Lower Snake River Dams sourced from US Army Corps of Engineers Northwestern Division Website (aggregated to calculate total hourly production)
  - Constraint ensures **replacement portfolios generate monthly power greater than or equal to** what the dams have generated historically
- **An annual energy value constraint was calculated based on hourly production and coincident hourly historical prices at Mid-C**
  - The **median-year energy value of $182M** was selected as the requirement for candidate resources
  - Constraint ensures energy produced by replacement portfolios has **system value that is greater than or equal to** what dams have provided historically
- **A capacity value constraint was introduced to ensure that the replacement portfolio provides the region with equal or greater levels of resource adequacy**
  - LSR Dams assumed to convey 1,000 MW of **capacity value**, based on prior study work performed by Energy Strategies in 2018

Monthly Energy



Energy Value



Candidate Resources Represent Actual Projects and Market Supply of Replacement Assets

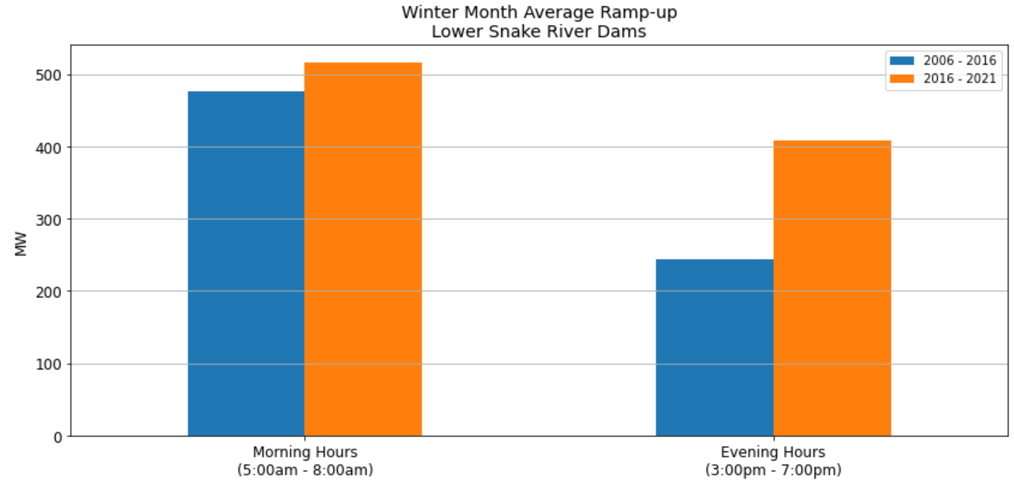
- **Set of candidate generation/storage resources total nearly 30 GWs of capacity split among eight technology types and three regions**
  - **25 GW of supply:** BPA interconnection queue was screened for candidate resources, capturing those project undergoing system impact study with in-service dates between 2024-2028, and a max capacity >20 MWs
  - **1.5 GW of supply:** Assumed to be available from Montana in the form of wind generation
  - **2.8 GW of supply:** Assumed to be available from California in the form of solar generation
- **300 MWs of Mid-C on/off-peak market purchase options were also assumed as a candidate resource**
- **559 MWs of regional demand response, sourced from the NWPCC Power Plan, assumes that 25% of unused regional supply in 2028 could be used for LSR dam replacement**
- **Each candidate was assigned an annualized cost based on technology, cost forecasts, and resource quality**
- **Wind & solar production profiles generated for each project using NREL WIND and SIND datasets**
  - Mid-C prices used to derive energy value from each resource
- **To assign each resource a capacity value regional effective load carrying capability (ELCC) assumptions sourced from regional IRPs and assigned**

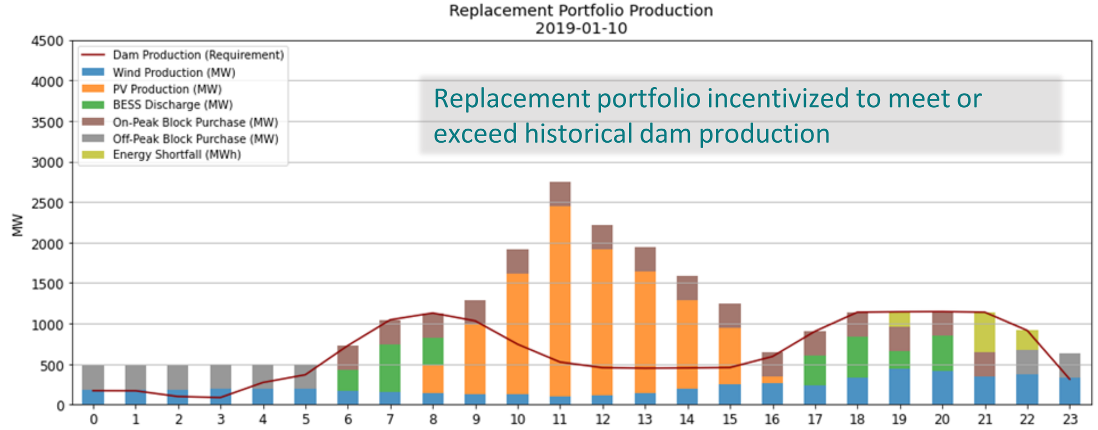
Candidate Resource Pool & Modeled Capacity Factor

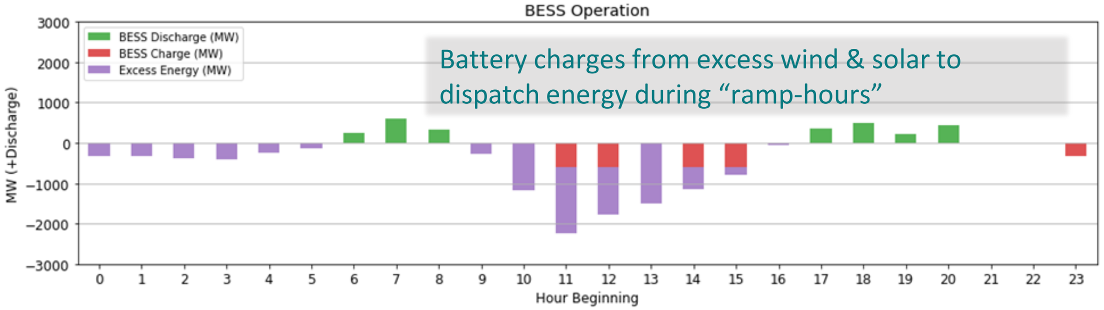
Resource Type	Number of Candidates	State	Interconnection Capacity (MW)	Avg. Capacity Factor (%)	Assumed ELCC (%)
BESS	1	MT	120	-	100%
	5	OR	2,600	-	
	3	WA	1,775	-	
PV	1	CA	100	25%	7%
	13	OR	3,609	25%	
	6	WA	640	23%	
PV+BESS	7	CA	2,700	31%	30%
	18	OR	8,300	29%	
	7	WA	2,225	23%	
WT	4	MT	1,456	36%	17%
	3	OR	1,077	33%	
	5	WA	1,483	33%	
WT+BESS	1	OR	500	29%	35%
	1	WA	200	30%	
WT+PV+BESS	2	WA	1,500	35%	40%
Pumped Storage	1	WA	500	-	100%
DR	23	-	559	-	100%
On-Peak Block	3	-	100	-	100%
Off-Peak Block	3	-	100	-	0%

Ramping Assessment

- **The objective of this study is to identify the lowest-cost portfolio of resources that can replace grid services provided by the LSR Dams**
    - ❖ Methodology up to this point identifies portfolios that meet energy and capacity requirements, but has not assessed their ability to provide ramping value during critical morning & evening hours during winter months
    - ❖ **A review of historical dam production suggests that the LSR dams have provided a significant, and increasing, amount of morning & evening ramp capacity in the last 5 years**
    - ❖ Using statistical analysis, we selected the top 10% of **"high-ramp-days"** in last 15 years during which the dams provided significant morning/evening ramp within winter months (occurred between Dec – Mar)
- **Replacement portfolios were dispatched against dam production on these high-ramp days to test the ability of the portfolios to provide "like" ramping capability**
    - ❖ **Percent Energy Served (%)** measured during morning ramp hours (5:00am – 8:00am), and evening-ramp hours (3:00pm – 7:00pm), respectively
    - ❖ A portfolio that met an **average ramp-hour energy served of 80%** was considered a sufficient replacement portfolio
    - ❖ 80% threshold is a planning estimate, recognizing that within the region there may be "latent" or unused flexibility that can be sourced to assist with dam replacement – regional analysis investigating this issue is recommended
- **Based on these results, a "minimum battery storage constraint" was re-introduced into the portfolio optimization tool, and replacement portfolio re-optimized and dispatched until this criteria was met**

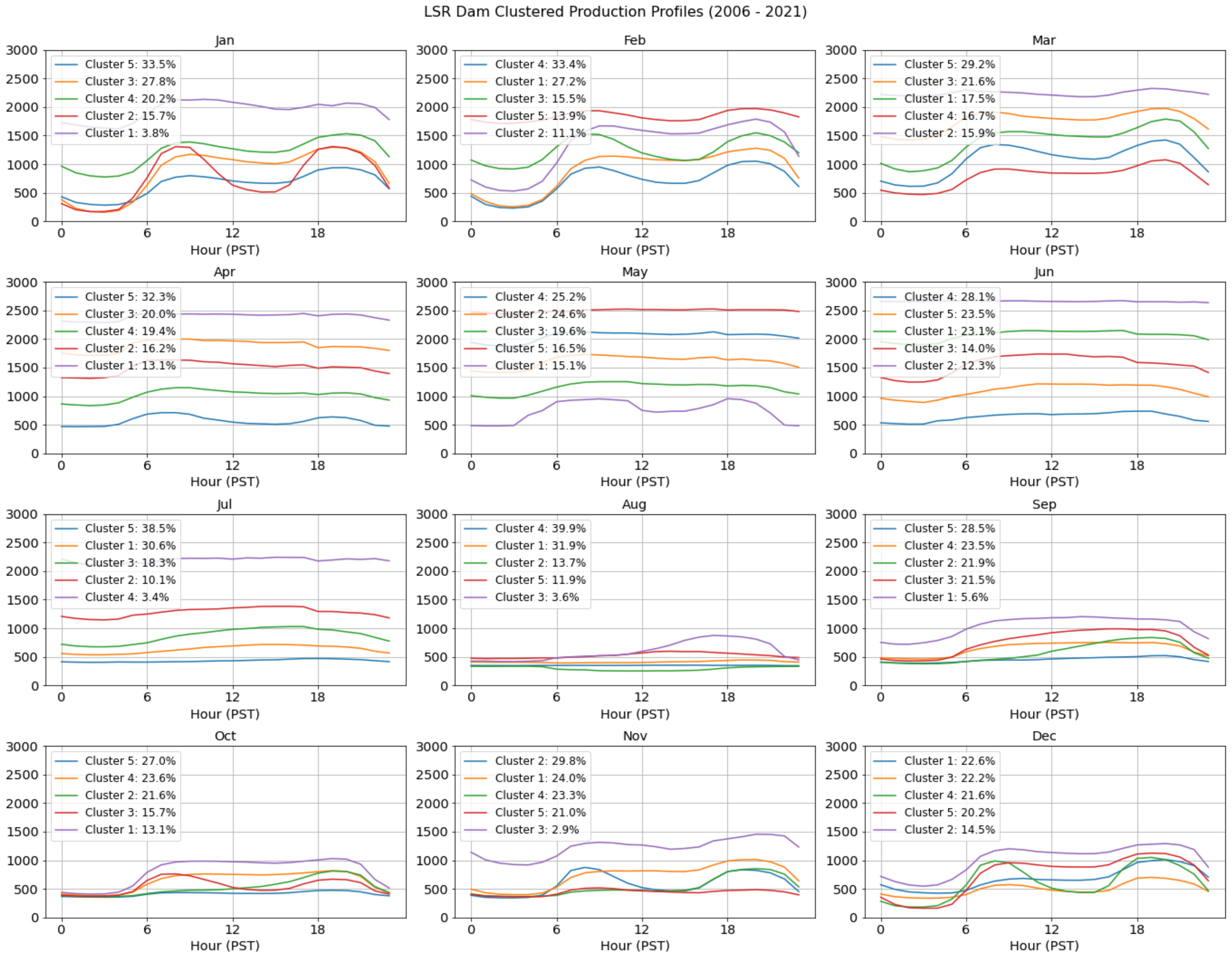






Dam Ramping Analysis

- **K-means clustering algorithm used to classify daily dam profiles into 5 clusters for each month**
  - ❖ Based on 15 years of historical dam production data
- **Clustering results suggest prevalence of morning & evening ramp-up service generally in winter months**
  - ❖ These shapes were used to inform ramping analysis



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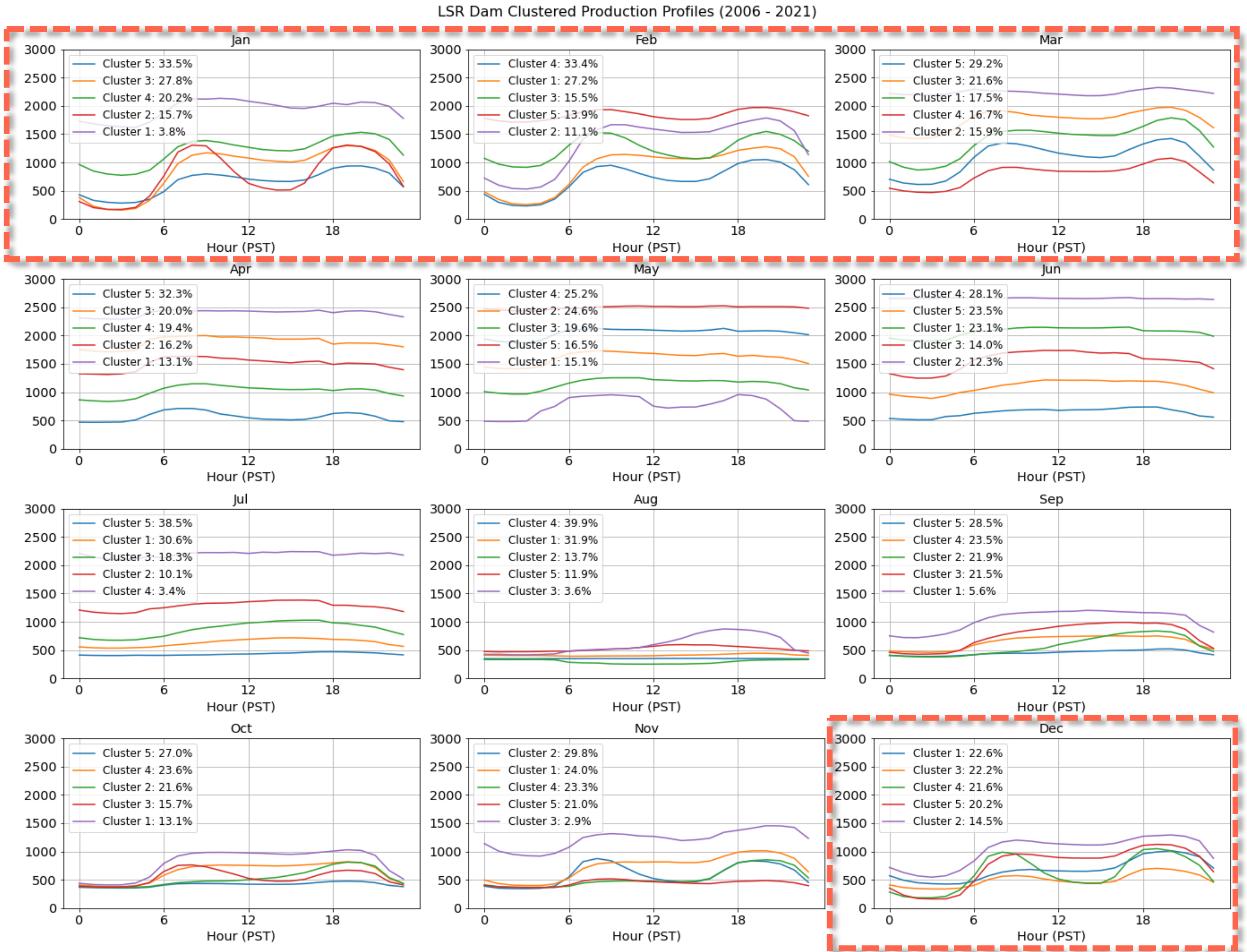
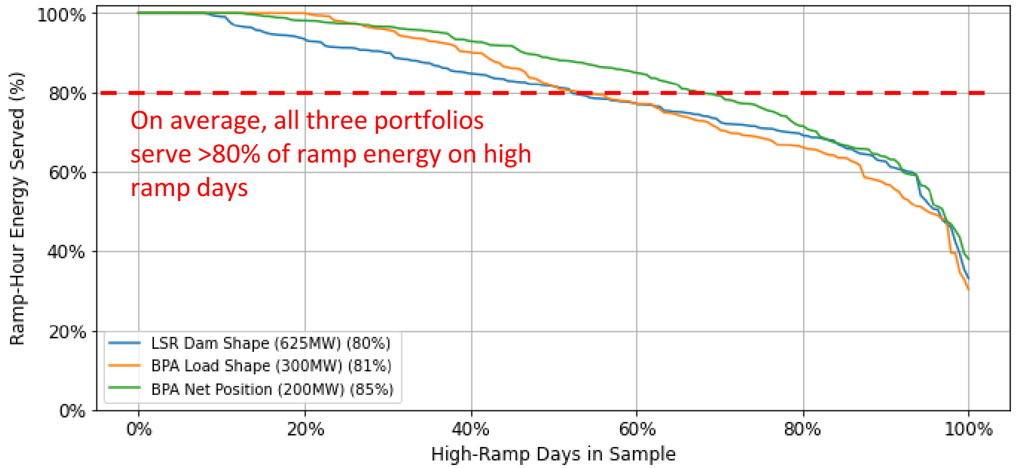
- **Results demonstrate material ramping service provided in winter months only**



Sensitivities & Summary of Results

Summary of Study Results

- **The optimization model was able to select least-cost portfolios of resources that met the planning constraints established for the study**
  - Portfolios featured between 200-625 MW of battery storage resources to meet the 80% ramp-hour energy served requirement
- **Resource selection outcomes based on trade-offs:**
  - PV tends to be the cheapest replacement resource per MWh
  - Wind provides generation around-the-clock & has a higher ELCC than PV
  - Demand response and market purchases necessary for replacement portfolio to meet capacity value
  - Portfolio selection sensitive to ELCC assumption
  - Market purchases selected



Result Metric	Base	BPA Load Shape	BPA Net Position
Number of Replacement Units (Not including DR)	19	16	22
Replacement Capacity (MW)	4,884	3,484	3,532
Wind Nameplate Capacity (MW)	600	1,709	1,415
Solar Nameplate Capacity (MW)	3,548	930	1,296
Battery Capacity (MW) – 4hr	625	300	200
Demand Response (MW)	136	245	221
Off-Peak Market Purchases (MW)	300	300	300
On-Peak Market Purchases (MW)	300	300	300
Annualized Cost ($M)	$452	$353	$362
Annual Value of Energy ($M)	$325	$251	$267
LSR Dam Annual Value of Energy ($M)	$182	$182	$182
Incremental Energy Value ($M) (Portfolio Energy Value – Dam Energy Value)	$143	$69	$85
Incremental Energy Value (%)	79%	38%	47%
Net Replacement Cost ($M) (Annualized Cost – Incremental Energy Value)	$309	$284	$277
Capacity Value	1,204	1,002	1,002
Net Capacity Cost ($/MW-year) $\frac{\text{Annualized Cost} - \text{Annual Value of Energy}}{\text{Capacity Value}}$	$105,481	$101,621	$94,976
Binding Energy Month	March	June	December
Largest Excess Energy Month	August	October	May
Ramp-Hour Energy Served	80%	81%	85%

Areas of Additional Study and Caveats

- **Identifying the most cost effective, environmentally efficient, and robust/adequate replacement portfolio will require scenario-based optimization studies that include modeling of the entire Northwest regional footprint. This approach differs from the approach taken in this analysis, which explored a one-for-one replacement analysis and focused on selecting specific resources to assess feasibility.**
  - ❖ A regional approach will allow for a more comprehensive assessment of resource adequacy and flexibility issues, which were addressed in this study through assumptions
  - ❖ Methods similar to Energy Strategies 2018 study are appropriate for evaluating system-wide issues
- **Given the weather-dependent nature of the replacement portfolios, any final or "binding" assessment of the optimal mix of replacement resources should take a multi-year stochastic approach to weather modeling, versus the more deterministic analysis featured in this study**
  - ❖ However, given the intent and purpose of this study, the scope of weather-years and data used were reasonable an inline with industry standards
- **Unlike the 2018 study of LSR dam replacement, this analysis did not consider the potential for energy efficiency to play a role in the replacement portfolio. Assuming EE could be acquired at a low cost, that suggests the cost results in this study could be conservative.**
- **Much of the pricing and dam output data used in this analyses were historical. It will be important for future analyses to incorporate changes in power prices in the future, along with drought or climate-driven impacts to LSR and Northwest hydro output. Such effects add uncertainty regarding the value of future dam production.**
- **Unlike prior efforts exploring replacement feasibility, this study did not evaluate the degree that that dam removal and replacement will impact regional generation dispatch.**
- **This study required several important assumptions that impacted the findings, including:**
  - ❖ Estimated capacity value of the dams at 1000 MW of capacity, based on Energy Strategies' 2018 study which used GENESYS to estimate dam capacity value.
  - ❖ Capacity contribution, or ELCC, of most replacement resources were sourced from regional or IRP planning assumptions. No such assumptions were available for hybrid resources, so Energy Strategies made rule-of-thumb adjustments to the ELCC values of non-hybrid resources based on planning assumptions from other regions, such as California
- **Market purchases in this study were assumed to be bilateral market purchases at Mid-C, which typically do not include environmental attributes (e.g., RECs). However, should 100% clean replacement be sought, associated purchases could be paid with unbundled RECs to achieve this environmental outcome.**
  - ❖ The incremental cost of these RECs was not considered in this study. However, relative to the cost of the replacement portfolio it is anticipated this cost may be small.

THANK YOU

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Technical Appendices

- Replacement Candidates and Assumptions
- Replacement Portfolio Details
- Ramping Analysis Methodology and Results

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Summary of Options for Replacement Resources

Type	Technologies Considered	Locations	Key Assumptions / Sources
Clean Energy Generation and Storage	Wind, Solar, Storage, Hybrid	Individual proposed projects sourced primarily from BPA interconnection queue, with additional projects in California and Montana were made available for selection	Details: Interconnection queues screened to identify viable projects Costs: Technology-specific Production: Location-specific, hourly output based on NREL integration study datasets Capacity value: Sourced from IRPs
Other Resources	*Not considered – no thermal or carbon emitting resources were included as options*	N/A	N/A
Market Purchases	On/Off-peak block purchases at Mid-C, up to 300 MW of each in 100 MW increments	Mid-C, which is the primary bilateral trading hub in the PNW (very liquid supply)	Details: N/A Costs: Based on historical ICE Mid-C prices Production: Assume power physically delivered Capacity value: 100% capacity value
Demand Response	Irrigation DLC, commercial, space cooling DLC, residential water heaters, heat pumps, etc.	Specific location of DR not considered but supply was limited to what was available in PNW region, per Northwest Power and Conservation Council (NWPCC)	Details: NWPCC 2021 Plan primary source Costs: Based on NWPCC 2021 Plan Production: N/A, not included in dispatch Capacity value: Based on NWPCC forecast @ 100%
Energy Efficiency	*Not considered – did not have method to select "tranches" or specific programs of EE*	N/A	N/A

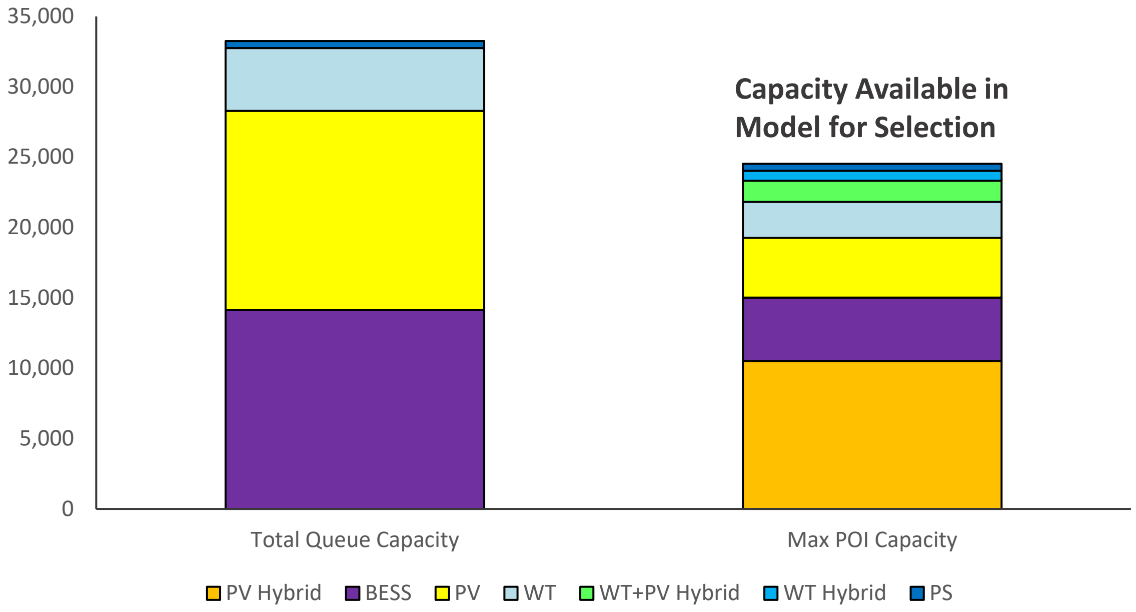
BPA Queue Analysis to Identify Candidates

- **The BPA generator interconnection queue was used to identify candidate renewable energy projects which could, hypothetically, be contracted to replace LSR dam services**
- **The following criteria was applied to the screen down the queue to a set of candidate resources:**
  - Consider queue projects which are currently undergoing studies or that have a status of "Received"
    - Projects which have completed their studies or have executed interconnection agreements are likely to have contracts already and were therefore screened out of analysis
  - Fuel types included were solar, wind, battery, pumped storage
  - Projected In-Service Dates ranged from 2024-2028
  - Max capacity ≥ 20 MW
- **Screening led to nearly 25 GWs of candidate resource capacity (at point-of-interconnection)**
- **Several wind projects in Montana connecting to the Colstrip transmission system were added, along with a few solar projects in California**
  - Supply in both of these areas is sufficient that detailed analysis was not required

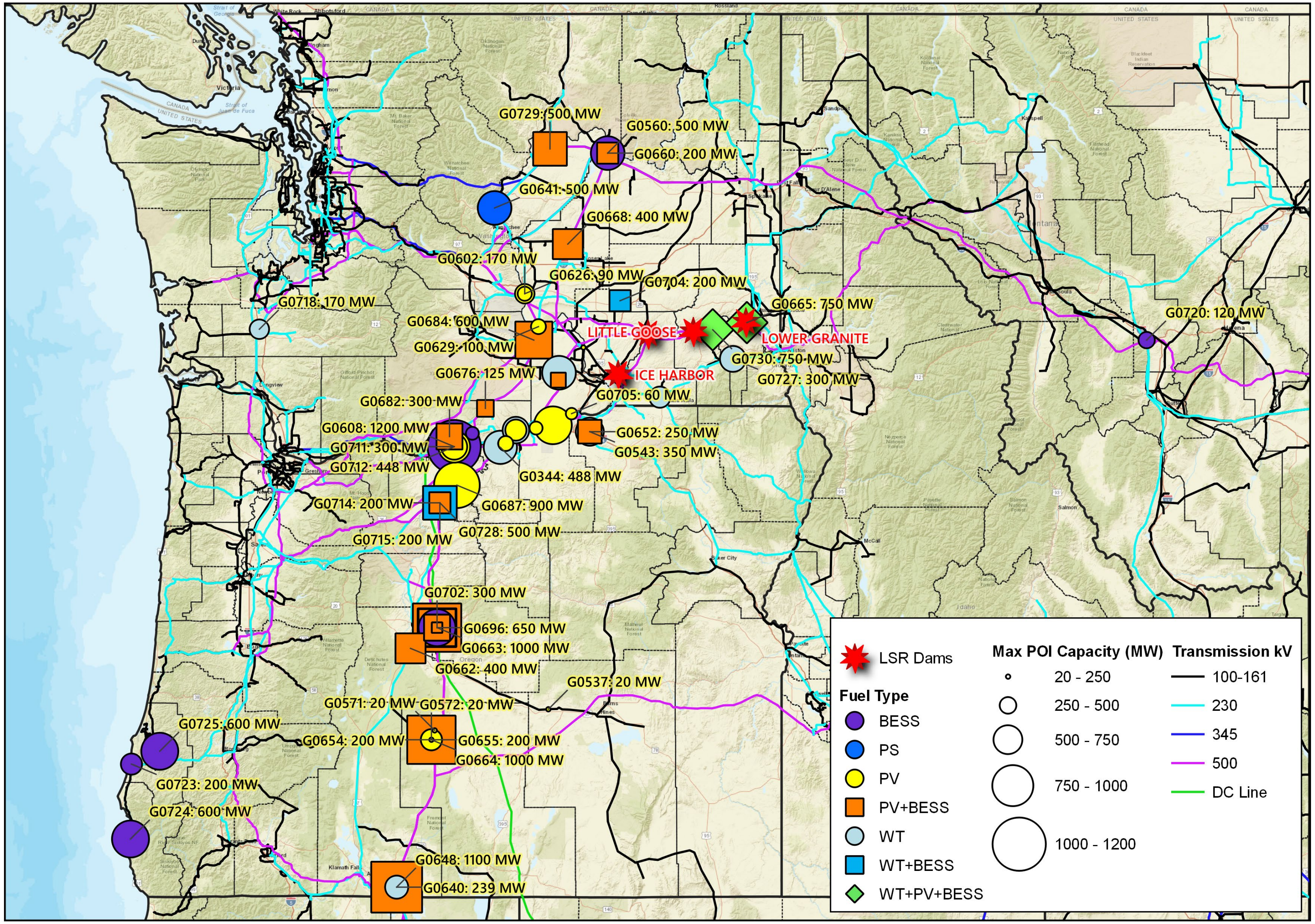
BPA Queue Capacity as of 2/16/2022

Status	Max Capacity (MW)
Received	4,483
Study	31,426
Study Completed	2,826
IA Executed	500
Energized	5,528
Withdrawn	54,287

Potential BPA Queue Capacity (MW) to Replace LSR Dams



Screening of BPA Queue Identified 25 GW of Viable Capacity



Candidate Resource Cost Assignment

- **Energy Strategies utilized cost information from a variety of sources with the intention of creating annualized costs for each project to allow for the optimization tool to make cost-minimizing decisions**
- **Energy Strategies used NREL 2021 Annual Technology Baseline (ATB) database to assign a levelized cost of energy to solar and wind resources, including hybrid configurations.**
  - The Pacific Northwest National Laboratory data repository was used to feed cost information into the WECC Capital Cost Model to determine annualized costs for storage resources on a $/kW-Yr basis.
- **The Northwest Power and Conservation Council 2021 Power Plan was used to determine demand response product options and their associated potential capacities and costs**

Annualized Cost of Standalone Renewable **= Standalone LCOE x Annual Energy**
Annualized Cost of Standalone Storage **= Annualized Capital Cost x Storage Capacity**
Annualized Cost of Hybrid Resource **= (Hybrid LCOE x Annual Energy) + Annualized Cost of Standalone Storage**
Annualized Cost of Demand Response **= Levelized Cost x (Max Potential x 25%)**

NREL Transforming ENERGY

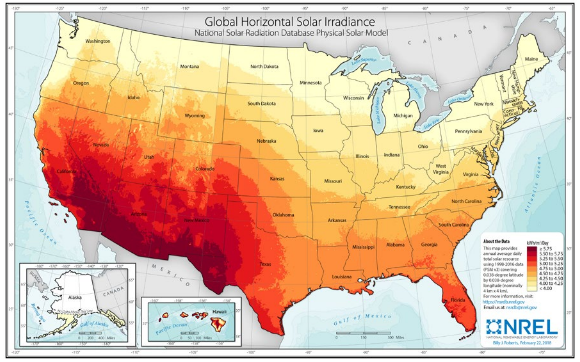
Pacific Northwest NATIONAL LABORATORY

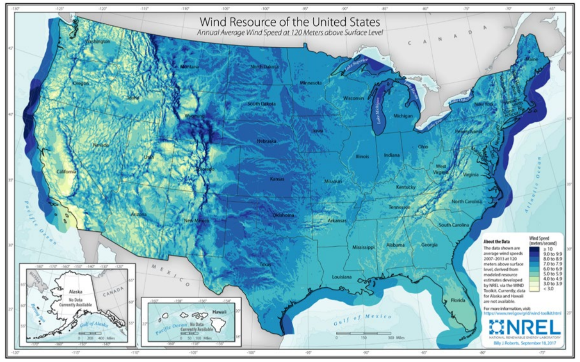
Northwest Power and Conservation Council

WECC

Candidate Resource Cost Assignment – Renewables

- **Wind speed and irradiance quality have a significant impact on the levelized costs of their respective projects**
- **Energy Strategies inherently accounts for resource quality when applying the productions profiles leveraged from the NREL WIND and SIND datasets.**
  - ❖ In order to not bias the annualized cost development, Energy Strategies applied a single LCOE for each resource type, which is based on an average in-service date year and the most typical resource class, allowing for production to be the main driver of annualized costs across resources classes
- **Since hybrid renewable pairings are more cost-effective than building separate resources of the equivalent capacities, NREL ATB represents these cost savings as a lower levelized cost for the renewable resource (WT or PV) compared to their standalone counterparts. Storage costs remain the same**





LCOE Assumptions for Select Resources

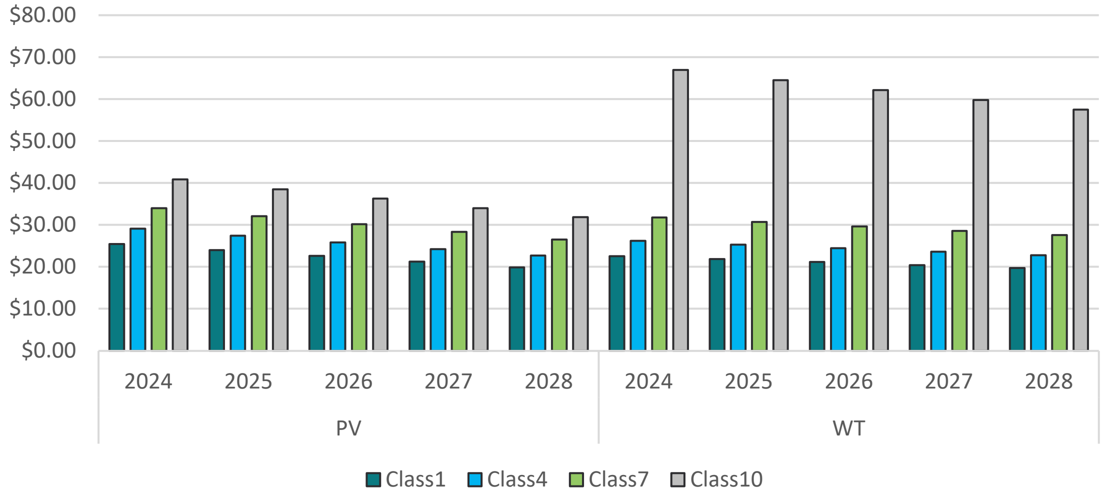
Resource Type	Avg ISD Year	Resource Class	LCOE (2020 $/MWh)
PV	2025	5	$29.39
PV (Hybrid)*	2025	5	$26.47
WT	2025	8	$34.66
WT (Hybrid)*	2025	8	$31.81

Resource Type	Annualized Capital Costs (2020 $/kW-Yr)
BESS (4hr)	$154.00
PS Hydro	$256.00

*Values marked as "Hybrid" only account for the energy-producing resource (WT or PV) in a hybrid unit. Supplemental storage costs are then applied separately

Annualized Cost of Hybrid Resource =
Resource Annual Energy (MWh) * Resource LCOE ($/MWh)
+ Battery Capacity (kW) * Annualized Capital Cost of BESS (4hr) ($/kW-Yr)

NREL ATB LCOE by Resource Type (2020 $/MWh)



Candidate Resource Cost Assignment – Demand Response

- **Demand response (DR) products and levelized costs were derived from the Northwest Power and Conservation Council's 2021 Power Plan**
- **Max potential is defined as a cumulative capacity value, with summer and winter providing different ratings for each product**
- **Energy Strategies only allowed for 25% of the 2028 max potential to be a resource option, given the infeasibility of integrating DR products across the entire BPA footprint**
    - ❖ Winter DR products assessed in this analysis

Annualized Cost of Demand Response **= Levelized Cost x (Max Potential x 25%)**

Product	Product Name	25% of 2028 Max Potential (MW)
NRCurtailCom	Demand Curtailment - Commercial	7.25
NRCurtailInd	Demand Curtailment - Industrial	37
NRIrrLg	Irrigation DLC - Large Farm	0
NRIrrSmMed	Irrigation DLC - Small/Medium Farm	0
ComCPP	Commercial Critical Peak Pricing	12.25
IndCPP	Industrial Critical Peak Pricing	12
DVR	Demand Voltage Response	124
IndRTP	Industrial Real Time Pricing	2.75
ResCPP	Residential Critical Peak Pricing	29.75
ResTOU	Residential Time of Use	21.25
NRCoolSwchMed	Space Cooling DLC - Commercial Medium	0
NRHeatSwchMed	Space Heating DLC - Commercial Medium	3.25
NRCoolSwchSm	Space Cooling DLC - Commercial Small	0
NRHeatSwchSm	Space Heating DLC - Commercial Small	3.75
NRTstatSm	Space Heating/Cooling DLC Thermostat - Commercial Small	3
ResACSwch	Residential Space Cooling DLC Switch	0
ResHeatSwitch	Residential Space Heating DLC Switch	122.75
ResBYOT	Residential Bring Your Own Thermometer	10
ResERWHDLCSwch	Residential Electic Resistance Water Heater DLC Switch	99.5
ResERWHDLCGrd	Residential Electric Resistance Water Heater DLC Grid-Ready	64.5
ResEVSEDLCSwch	Residential Electric Vehicle Supply Equipment DLC Switch	3.75
ResHPWHDLCSwch	Residential Heat Pump Water Heater DLC Switch	1
ResHPWHDLCGrd	Residential Heat Pump Water Heater DLC Grid-Ready	1

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Base Replacement Portfolio

All results in 2020$

Resource Type	POI Capacity (MW)	Annualized Cost ($M)	Annual Value of Energy ($M)	March Energy (MWh)	May Energy (MWh)	August Energy (MWh)	December Energy (MWh)	Capacity Value (MW)	Number of Units Selected
DR	136	$0	$0	-	-	-	-	136	2
Mkt - On Peak	300	$57	$52	148,800	148,800	148,800	148,800	300	3
Mkt - Off Peak	300	$22	$20	74,400	74,400	74,400	74,400	-	3
PV	2,398	$144	$133	397,071	532,170	569,212	201,597	168	10
PV+BESS	1,000	$103	$67	179,629	261,402	285,192	108,947	300	2
WT+PV+BESS	750	$127	$54	250,732	220,714	217,742	105,319	300	1
Candidate Resource Portfolio	4,884	$452	$325	1,050,630	1,228,490	1,295,350	639,045	1,204	19 (+ 2 DR)
LSR Dams			$182	1,050,622	1,223,523	290,678	507,193	1,000	
Constraint Ratio			1.783	1.000	1.005	4.456	1.259	1.204	

- **The optimal replacement portfolio determined by our in-house tool is comprised of 19 replacement resources totaling a 4,884 MW nameplate capacity**
  - Winter & spring monthly energy constraints represent the binding factors in portfolio selection
  - Portfolio is PV-heavy, which would result in excess energy without sufficient storage resources
- **The LSR Dam Shape (Base) portfolio is energy-long in summer & fall, since the portfolio procured energy to meet high spring production**
- **Replacement portfolio provides an energy value increase of 79%, resulting in a net portfolio cost of $309M/year**

BPA Load Shaping Replacement Portfolio

All results in 2020$

Resource Type	POI Capacity (MW)	Annualized Cost ($M)	Annual Value of Energy ($M)	March Energy (MWh)	May Energy (MWh)	August Energy (MWh)	December Energy (MWh)	Capacity Value (MW)	Number of Units Selected
DR	245	$1	$0	-	-	-	-	245	11
Mkt - Off Peak	300	$22	$20	74,400	74,400	74,400	74,400	-	3
Mkt - On Peak	300	$57	$52	148,800	148,800	148,800	148,800	300	3
PV	880	$65	$61	158,326	229,895	256,343	111,380	62	4
PV+BESS	50	$11	$4	9,547	14,162	15,861	6,886	15	1
WT	1,209	$118	$83	395,329	296,730	200,077	275,533	206	4
WT+BESS	500	$79	$31	154,136	104,609	64,549	110,161	175	1
Candidate Resource Portfolio	3,484	$353	$251	940,538	868,597	760,029	727,158	1,002	16 (+11 DR)
LSR Dams			$182	622,636	712,982	759,315	726,755	1,000	
Constraint Ratio			1.375	1.511	1.218	1.001	1.001	1.002	

- **The optimal replacement portfolio determined by our in-house tool is comprised of 16 replacement resources totaling a 3,484 MW nameplate capacity**
    - Winter & summer monthly energy constraints and capacity constraints represent the binding factors in portfolio selection
    - Portfolio represents a balanced selection between solar and wind energy resources, supplemented by DR and block market purchases
- **The BPA Load Shape sensitivity shows the lowest level of excess energy**
- **Replacement portfolio provides an energy value increase of 38%, resulting in a net portfolio cost of $284M/year**

BPA Net Position Replacement Portfolio

All results in 2020$

Resource Type	POI Capacity (MW)	Annualized Cost ($M)	Annual Value of Energy ($M)	March Energy (MWh)	May Energy (MWh)	August Energy (MWh)	December Energy (MWh)	Capacity Value (MW)	Number of Units Selected
DR	221	$0	$0	-	-	-	-	221	7
Mkt - Off Peak	300	$22	$20	74,400	74,400	74,400	74,400	-	3
Mkt - On Peak	300	$57	$52	148,800	148,800	148,800	148,800	300	3
PV	646	$40	$37	100,636	137,475	151,837	68,675	45	8
PV+BESS	650	$77	$49	124,105	184,111	206,192	89,512	195	2
WT	1,415	$165	$109	430,492	360,530	256,449	412,535	241	6
Candidate Resource Portfolio	3,532	$362	$267	878,434	905,316	837,678	793,922	1,002	22 (+ 7 DR)
LSR Dams			$182	687,516	313,134	788,033	793,739	1,000	
Constraint Ratio			1.463	1.278	2.891	1.063	1.000	1.002	

- **The optimal replacement portfolio determined by our in-house tool is comprised of 22 replacement resources totaling a 3,532 MW nameplate capacity**
  - Late-Summer & Winter monthly energy constraints and capacity constraints represent the binding factors in portfolio selection
  - Portfolio represents a balanced selection between solar and wind energy resources, supplemented by DR and block market purchases
- **The BPA Net Position portfolio is energy-long in spring months when hydro runoff is at its peak**
- **Replacement portfolio provides an energy value increase of 47%, resulting in a net portfolio cost of $277M/year**

Technical Appendices

- Replacement Candidates and Assumptions
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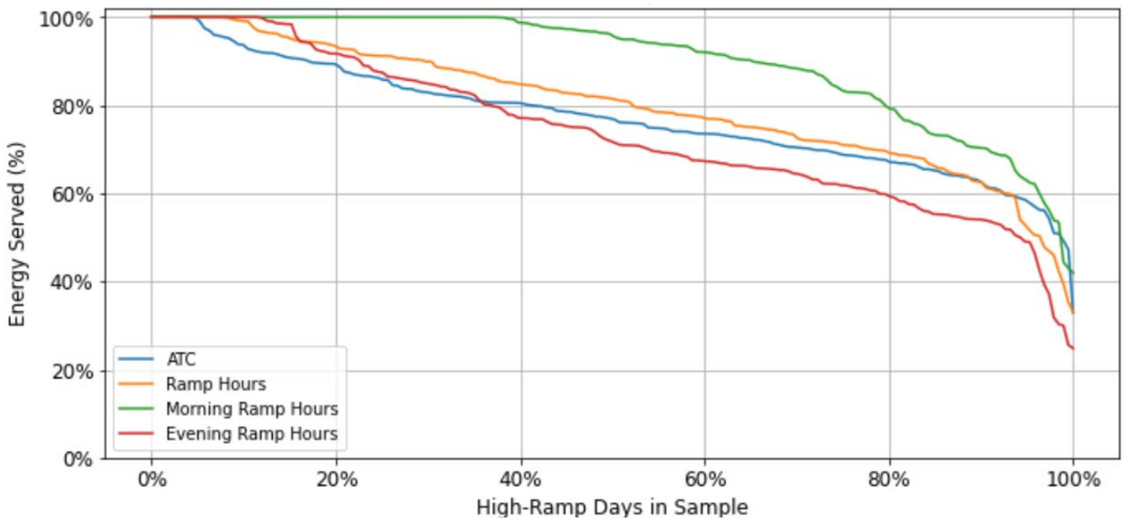
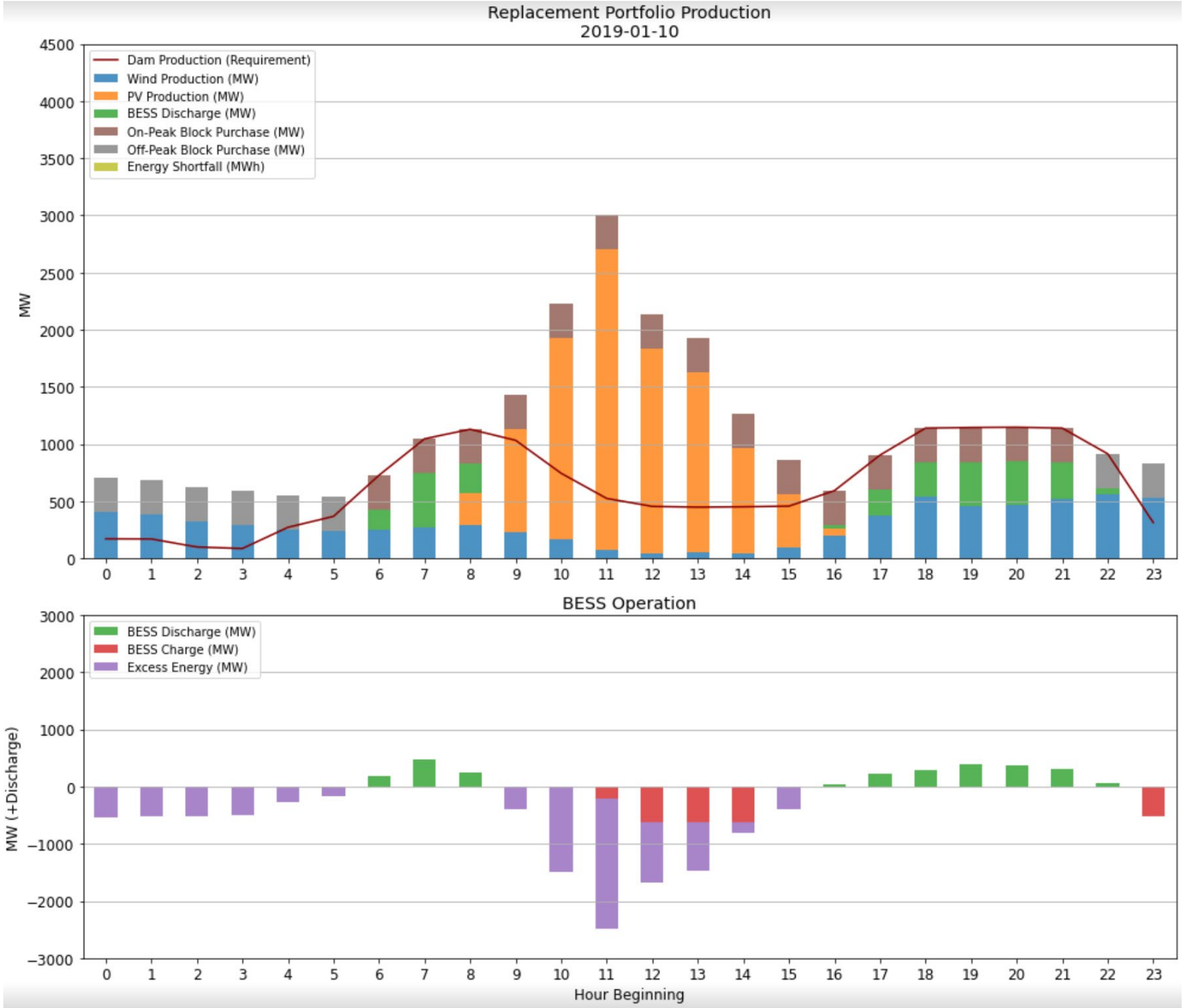
Ramping Analysis: Base Replacement Portfolio

(600 MW BESS)

- **Observations:**
  - For this sample day, addition of 625 MW to BESS allows replacement portfolio to match dam production
  - BESS discharge critical to morning/evening ramp
- **Average RH Energy Served: 80% (Viable)**

Energy Served in "High Ramp Days"



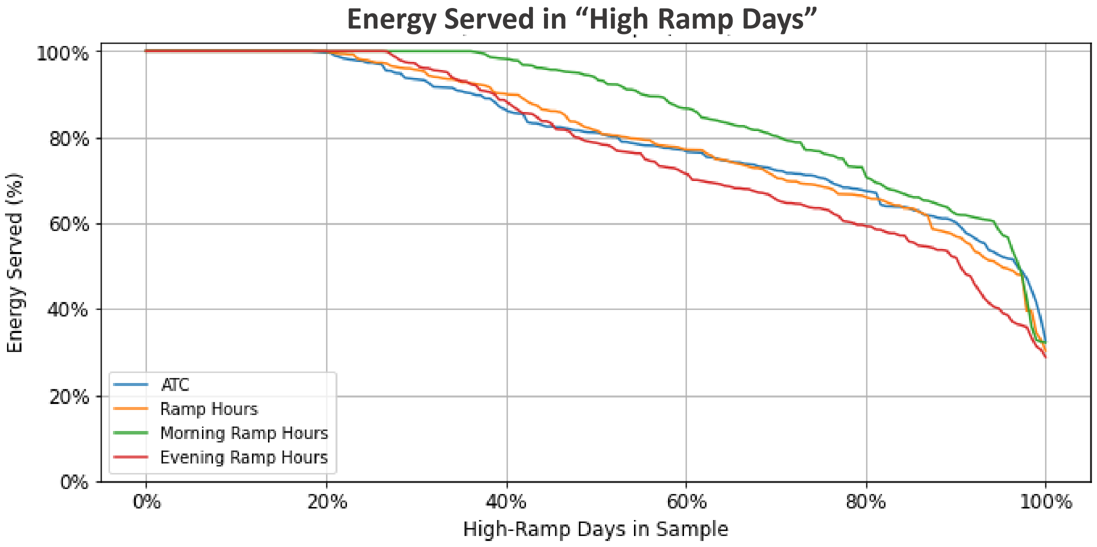


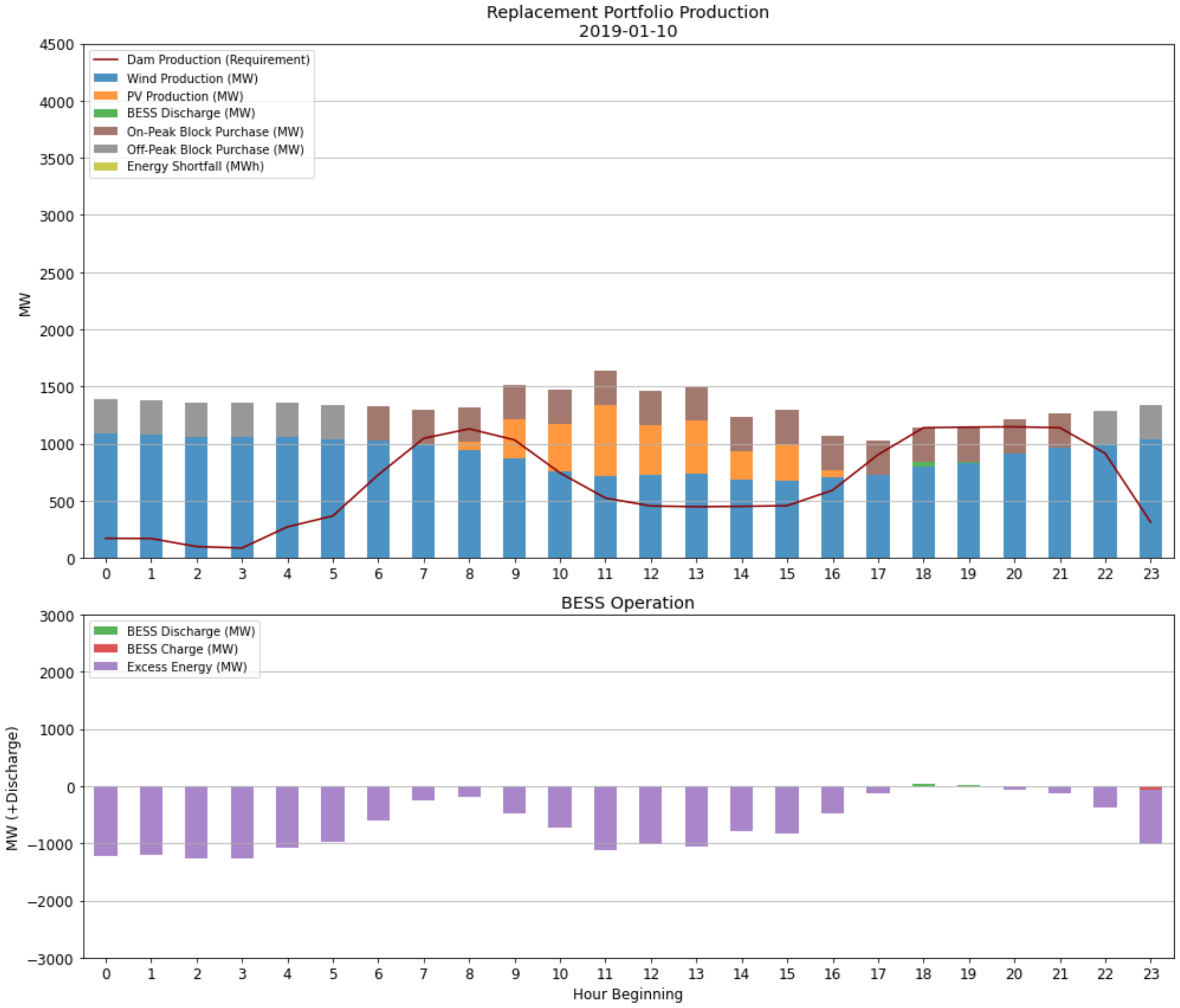
Ramping Analysis: BPA Load Shaping Sensitivity Portfolio

(300 MW BESS)

- **Observations:**
  - ❖ In this sample day, wind power provides around-the-clock power that meets a majority of dam energy
  - ❖ Implementation of 300 MW of battery storage into the portfolio drastically improves ramp-hour energy served for a majority of high ramp days

- **Average RH Energy Served: 81% (Viable)**





Ramping Analysis: BPA Net Position Sensitivity

(200 MW BESS)

- **Observations:**
  - In this sample day, wind power provides around-the-clock power that meets a majority of dam energy
  - Implementation of 200 battery storage into the portfolio drastically improves ramp-hour energy metrics for a majority of high ramp days

- **Average RH Energy Served: 85% (Viable)**