U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Hydropower Value Study

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Hydropower Program

Tuesday, October 8, 2019

Abhishek Somani

PNNL, ANL, INL, NREL, ORNL

Project Overview

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Project Summary

The primary purpose of this project was to comprehensively understand the current landscape of hydropower operations and resulting value of resources in power markets across the country. The project was also designed to lay out the foundation for future research that enables comprehensive understanding of the value of hydropower resources in a variety of future grid states.

Project Objective & Impact

This project's main objective was to perform foundational work to understand recent trends in hydropower operations, future expected changes, and technical and technological abilities of hydropower resources to adapt their operations in the future. The work products included a landscape review of the recent trends in provision of various power grid services by hydropower resources. The project was also designed to identify high-impact research questions to lay the foundation for future research.

Project Information

Project Principal Investigator(s)

Abhishek Somani, Pacific Northwest National Laboratory

WPTO Lead

Samuel Bockenhauer

Project Partners/Subs

Argonne National Laboratory
Idaho National Laboratory
National Renewable Energy Laboratory
Oak Ridge National Laboratory

Project Duration

- March 2018
- December 2019

Alignment with the Program

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Hydropower Program Strategic Priorities

Environmental R&D and Hydrologic Systems Science

Big-Data Access and Analysis

Technology R&D for Low-Impact Hydropower Growth

R&D to Support Modernization, Upgrades and Security for Existing Hydropower Fleet

Understand, Enable, and Improve Hydropower's Contributions to Grid Reliability, Resilience, and Integration

Alignment with the Hydro Program

Understand, Enable, and Improve Hydropower's Contributions to Grid Reliability, Resilience, and Integration

- Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower and PSH.
- Investigate the full range of hydropower's capabilities to provide grid services, as well as the machine, hydrologic, and institutional constraints to fully utilizing those capabilities.
- Optimize hydropower operations and planning—alongside other resources—to best utilize hydropower's capabilities to provide grid services.
- Invest in innovative technologies that improve hydropower capabilities to provide grid services

The project team collected and analyzed data on various grid services provided by hydropower – conventional and PSH, from various regions in the country (MISO, ISO-NE, WAPA, CAISO, BPA).

The project team extracted and analyzed hydropower specific results from existing studies and models that simulate the operations of the power system in various future grid scenarios.

Project Budget

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Lab	FY17	FY18	FY19 (Q1 & Q2 Only)	Total Project Budget FY17–FY19 Q1 & Q2 (October 2016 – March 2019)	
Lab	Costed	Costed	Costed	Total Costed	Total Authorized
PNNL	[$0K]	[$302K]	[$182K]	[$484K]	[$495K]
ANL	[$0K]	[$191K]	[$68K]	[$259K]	[$259K]
NREL	[$1K]	[$187K]	[$39K]	[$227K]	[$229K]
ORNL	[$0K]	[$168K]	[$94K]	[$262K]	[$266K]
INL	[$0K]	[$91K]	[$72K]	[$163K]	[$191K]
TOTAL	[$1K]	[$848K]	[$383K]	[$1,395K]	[$1,440K]

Management and Technical Approach

The project team comprised of experts in the fields of economics, statistics, data analytics, power market design and analysis, hydrology and hydraulics, plant-level controls and operations, and power systems operations and planning. To ensure successful completion of project's multiple objectives, the team identified three major tasks, with a few sub-tasks within each. A lead lab was identified for each of the main tasks, and other labs served in supporting role, which ranged from performing complementary technical work to reviewing the intermediate and final set of results. Each lab participating in this study possessed complementary hydropower expertise:

- PNNL: Analysis of grid services by hydropower resources and market rules for hydropower
- ANL: Statistical analysis of grid services by hydropower resources
- INL: Assessment of non-monetized services provided by synchronous generators
- NREL: Analysis of renewable integration and future grid research
- ORNL: Assessment of technological characteristics of hydropower plants

Subcontract with University of North Carolina – Chapel Hill (executed by INL): A team at University of North Carolina (UNC) Chapel Hill led by Professor Greg Characlis utilized their integrated water and power system model to inform the report on non-monetized services provided by hydropower.

End-User Engagement and Dissemination Strategy

- The project team has engaged and continues to engage stakeholders ranging from hydropower plant operators, hydropower utilities, power systems operators, and power marketing authorities and ISO/RTOs in different parts of the country.
- The engagement has ranged from collecting and analyzing hydropower operations data, to getting feedback on intermediate and final set of results.
- In a few instances, the analysis has been carried jointly with the stakeholders themselves, such as with Chelan PUD and TVA.
- The results have been presented at various conferences, such as CEATI, Water Power Week, and NWHA, as well as workshops such as the one organized by EPRI at NYPA.
- The project team has identified and reached out to external reviewers (outside the National Lab and DOE complex) to provide feedback on various reports that are in the process of being finalized.

Technical Accomplishments

Slides 10 – 33

Project Overview

- **Motivating questions:**
  - How is hydropower currently contributing to grid services?
  - What services/capabilities will be needed by the grid in the future?
  - Can hydropower provide the services based on technical capabilities and costs?
- **Project intent:**
  - Foundational work to understand present hydropower operations trends, future expected changes, and hydropower capabilities analysis
- **Project design:**
  - Involved extensive data collection and analysis on market participation trends, operational practices, and technological capabilities

Principle Findings

- Hydropower operations are changing in many parts of the country. The changes, however, are manifesting differently regionally.
- Changing operations and value streams are impacting hydropower resources financially; revenues are exhibiting declining trends in some parts of the country. Conversely, new markets for grid services offer opportunities to enhance hydropower's revenues.
- Hydropower continues to be a significant contributor to system reliability. Reliability requirements and standards are evolving; it will be important to continue assessing the role or hydropower in the evolving power system.
- The ability of hydropower resources to provide grid services depend on the electro-mechanical attributes, which are in turn governed by the hydrological and geological conditions at a given location.
- Changes in hydrological conditions due to extreme weather events will impact water availability, which will in turn impact the ability of resources to generate electricity and provide other grid services.
- Not accurately accounting for water availability and management practices can lead to overestimation of the amount of flexibility hydropower facilities.

Changes on the Horizon: CAISO Net Load and Renewables Supply

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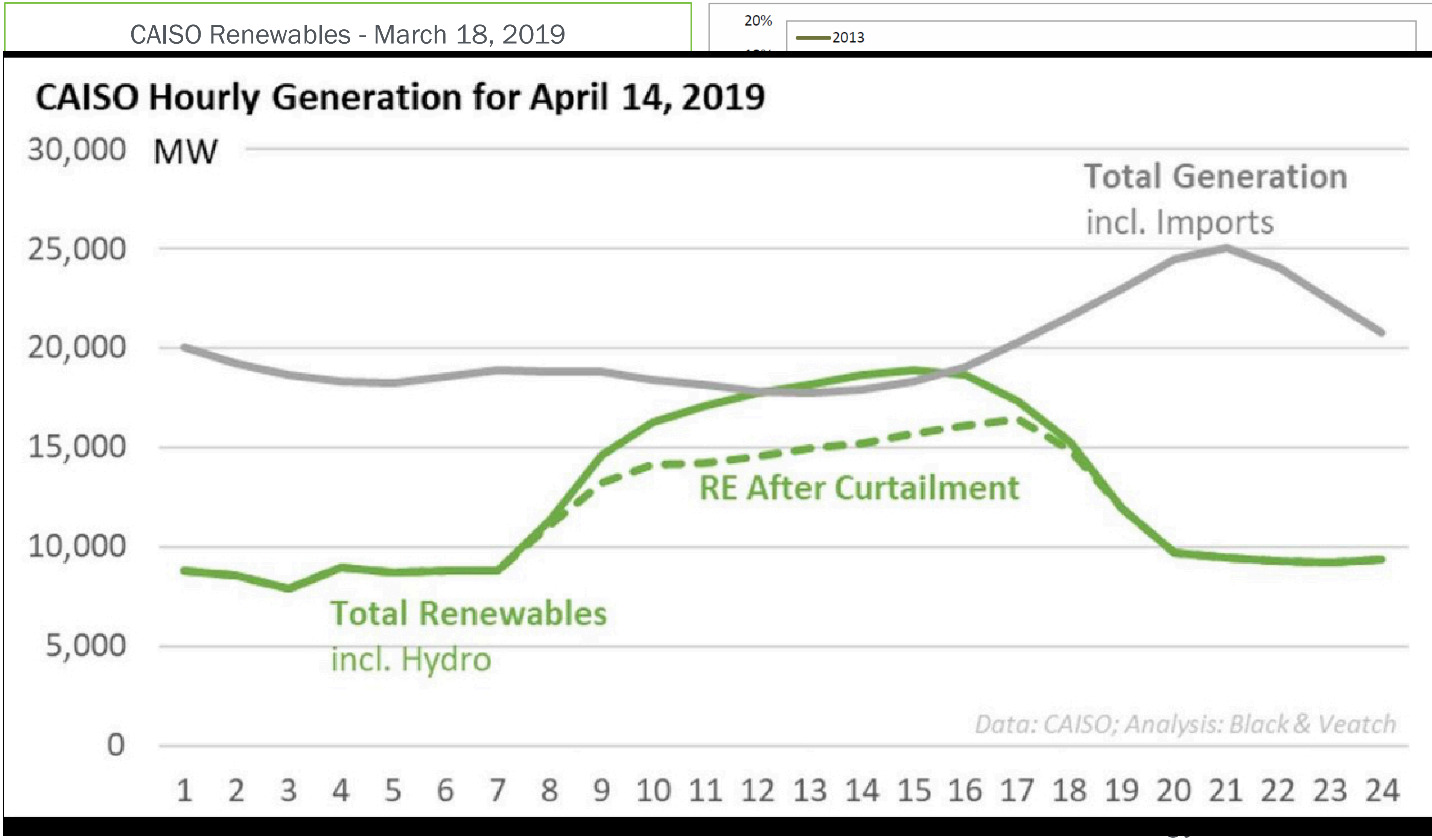

Source: CAISO

What we are hearing from Industry

- **Machine wear and tear issues need to be studied extensively:**
  - Nature of replacement and restoration projects are changing: Customers are asking to replace/restore not to original specifications, but to new ones based on different operating requirements
  - Extensive wear and tear cost studies are needed because resources are being cycled more or operated differently
- **Hybrid systems may be the way of the future:**
  - Small hydro + storage + solar
  - Pumped/reservoir hydro + batteries:
- **Some utilities are operating hydro units only during peak periods while spilling during other hours**
  - FERC licenses are still an issue: Rate of Release are baked into FERC licenses, which means that entities have very little to no flexibility to avail opportunities such as arbitrage, even if those exist presently

Changing Landscape of Revenues from Grid Services – ISO NE Example

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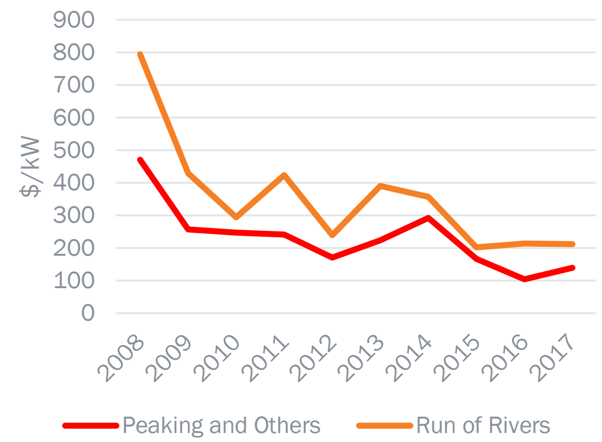
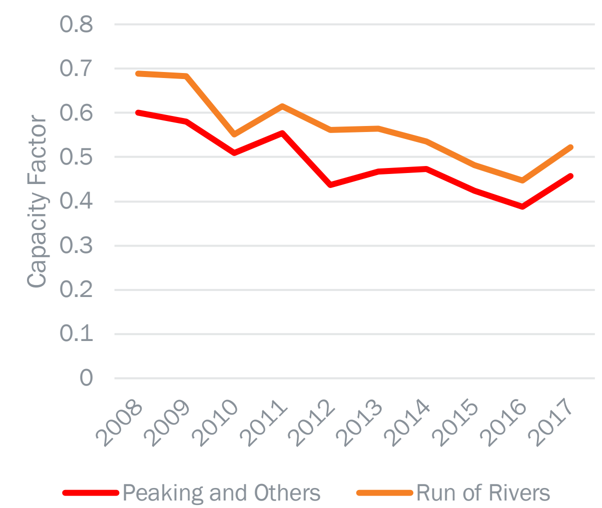
- Clear declining trend in the total revenue received by hydropower plants associated with the declining energy price
  - Run-of-river plants have a higher revenue measured in (normalized) capacity ($/kW) due to higher capacity factors
  - Peaking plants have a higher revenue measured in (normalized) energy ($/MWh) due to their operating strategy

- Major revenue source is still energy, followed by capacity payment and other ancillary services, including uplift, which constitutes small part of the total revenue





Mid-Continent ISO Hydropower Revenue Trends for Different Grid Services

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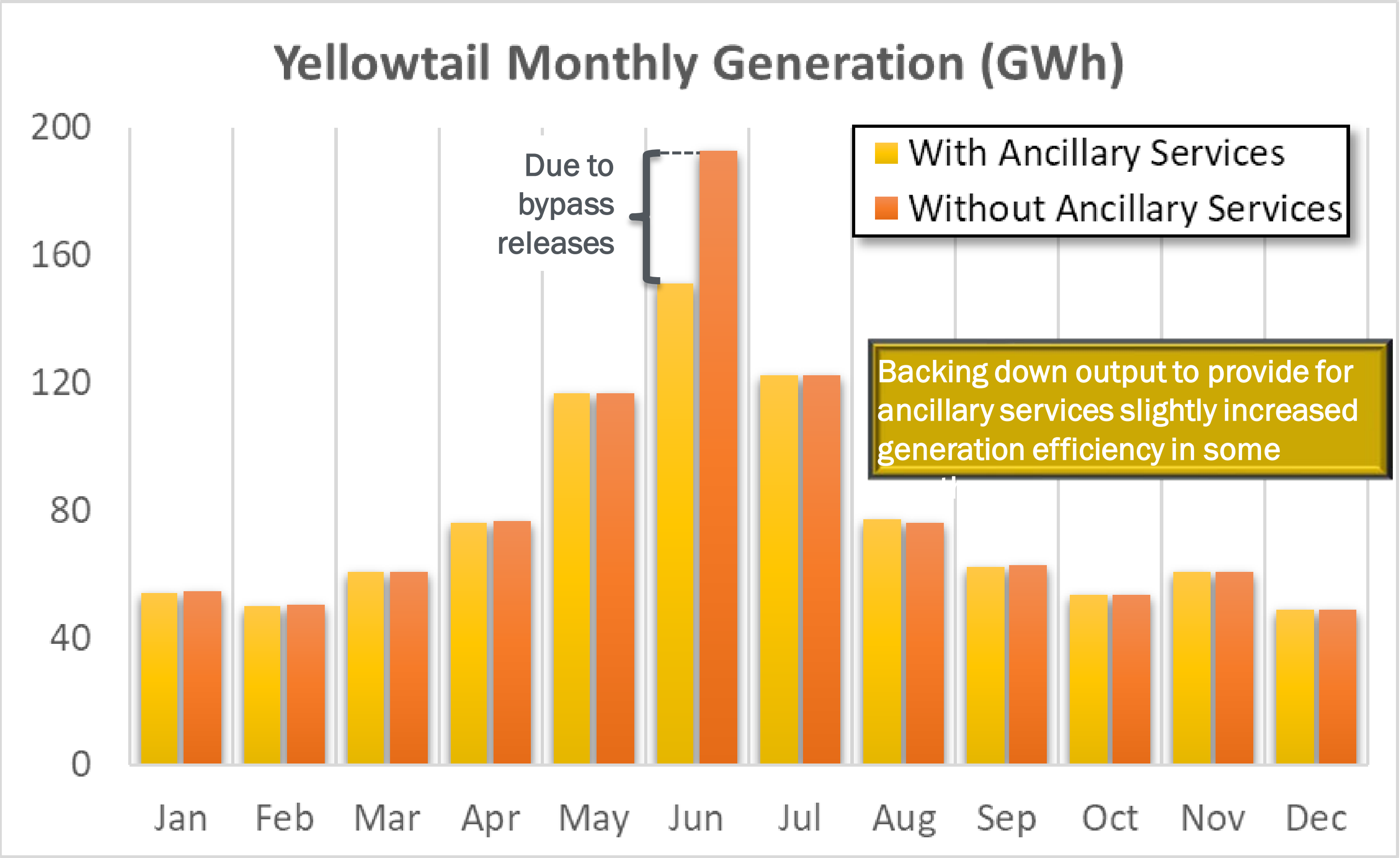
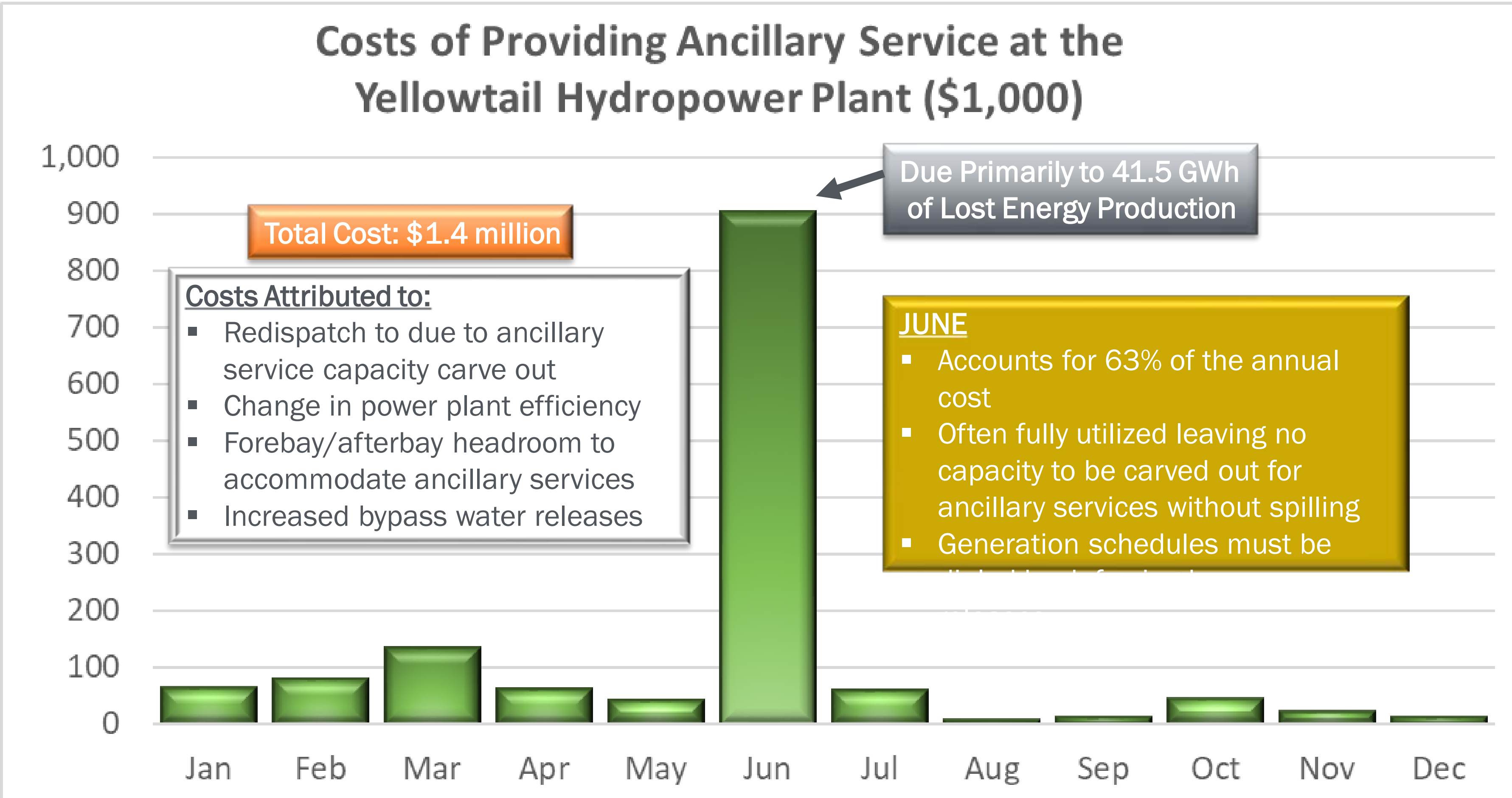
- **We estimate that energy market revenues were much greater than regulation market revenues, although hydro power contributed more to regulation as a percentage of total requirement than energy**
  - Contribution in regulation market was as high as 36% by pumped hydro and 31% by run of river, of the hourly regulation requirement (not the same hour)

Regulation	Average of Total Daily Regulation Supply (MW)	Max Cleared as a % of MISO Total Regulation Required for an Hour	Average % of MISO Daily Regulation Requirement	# of Days Supplied	Estimated Total Revenue ($)
Pumped Hydro	255	36.22%	2.45%	656	$2,384,369
Run of River	241	31.64%	2.31%	363	$1,613,101
Energy	Average of Total Daily Energy Supply (MWh)	Max Cleared as a % of MISO Total Energy Required for an Hour	Average % of MISO Daily Energy Requirement	# of Days Supplied	Estimated Total Revenue ($)
Pumped Hydro	4573	3.30%	0.25%	693	$129,589,504
Run of River	20086	2.30%	1.19%	764	$345,074,373

Energy Generation from Hydropower can be Substituted to Provide Ancillary Services

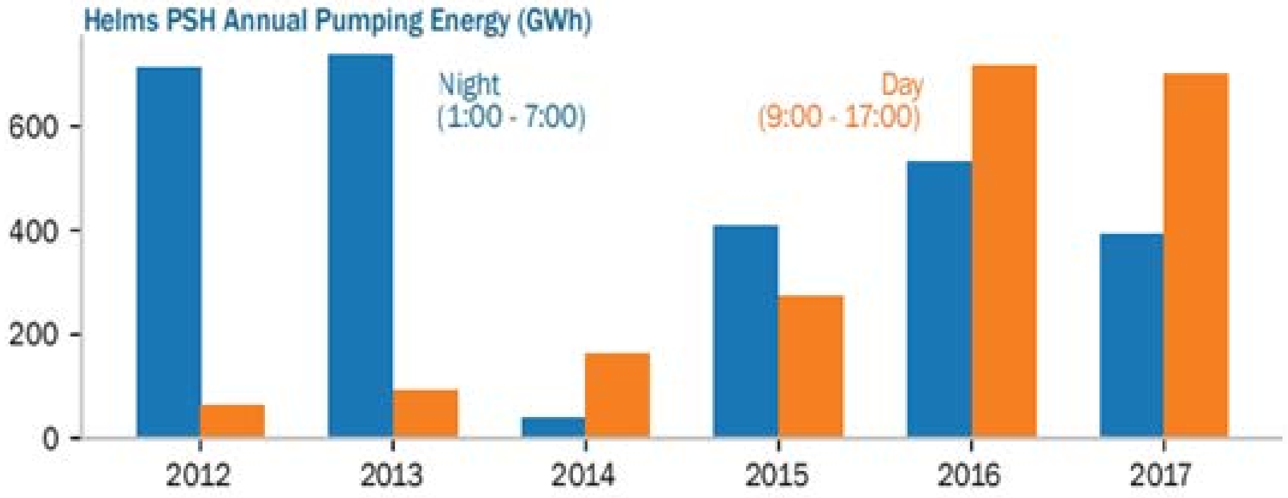


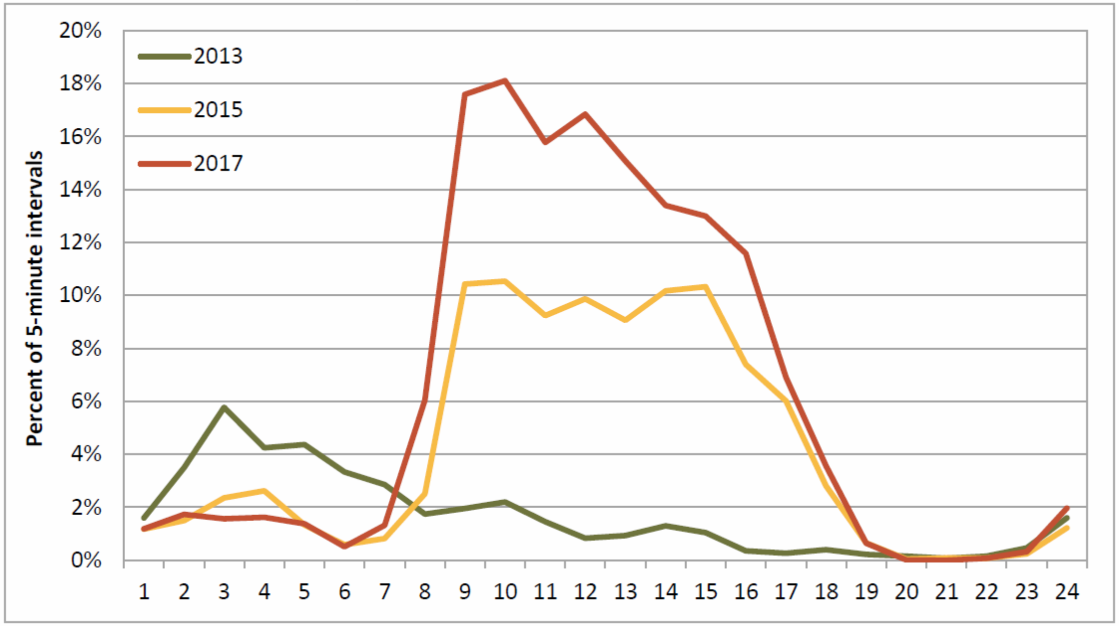
..But there are Opportunity Costs of Curtailing Hydropower



Changing Operations of PSH due to Changing Grid Conditions – CAISO Example

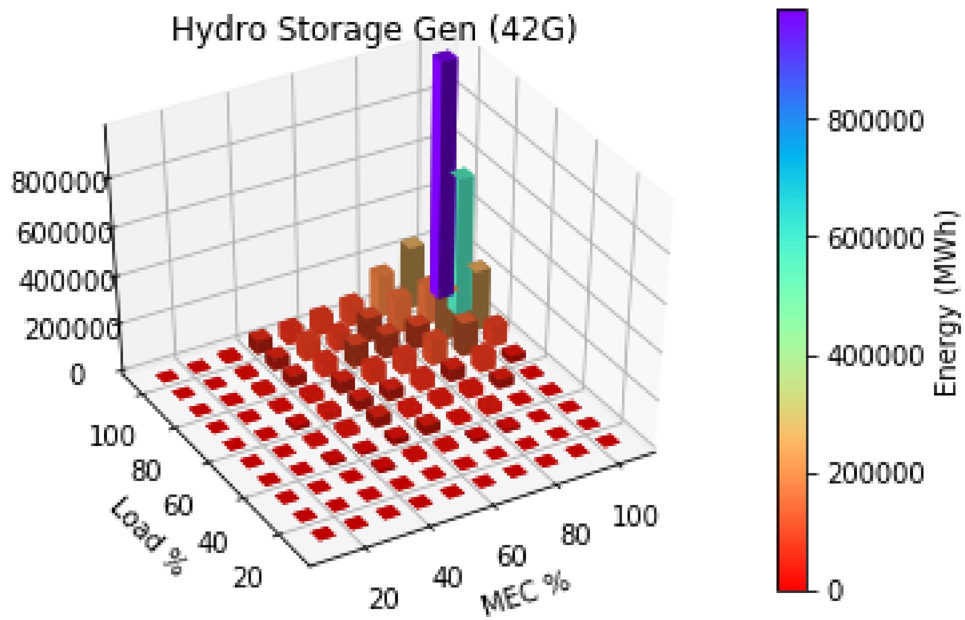
PSH conventionally operated in day-night arbitrage patterns, but the patterns are now changing presumably to provide other grid services





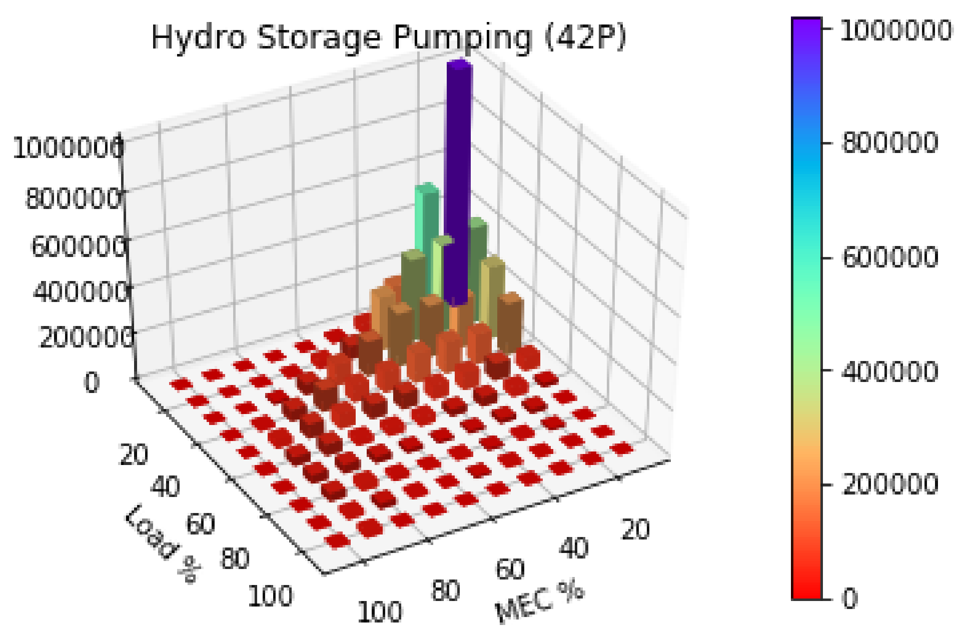
Are the increased day-time pumping operations at Helms plant due to increase in negative price during the day-time hours, corresponding to periods with high PV production?

PSH Operations in MISO are based on Arbitrage due to Load Patterns (NOT Wind)



Generation: PSH plants generate most of the times during high price periods, as expected

Pumping: PSH plants operate in pumping most of the times during low price periods, as expected



Wind is Consistently Under-scheduled Day-Ahead relative to Real-time Dispatch

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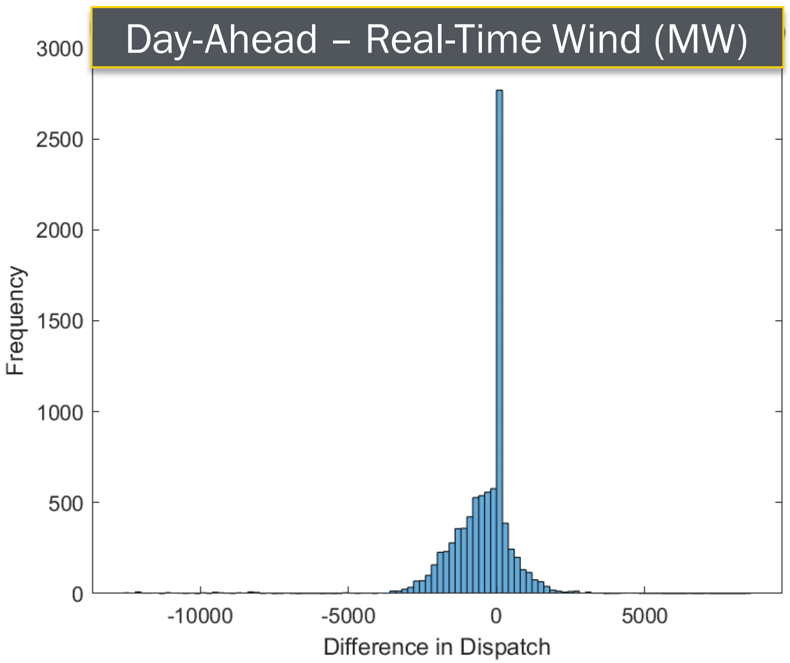
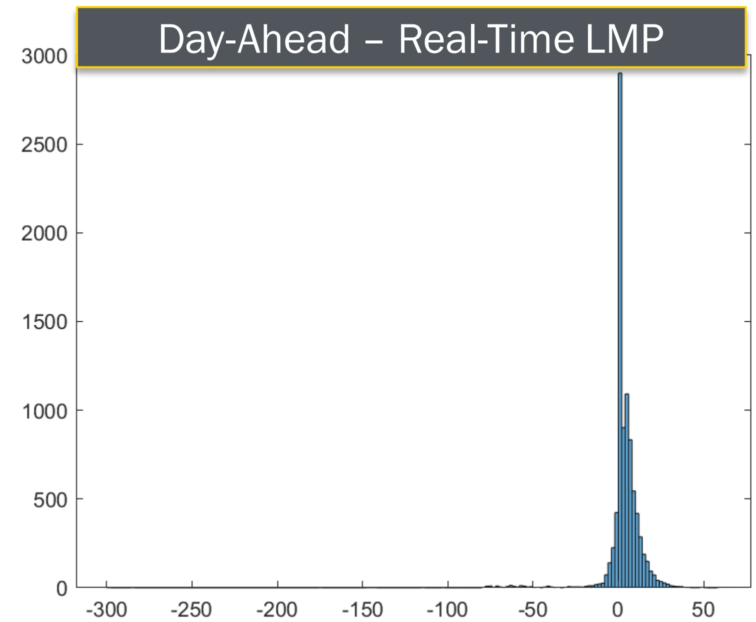
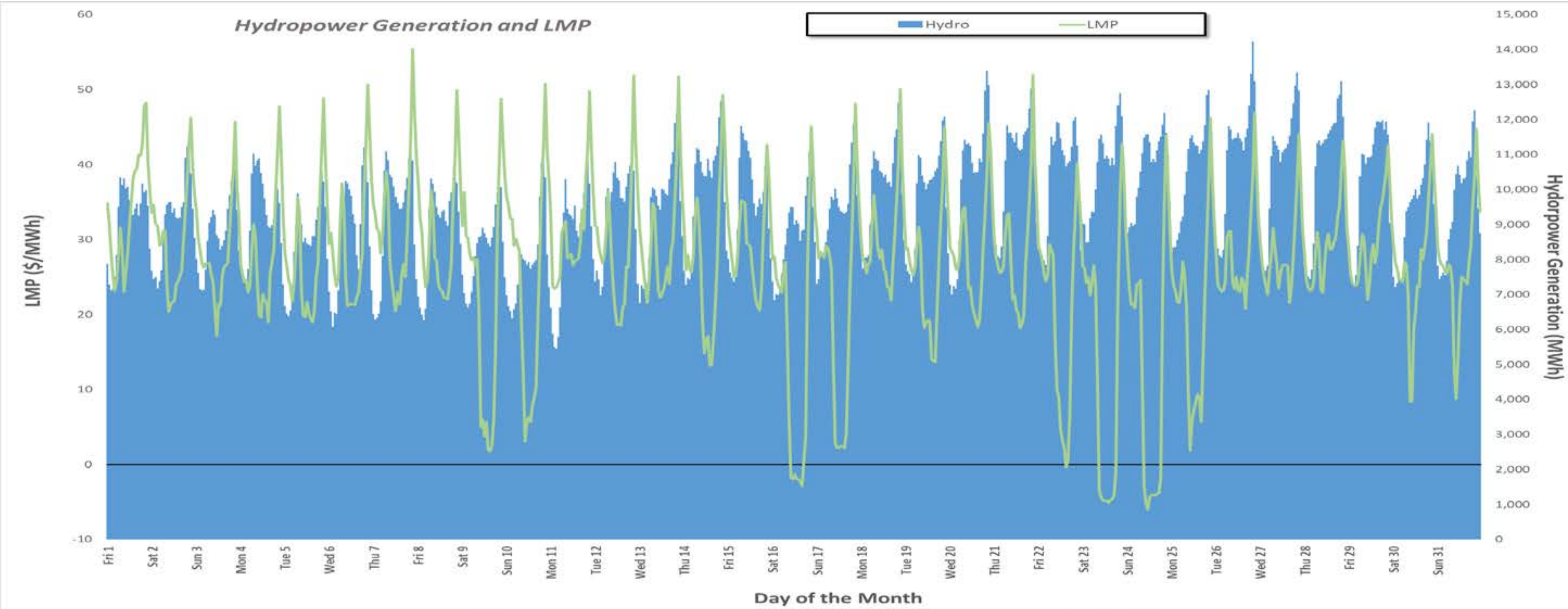
- Day-ahead schedule < Real time dispatch → under-scheduling
- Day-ahead prices > Real time prices → inter-day arbitrage opportunity
- PSH is mostly scheduled day-ahead to generate energy, while pumping load is scheduled separately
- Energy generation takes place during periods of high loads, pumping load is scheduled off-peak, but can be used to absorb excess wind





Hydropower in CAISO and BPA has historically operated in Load-Following Mode



- Existing hydropower and pumped storage systems were originally designed to operate under very different conditions, but the electricity system is changing rapidly.
- The value of hydropower's flexibility and quick response is likely to increase, but its precise future role is difficult to evaluate, likely resulting in sub-optimal designs and equipment, attrition of existing hydro resources, and stalled investments.

Provision of Reliability and Resilience Services by Hydropower : Inertial and Primary Frequency Response

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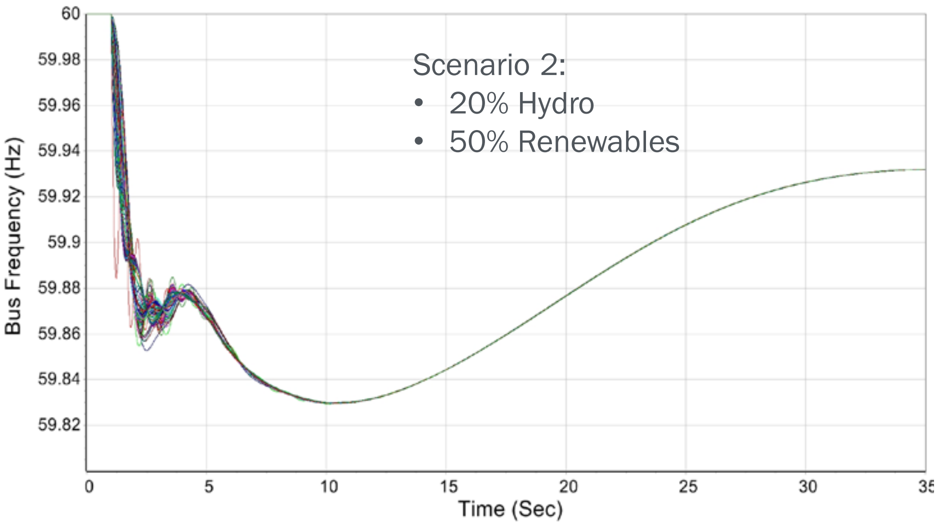
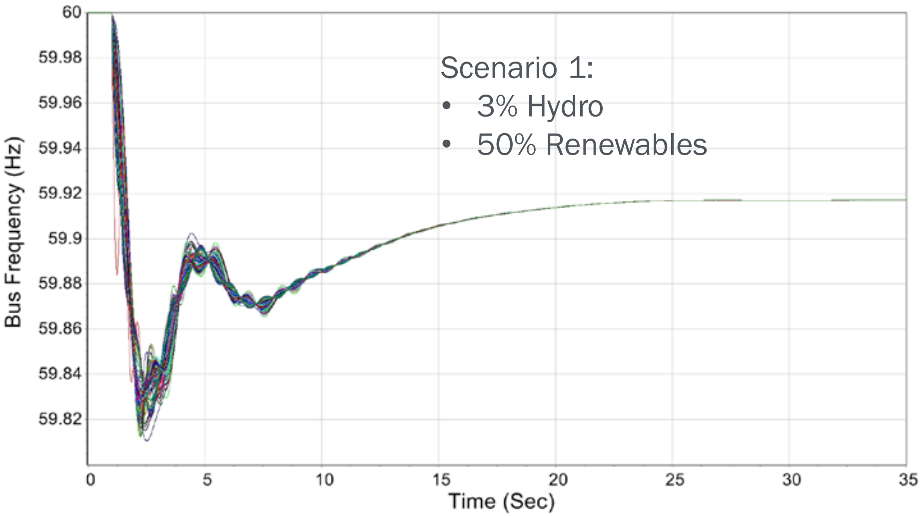
- System Characteristics: 20% Hydro and 50% VER
- Renewables are assumed to provide no governor response





Hydropower responds reliably during frequency arrestation period (0-5 sec) and during recover period (>20 sec), but can be slow to respond in the interim

FERC Order 842 (2018) will require all new resources to reserve headroom for frequency response, but the exact requirements are yet to be determined

Compensation for Fast Frequency/Primary Frequency Response

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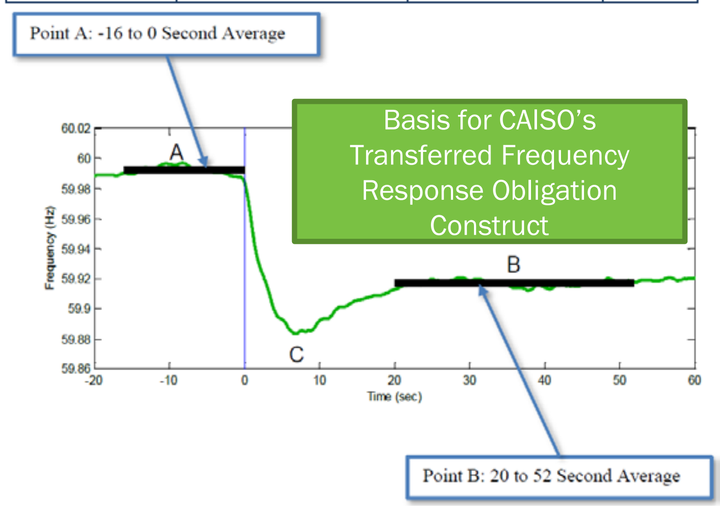
	Ireland	UK	Nordic	Quebec	South Australia	ERCOT
Monitor inertia & possible contingencies in Real-Time	✓	✓	✓	✓	✓	✓
Forecasts Inertia from DA into Real-Time	✓	✓				✓
Dynamic Assessment of Reserves based on inertia conditions and largest resource contingency		✓				✓
Limit RCC based on inertia conditions	✓	✓		✓	✓	
Synchronous Condensers (for inertia)	✓	✓			✓ (particularly looking at high inertia SCs)	
Enforce minimum inertia limit	✓	✓			✓ (for minimum inertia req.)	✓
Inertia market/auction/service inertia	✓				✓ (for above minimum inertia levels)	
Faster Responding Reserves	FFR	Enhanced Frequency Response Service		Synthetic inertia from wind	"Contingency" FFR (frequency trigger) and "Emergency" FFR (direct event detection)	Load Resources providing RRS

Planned mitigation measures are shown in blue, while already existing mitigation measures are shown in black; Source: ERCOT

NERC BAL-001 Standard: Frequency Response Measure

Table 11: Recommended Resource Contingency Protection Criteria

Interconnection	Resource Contingency	Basis	MW
Eastern	Largest Resource Event in Last 10 Years	August 4, 2007 Disturbance	4,500
Western	Largest N-2 Event	2 Palo Verde Units	2,740[46]
ERCOT	Largest N-2 Event	2 South Texas Project Units	2,750[47]



In 2016, CAISO contracted with Seattle City Light (SCL) and the Bonneville Power Administration (BPA) for provision of primary frequency response: The BPA contract transfers 50 MW/0.1 Hz of frequency regulation to BPA at a contract price of $2.22 million or $44.40 / kW-year (CAISO 2016b). More recently, CAISO has also signed a contract for provision of the service with Chelan PUD.

Reservoir Water Storage Significantly Adds to Hydropower's Value

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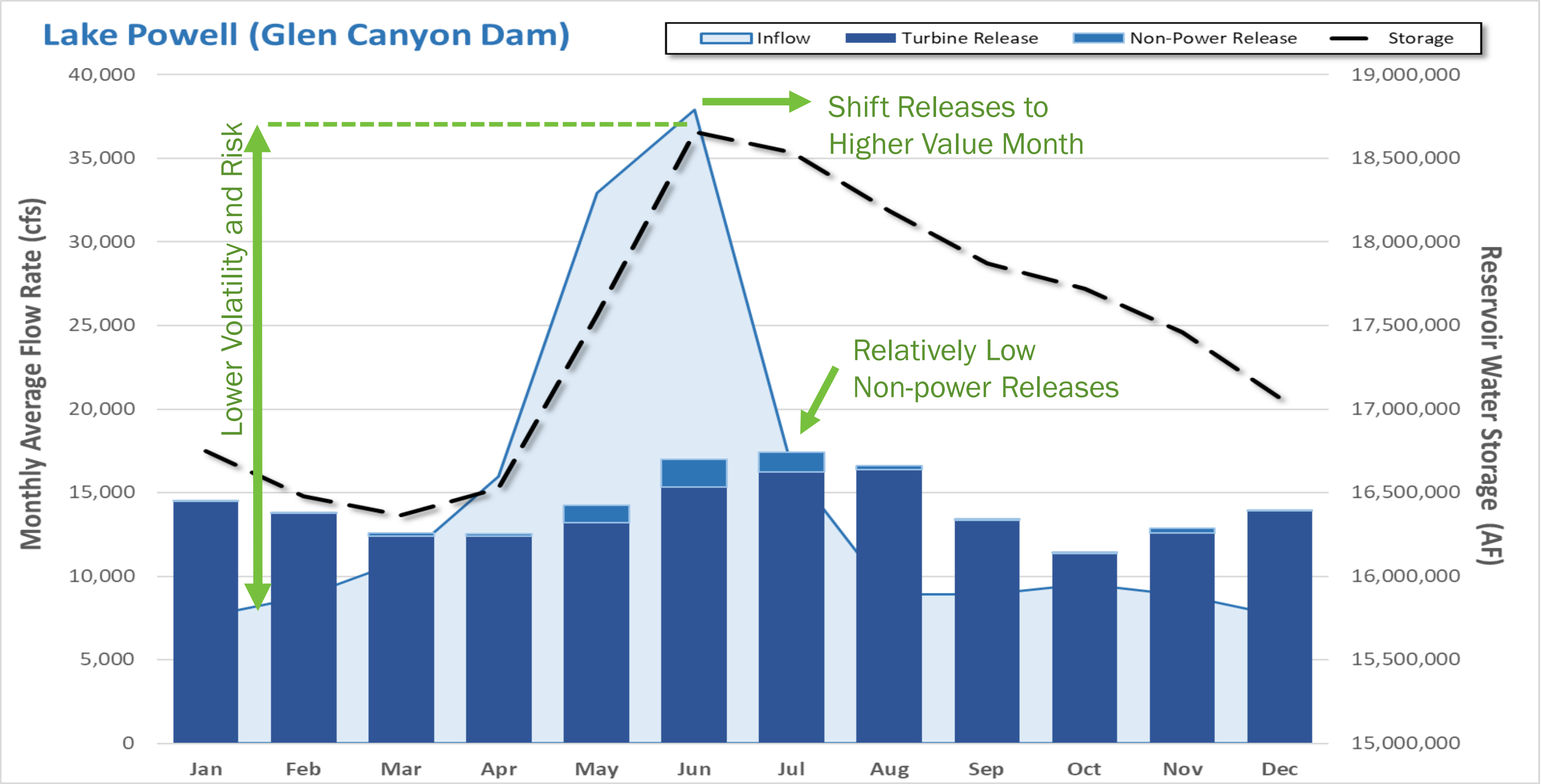
Lake Powell (Large Reservoir) – Monthly Averages (Jan 1980 – July 2018)
Full Reservoir: 26 million acre-feet of water (MAF)



Hydropower Provides Flexible Resource Adequacy Capacity in CAISO

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	Category 1 – Base Ramping	Category 2 – Peak Ramping	Category 3 – SuperPeak Ramping
Economic Bid – Must offer Obligation	5:00AM – 10:00PM	5 hour block	5 hour block
		12 PM to 5 PM for May – September 3 PM- 8 PM for January- April and October-December	
Energy Requirement	Minimum 6hrs at Effective Flexible Capacity (EFC)	Minimum 3hrs at Effective Flexible Capacity (EFC)	Minimum 3hrs at Effective Flexible Capacity (EFC)
	up and down time		
Other limitations	No limitations that translate to less than the daily requirements	No limitations that translate to less than the daily requirements	Must be capable of responding to at least 5 dispatches per month
Examples of types of resources	Conventional gas fired resources, wind, hydro, storage with long discharge capabilities	Use-limited conventional gas fired generation, solar, conventional gas fired peaking resources	Short discharge battery resource providing regulation and demand response resources

Resource type	Category 1		Category 2		Category 3	
	Average MW	Total %	Average MW	Total %	Average MW	Total %
Gas-fired generators	8,890	76%	293	25%	3	3%
Use-limited gas units	1,665	14%	819	71%	61	72%
Hydro generators	1,099	9%	47	4%	6	7%
Geothermal	28	0.2%	0	-	0	-
Energy Storage	17	0.1%	1	0.1%	15	17.6%
Total	11,700	**100%**	1,160	**100%**	85	**100%**

Multiple Factors Influence the Flexibility of Hydropower Operations

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Assessing the Flexibility Characteristics of Hydropower Resources is Complex

✓ well understood relationship, ✓possible relationship, ✓ relationship exists, not well understood

	Constraints Involved				
Multipurpose Benefits	Water Use Priorities	Min Pool Elevation	Max Pool Elevation	Minimum Flow	Flow Max Ramp Rate
M&I Water Supply	✓	✓			
Irrigation	✓	✓			
Recreation	✓		✓		
Seasonal Flood Control		✓	✓		
Navigation		✓	✓	✓	✓
Fish and Wildlife				✓	✓
Capabilities Restricted	Water Use Priorities	Min Pool Elevation	Max Pool Elevation	Minimum Flow	Flow Max Ramp Rate
Fast Cold Start Up	✓				
Flexible Power Dispatch	✓	✓	✓	✓	
Fast Ramp Rate					✓

Constraints on Hydropower Capabilities from Multipurpose Benefits

✓ well understood relationship, ✓possible relationship, ✓ relationship exists, not well understood

		Capabilities						
	Attributes	Large Inertial Constant	Reactive power control	Synch. Cond. Mode	Flexible Power Dispatch	Fast Cold Start up	Fast ramp rate	Isolated Unit Start-Up
Unit Level Design	Rated Speed	✓						
	Turbine/generator physical design parameters	✓						
	Wide efficiency band				✓			
Unit Level Technology	Air Suppression system			✓				
	Governor controls		✓	✓	✓	✓	✓	✓
	Automatic Voltage Regulator		✓	✓	✓	✓	✓	✓
Facility Level	Energy in Storage				✓			
	Water Conveyance Design				✓	✓	✓	
	Computer based controls				✓	✓	✓	
	On-site diesel generator							✓

Hydropower Attributes and Capabilities

HVS Task 3 Report:
Stephen Signore, Boualem Hadjerioua, Brennan Smith, and Patrick O'Connor, "Context, Capabilities, Constraints, and Costs for the Provision of Ancillary Services by Hydropower Assets", TO BE PUBLISHED

Evolving Operating Guidelines for the Glen Canyon Dam

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Scenario/ Power Plant	Minimum Release Rate (cfs)	Maximum Release Rate (cfs)	Maximum Daily Fluctuation (cfs/day)	Up-Ramp Rate (cfs/hr)	Down-Ramp Rate (cfs/hr)
Prior to Environmental Constraints					
Glen Canyon	1,000[a] or 3,000[c]	31,500	NR[b]	NR	NR
Interim Flow Restrictions (August 1991 through the end of January 1997)					
Glen Canyon	8,000 or 5,000[d]	20,000[e]	5,000, 6,000, or 8,000[f]	2,500	1,500
Post-ROD (after January 1997)					
Glen Canyon	8,000 or 5,000[d]	25,000[e]	5,000, 6,000, or 8,000[f]	4,000	1,500

[a] Labor Day to Easter.

[b] NR denotes no restriction.

[c] Easter to Labor Day.

[d] 8,000 (7:00 a.m.–7:00 p.m.); 5,000 (all other hours).

[e] During wet years, the maximum flow rate may be exceeded; however, flows during this time must be steady at or above 25,000 cfs.

[f] Limited to 5,000 cfs/day for months with water releases of less than 600 thousand acre-feet (TAF); 6,000 cfs/day for months with water releases of 600 TAF to 800 TAF; and 8,000 cfs/day for months with water releases greater than 800 TAF.

https://www.wapa.gov/regions/CRSP/environment/Documents/PostRODFinal.pdf

Environmental Operating Criteria Reduced Flexibility: Glen Canyon Dam

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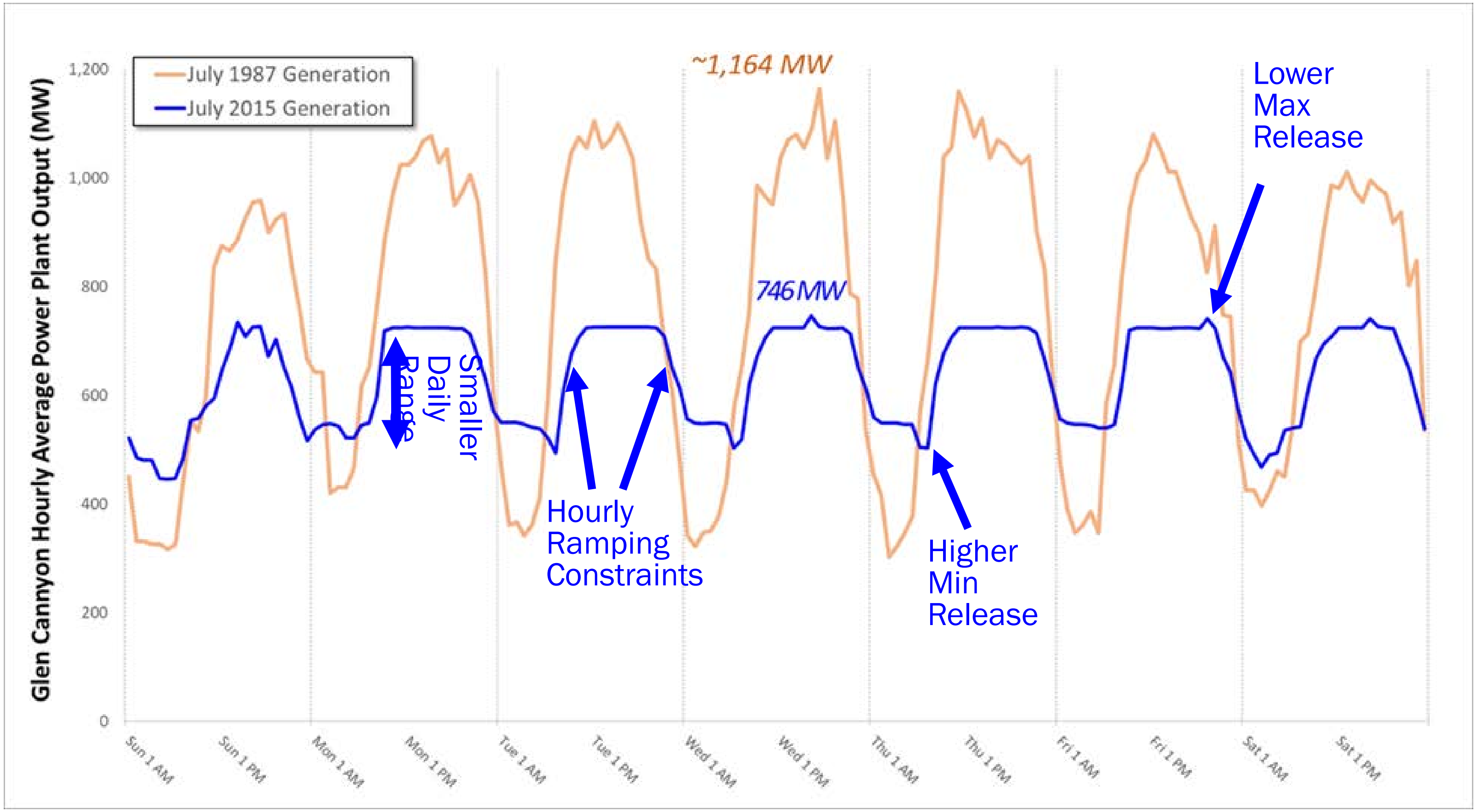

Impact of Water Availability on Flexibility of Hydropower Operations – Chelan PUD

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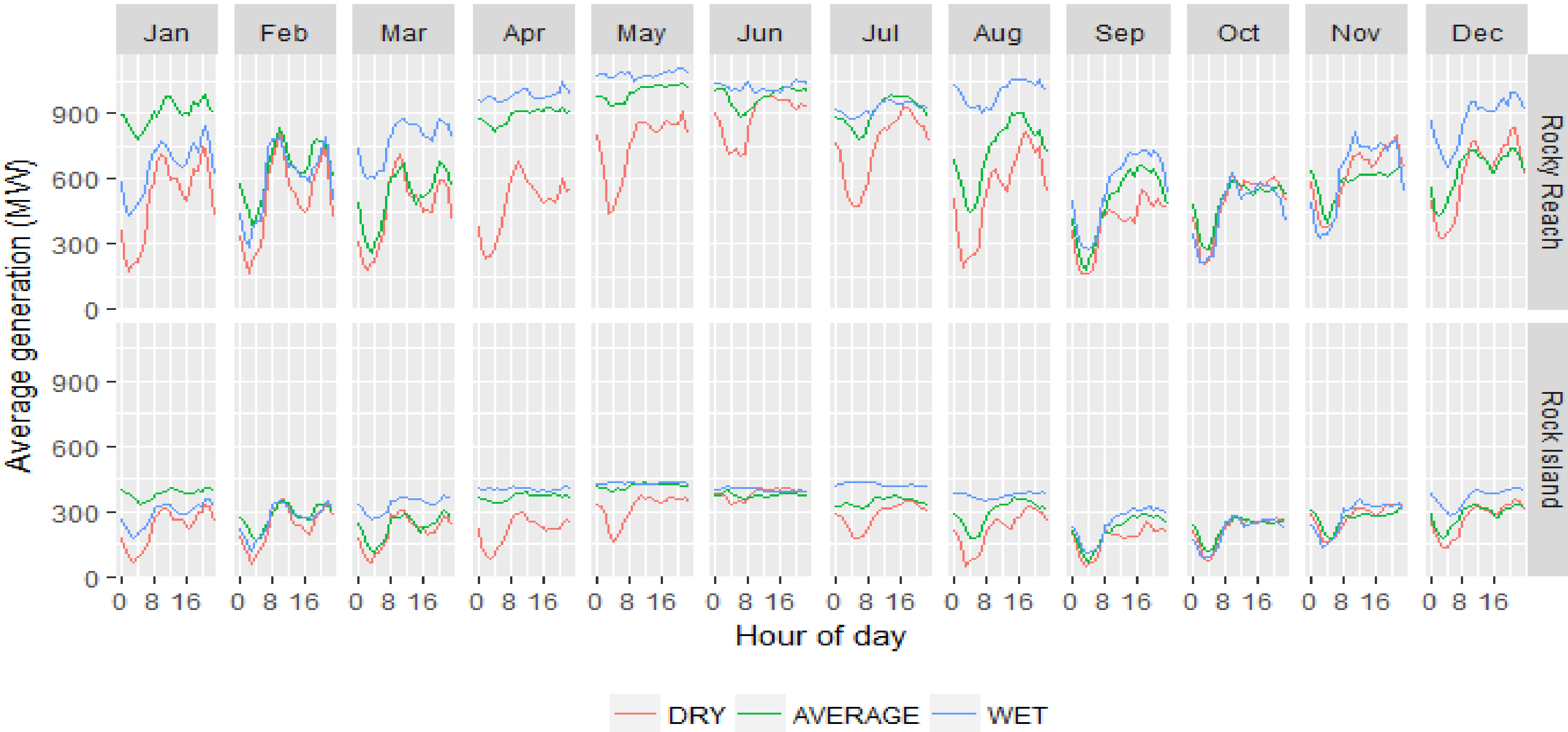

Water availability, and resultant water management issues impact operations

Hydropower Value Study Reports

- **Landscape Analysis – Historical Operations in the US:**
  - MISO, WECC, ISONE
- **Case Studies on Impacts of Water Management and Availability on Power Operations:**
  - Chelan PUD and TVA
- **Future System States: Value Drivers and Operations of Hydropower**
- **Context, Capabilities, Constraints, and Costs for the Provision of Ancillary Services by Hydropower Assets**
- **Valuing Water: Value of competing water uses and non-power benefits**

Conclusions and Additional Questions

Understanding the future role and value of hydropower will depend on the evolving future value streams:

- The nature, requirement, and value of grid services are still not well understood, and need to be examined thoroughly

The constraints and capabilities of hydropower resources are influenced by many factors – electro-mechanical, hydrological, and institutional

- The impact of each of these factors is well understood individually, but not in relation to each other; concerted efforts is needed to fully understood the impact of the combination of these factors

Conclusions and Additional Questions

Hydrological conditions influence resources' abilities to generate electricity and provide grid services.

- The operations of hydropower resources under a variety of future extreme weather scenarios need to be examined.

Changes in operational strategies, and technical and technological innovations will be necessary to operate and provide grid services in the future.

- Resources are likely to be co-operated with batteries and other storage devices, and hence, comprehensive analysis on coordinated operations needs to be performed.