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Deployment of Energy Storage to Improve Environmental Outcomes of Hydropower

White Paper

May 2021

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U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

Hydropower operators have many reasons to integrate energy storage, either co-located onsite or located elsewhere, but co-optimized with facility operations. Storage systems can be configured to have complementary performance profiles to hydropower projects, opening a broad spectrum of operational patterns.

Integrating energy storage can allow hydropower operators to accomplish the following:

- Capture additional revenue by using more agile operational characteristics for fast-response ancillary services or by generating greater amounts of peak energy with expanded operational limits.
- Adapt to changing regulatory and market conditions, such as evolution of the Energy Imbalance Market in the western United States, without pushing equipment beyond design parameters or optimal hydraulic performance.
- Improve asset management conditions by minimizing equipment wear and tear using energy storage to support fast-response ancillary services or support demands beyond optimally efficient setpoints.

An important but unexamined opportunity is to integrate energy storage systems with hydropower facilities to improve environmental outcomes. Integrated operations support increased flexibility in the management of the underlying water system and the associated ecosystem. The connections are particularly clear in modifying power generation relative to water storage, release, and flow regimes. Such integrated operations support regulatory requirements, including maintaining upstream reservoir levels, ensuring adequate downstream flows to meet an ecological target, or for human uses of a river such as fishing or boating.

This document provides an organized discussion of the relationship between hydropower-storage integration and improved localized environmental outcomes. Which includes:

- An overview and survey of current uses of energy storage in the hydropower industry.
- A comprehensive framework describing the range and type of potential localized environmental benefits realized through integrating energy storage and hydropower.
- Case study examples comparing real conditions with environmental requirements.
- Methodological guidance to analyze potential benefits, technology characteristics, and tradeoffs.
- A discussion of co-optimizing versus co-locating storage within the facility footprint.
- A concluding summary of the steps necessary for industry to fully develop and implement this concept.

This paper is a fundamental exploration of local environmental outcomes that can be realized through integration of energy storage systems with hydropower facilities. It provides a methodological foundation for future analysis rooted in expert knowledge of both hydropower–environmental interactions and attributes of energy storage technologies.

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1.0 Problem Overview

Hydroelectric dams have been operating in the United States (U.S.) for more than 100 years, and throughout this time, the range of potential environmental effects from hydroelectric dams has become well-established. As part of the periodic authorization or review of these dams, environmental effects are studied, evaluated, and in some cases mitigated. Mitigation may require investing in habitat restoration, improving river connectivity for migratory species, monitoring water quality, engaging the public, developing and implementing new technologies (hardware or software), and directly adjusting dam operations.

As dam operators balance the management of environmental impacts with maintenance of their electricity resource, new storage technologies may help to meet both needs. Most federally operated hydropower projects, as well as those operating under licenses granted by the Federal Energy Regulatory Commission (FERC), have limits on their operations to reduce environmental impacts. These limitations include spilling water outside of generating turbines, or managing flow on daily, seasonal, or yearly time scales balanced around the needs of fish and other aquatic species, reservoir levels, or downstream ecological needs. These flow management practices affect the economic viability of a given hydroelectric project by limiting its full operational flexibility. Additionally, the increase in renewable energy production has challenged the contribution of hydropower to the grid, and maintaining environmental flows mandated by FERC license requirements will become increasingly challenging (Kern et al. 2014). As storage technologies advance and become commercially available at utility-grade, grid-scale, and cost-effective levels there is a new opportunity to imagine how they can integrate with hydroelectric operations to support the larger electrical grid, while maintaining financial stability and improving environmental outcomes.

This paper describes how the installation of energy storage systems, co-sited with hydroelectric projects, offer operational, economic, and environmental benefits by enabling a broader range of electricity performance, capitalizing on its flexibility and grid reliability, while mitigating critical environmental impacts or improving environmental outcomes across U.S. rivers and streams. The paper attempts to link environmental outcomes to energy storage utilization. It offers a comprehensive inventory of research-grade work, site-specific studies, policies, and pilot projects regarding energy storage and hydropower that show significant environmental implications. It provides an outline of methodologies given the known costs and attributes of storage technologies, with case study illustrations. It also outlines the key components of a methodology that could be applied within the context of specific projects to reveal the environmental benefits of energy storage paired with hydropower production to properly size the storage systems to capitalize on potential benefits.

This paper provides a framework for assessing the degree to which energy storage can support operational strategies to improve environmental objectives, including where flow releases or other operational changes are provided to match a water quality, fish, or other ecological objective. Factors driving the integration of hydropower and energy storage will be site-specific, and include combinations of operational, maintenance, economic, and environmental considerations. The focus of this paper will strongly support the validity of the environmental approach. A set of knowledge gaps to be addressed in future work is provided. To validate and support the information provided in this paper, further analysis will be required on a physical facility to serve as a test case.

2.0 Current Use of Energy Storage by the Hydropower Industry

Hydroelectric plants currently offer energy storage due to the presence of water reservoirs, but to increase storage, operators have at times considered batteries to be a competitive resource. Energy storage could be accomplished by expanding the impoundment and raising the height of a dam; however, raising dam height introduces a host of civil engineering requirements, costs, and timelines, as well as regulatory authorizations, and doing so would inundate new lands. Despite these challenges, dam-raising efforts are being considered.[1] In contrast, energy storage systems can be installed in as little as 6 months, when physical space, electrical infrastructure, and construction permits are readily available (Pyper 2017). Larger reservoirs offer similar characteristics of storage that are already available; energy storage systems can offer a complementary capability rather than an expansion of existing flexibility.

As batteries become more reliable and efficient, an emerging idea is to directly integrate batteries with hydroelectric plants and hybridize their operations for overall improved plant performance. To date this idea has been explored for power flexibility benefits or market participation eligibility, such as provision of ancillary services, market eligibility as a fast-responding resource, or improved operational integration across cascading plants. Many energy storage systems are sited at utility infrastructure based on reliability, or distribution or transmission requirements. The appropriateness of whether to co-site or to co-optimize storage systems with hydroelectric plants, given ownership model, revenue mechanism, and grid operation conditions, is discussed in a later section.

Examples of power flexibility achieved by incorporating different types of storage on-site at hydroelectric plants, either simulated or actual, are provided below.

- In Sweden, Fortum has connected a 5 MW battery system to a 44 MW hydropower plant to improve its quick response time and the precision of its regulation service, because wind power has created the need for increased flexibility. The site has also asserted that the battery helps to keep the market in balance and reduces wear on hydropower turbines, allowing for deferral of investment in maintenance or replacement (Hydro Review 2018).
- The Buck and Bullesby power plants owned by AEP in southwestern Virginia have installed a 4 MW battery system. The system is used to reduce peaking in the older hydropower plants and increase the value of frequency regulation in the PJM market. This allows AEP to leverage and enhance revenue by providing regulation services and offset the charges that customers incur.
- Idaho Falls Power has also implemented a black start field demonstration to show that run-of-river hydropower plants with energy storage can restore electric power without assistance from the transmission system. This capability is essential for small hydropower facilities to be able to operate a microgrid to power critical loads in the event of an outage.[2]

[1] San Vincente Dam in San Diego was raised more than 100 ft in 2012. See https://www.water-technology.net/projects/san-vicente-dam-raise-san-diego-california-us/. The Bureau of Reclamation intends to raise Shasta Dam in California by 18.5 ft. The project is currently in pre-construction. See https://www.usbr.gov/mp/ncao/shasta-enlargement.html.
[2] See the “Integrated” project, which explores the energy benefits to hydropower when paired with energy storage technology: https://factsheets.inl.gov/FactSheets/Integrating%20Hydropower.pdf.

- Other examples include the Cordova Electric Cooperative 1 MW battery and Kodiak Electric Association's 3 MW batteries. Both sites coordinate battery operations with small-scale hydropower to support small grids in Alaska. In Cordova, the battery system is designed to support a microgrid in the event of an outage due to harsh weather and avoid spill during dynamic seasonal loads. Kodiak aims to achieve reliability from an increase in the use of wind generation to support their microgrid, while reducing rates for customers with their two-battery system.
- Douglas County Public Utility District announced their intention to construct a 5 MW hydrogen electrolysis pilot project at its Wells Dam on the Columbia River (Shumkov 2020).
- In January 2020, Brookfield Renewable proposed an energy storage project at two of their hydro facilities along the Penobscot River—the Penobscot Mills and Ripogenus projects. Each project consists of a 10 MW, 20 MWh on-site system, which would be permitted under existing interconnection agreements. The batteries would allow the continued operation of the hydroelectric facilities during periods of high congestion and would have no impact on the operation or maintenance of the projects.[1]

It is clear from the examples above and the direction of the international industry that operational flexibility and asset management are the driving factors for hybridization of storage and hydroelectric plants. Even emerging "clean peak" policies such as Massachusetts' new Clean Peak Standard require hybridization of storage on clean energy projects to qualify for special treatment and remuneration, based on the premise that this additional flexibility is necessary to meet reliable system operations and clean energy goals.[2] [3] Additional power benefits for energy storage installations are yet to be analyzed, to the authors' knowledge. For example, storage systems could replace end-of-life small hydropower turbines to support station service at large plants.

3.0 A Novel Energy Storage Use Case: Environmental Benefits

This white paper posits that an additional class of benefits is derived from co-siting storage systems with hydroelectric plants—environmental benefits. As noted above, storage can improve the range of operational flexibility. Regardless of the primary investment driver, local environmental management is an essential part of the operational equation. Once hydropower plant operators install storage systems, the projects may operate differently to manage environmental constraints. Whether optimization occurs as an investment, regulatory, or planning tool, or after the fact as a new operational regime implemented from storage-integrated operations, improved environmental outcomes are possible with the installation of expanded on-site storage. New techniques such as advancements in multi-objective optimization of hydropower funded by the National Science Foundation (Roy et al. 2018) and

[1] FERC Project No. 2458-214 – Penobscot Mills Project, Great Lakes Hydro, LLC; FERC Project No. 2572 – Ripogenus Project, Great Lakes Hydro, LLC.
[2] Arizona, California, North Carolina, and New York have explored clean peak standards without success in implementation. Michigan has explored a "low-cost peak program," which would require renewable energy generation to be paired with energy storage.
[3] See the Low Impact Hydropower Institute's webinar with experts discussing how this standard may affect operational and economic outcomes for hydropower plants: https://lowimpacthydro.org/massachusetts-clean-peak-standard/.

data-rich demonstrations are needed to fully evaluate the flexibility and environmental opportunities.

The nexus between environmental objectives and operational flexibility is well-established, and research continues to define these relationships.[1] A short list of operational changes to improve environmental outcomes, depending on site-specific operational and structural configurations, includes discharge ramping rates, minimum flows, reservoir levels, downstream and upstream temperature, dissolved gases (too much or too little), turbine loading patterns, as well as recreational management, boating flows, fish passage, flood control, irrigation, and other uses of the river. How could batteries or comparable energy storage technologies permit a win-win opportunity—operational flexibility and environmental improvements?

Examples of direct advocacy for energy storage installation for environmental outcomes, under discussion in two open FERC proceedings exist, as indicated in the case studies highlighted below.

3.1 Case Study: Connecticut River Conservancy and Great River Hydro's Vernon Dam (White et al. 2020)

The Connecticut River Conservancy contracted a study with Synapse Energy Economics in February 2020 to analyze the potential for the Vernon Dam hydroelectric plant (P-1904), owned by Great River Hydro, to be re-operated in a run-of-river mode and paired with a 10 MW, 2 hr battery storage system. The researchers aimed to determine the energy market revenue impacts of transitioning Vernon Dam to run-of-river operations while quantifying the value of installing an integrated battery storage system to capture a portion of peak energy prices.

The researchers found that a transition to run-of-river operations would moderately affect energy market revenues by 3 to 10 percent, while the other revenue streams (capacity, ancillary services, and renewable energy credits) would have little to no impact. It may be necessary, however, to relax true run-of-river operations during peak-load hours to maintain capacity values (and thus capacity revenues). Energy price arbitrage can be leveraged by charging batteries from turbines during periods of low energy prices and discharging power during periods of high energy prices. As New England increases its renewable energy levels, price volatility may increase, increasing the value of energy arbitrage. The cost range of the 10 MW proposed storage system was determined to be $4.9 to $9.8 million—a cost-effective investment at the lower end of the range, but a loss at the higher end.

With five hydropower plants along the Connecticut River in Massachusetts, New Hampshire, and Vermont applying for new licenses, this case study illustrates the potential for battery storage to offset revenues if peak operating plants convert to run-of-river operations. The results of this case study have been provided to the applicants for their consideration and submitted to the FERC docket as an alternative scenario opportunity.

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[1] See U.S. DOE HydroWIRES grant to the Electric Power Research Institute to *Quantify Hydropower Capabilities for Operational Flexibility*: https://www.energy.gov/articles/doe-announces-249-million-funding-selections-advance-hydropower-and-water-technologies

3.2 Case Study: Alabama Rivers Alliance and Alabama Power's Harris Project[1]

One emerging case study with a goal of reducing hydropower peaking to reduce the impact of unnatural flows on the Tallapoosa River's ecosystem may begin to explain the potential environmental benefits of adding a battery and allowing greater flexibility to meet electrical demand. In June 2020, Alabama Rivers Alliance advocated for Alabama Power to conduct studies of downstream release alternatives and battery storage integration at the Harris Project (FERC #P-2628) on the Tallapoosa River. Current operations include discharge variations, occurring within a few hours' time, from zero to about 16,000 cubic feet per second (cfs) when both turbines are operating. FERC proceedings regarding downstream release alternatives included comments from FERC staff, Alabama Rivers Alliance, and the U.S. Environmental Protection Agency, each recommending specific study scenarios. Alabama Rivers Alliance requested a study to compare models simulating the release of the natural flow variability of the Tallapoosa River compared to several alternative operations scenarios. Simulation of "natural flows" will ultimately not occur, but the alternative scenarios to be studied will include (1) the current operation plan ("Green Plan," designed to reduce effects from peaking operations on the aquatic community), (2) the project's historical peaking operation, (3) a modified current operation plan, (4) a downstream continuous minimum flow of 150 cfs under the historical peaking operation scenario, and (5) six other operations scenarios including minimum flows of 300, 600, and 800 cfs; a derivation of the "Green Plan;" and two other scenarios resulting from an addition of a battery energy system.

Alabama Rivers Alliance requested that a new study be conducted by Alabama Power titled "Battery Storage Feasibility Study to Retain Full Peaking Capabilities While Mitigating Hydropeaking Impacts." This study would determine whether a battery storage system could be economically integrated at the Harris Project to provide power during peak demand periods—decreasing the need for peak generation flow released and reducing flow fluctuations downstream—by evaluating battery type, size, costs, ownership options, and barriers to implementation. In their response, FERC described the potential benefits of adding a battery energy system to include reducing the fluctuations in the reservoir by half, reducing peak flows from 16,000 to 8,000 cfs, and achieving the ability to release flows throughout the day and night versus only during peak demand hours. Alabama Power initially rejected the study, citing the high costs of battery storage systems and turbines that are not designed to operate gradually over an extended period. Using a 2018 National Renewable Energy Laboratory report (DOE 2018), Alabama Power estimated the cost of a 60 MW, 1 hr battery (the equivalent to power one turbine at the site) to be $36 million, with a combined cost for both turbines of $72 million. FERC further noted that a 4 hr 60 MW battery, costing $91 million may be needed because Harris Dam can generate for up to 4 hr. FERC recommended that the company conduct the battery storage feasibility study to include (1) a 50 percent reduction in peak releases associated with installing one 60 MW battery unit, and (2) a smaller reduction in peak releases associated with installing a smaller MW battery unit (i.e., 5, 10, 20 MW), including cost estimates. The study will be conducted through April 2021 and will be used to assess the project impacts on downstream resources including aquatic species, erosion, water quality, terrestrial resources, and recreation.

[1] Project No. 2628-065 – Alabama R.L Harris Hydroelectric Project, Alabama Power Company.

4.0 Environmental Benefits Associated with Increased Operational Flexibility

An initial framework of relationships between storage and environmental outcomes is provided in Table 1. Although the issue categories in the table are not mutually exclusive, they begin to elucidate the potential environmental improvements that pairing energy storage with hydropower may provide. Future work would further characterize these examples and conduct a more thorough review of potential environmental gains derived from augmenting hydropower with energy storage technologies.

Adding a storage system to a facility would allow owners flexibility in generation, by breaking the tie between river flows and fluctuating power demands. Site-specific conditions, location, and regulations will dictate the magnitude and type of environmental outcome that may be realized. Table 1 discusses the potential improvements and is not intended to be all-inclusive, nor are all benefits applicable to every unique case.

Table 1. Taxonomy of potential environmental benefits from pairing hydropower with energy storage.

Issue Category	Desired Positive Environmental Outcome	Change in Operation with Energy Storage	Knowledge Gaps
Fisheries	Release flows that are more similar to the historic hydrograph (e.g., run-of-river) that includes cues used by fish for spawning, rearing, migration, etc.; reduce fish-stranding mortality.	Maintain operations and absorption of energy to permit a higher (or lower) release of flows.	Characterize the duration and intensity of flows and turbine operations/energy generation in relation to fish behavioral cues and survival relationships.
	Allow historical seasonal peak flows to enable fish spawning.	Reduce wear-and-tear on components through steady operation during fluctuating generation and release requirements.	Determine sizing and controls between energy storage and turbine units to integrate operations.
	Foster safe passage through hydropower infrastructure.	Allow spill for downstream passage to maintain the same electricity production; offset efficiency losses from fish screens.	Optimize storage capacity, state-of-charge, duration, degradation, and efficiency.
Water Quality	Reduce supersaturated total dissolved gas (TDG) levels.	Support more advantageous release schedules and reservoir management, absorption of energy if released through turbines under oversupply conditions.	Potentially improve TDG throughout a cascading hydropower system with new operations and energy storage flexibility?

Issue Category	Desired Positive Environmental Outcome	Change in Operation with Energy Storage	Knowledge Gaps
	Optimize dissolved oxygen.	Allow oxygen injection to be combined with turbine operation and releases through absorption of energy or support more advantageous release schedules.	Potentially improve dissolved oxygen with new operations and storage flexibility?
	Allow for improved temperature regimes.	Enable temperature control via locally powered reservoir control structure to manage downstream temperatures where seasonally stratified reservoirs are present.	Explore added flexibility of batteries and hydro operations to control temperature.
	Reduce unwanted nitrogen/phosphorous contributions to algal blooms.	Use energy storage system to allow spill variation in reservoir levels; local energy could be used for removing nutrients from water.	Understand the impacts of alternative operations on the ability to control nutrient levels.
Flows	Reduce intensity of peaking flows and up and/or down ramping rates.	Charge energy device in advance of peak flows to increase the responsiveness of the project to signal and shave flow releases to lower ramp rates.	Measurably improve environmental resources through changes in intensity and ramping that are possible with storage integration?
	Maintain minimum flows (varied by season or otherwise as specified).	Permit cost-effective decrement in flows and generation with releases not timed to match electricity demand.	Acquire new environmental benefits when minimum flows are more easily obtained as well as make valuation possible to allow new environmental markets?
	Enable bypass reach flows.	Allow maintenance of revenues during flow releases in the bypass.	Support releases for non-power flows?

4.1 Reducing Hydro Peaking

Hydropeaking and load following operation modes, whereby pulses of water are released in rapid response to meet changes in electrical demand, can alter the quantity, quality, and accessibility of downstream aquatic habitats (Clarke et al. 2008; Fisk et al. 2013). Depending on their timing, frequency, duration, and magnitude, discharge fluctuations can have adverse effects on stream fishes and other aquatic life (Young et al. 2011). Discharge fluctuations during the period of fish spawning may cause adult fish to abandon nests or alter spawning site selection (Chapman et al. 1986; Auer 1996; Zhong and Power 1996; Geist et al. 2008). Fluctuations in discharge that occur shortly after the spawning period can dewater nests, resulting in mortality of eggs and larval fish (Becker et al. 1982; McMichael et al. 2005; Fisk et al. 2013). Discharge fluctuations that occur during the early rearing stage can strand fish along changing channel margins or entrap them in isolated pockets of water (Cushman 1985; Halleraker et al. 2003; Connor and Pflug 2004; Nagrodski et al. 2012). Repeated, rapid fluctuations in discharge may also negatively affect downstream fishes indirectly by altering the density, biomass, and diversity of their food supply (Cushman 1985; Gislason 1985; Bunn and Arthington 2002), which can reduce fish growth as well as the biological productivity of the ecosystem. Reductions in spawning success, survival, and growth have the potential to reduce the productivity of populations that reside downstream of hydroelectric projects (Harnish et al. 2014).

Co-sited energy storage may enable a hydropower facility to meet system peaking needs, provided that state-of-charge control is aligned with the peaks, without releasing such significant water volumes downriver. Thus, energy storage systems would decrease peak generation flow releases, thereby reducing flow fluctuations downstream of the hydroelectric project—and ultimately, lowering the potential impacts on threatened fish and other organisms using the river habitat. Response times are also much faster when using batteries and power factors of 0.0 are supported, so more than just maintained but *improved* power system benefits (i.e., energy and ancillary services) may be achievable along with environmental improvements.

4.2 Securing Safe Fish Passage through Hydro Infrastructure

In addition to fish populations experiencing the effects of hydropower operations downstream of dams, fish migrating in a downstream direction may sustain injury or death while passing hydroelectric dams. At many hydroelectric dams, downstream migrants can pass via several different routes (e.g., spillways, turbines); however, passage through turbines is generally associated with the highest mortality rate (Muir et al. 2001). At some hydroelectric projects, operations have been altered to deliberately release water through spillways to direct downstream migrants from the turbines to the spillway to increase dam passage survival. Many species display differences in depth distribution and/or migratory activity throughout the daily cycle, which can alter their probability of turbine or spillway passage (Haro et al. 2000; Li et al. 2015). Therefore, energy storage systems, instead of the hydropower turbine, could be used to provide power when needed, allowing more water to be spilled during periods of peak fish passage or times when turbine passage rates are expected to be high. For example, salmon and steelhead smolts are more likely to pass through the powerhouses of Snake River dams at night than during the day due to a diel shift in depth distribution. Approximately 60 MW of stored power exported for 4 hr nightly could reduce powerhouse passage of Snake River Chinook salmon smolts by 12 to 23 percent over the entire summer passage season, thereby increasing survival significantly. Added flexibility of spill operations, and in turn, improved fish survival, may help hydropower operators further improve fish survival and reduce mitigation costs (e.g., mid-Columbia River No-Net-Impact funds).

Fish passage is not limited to spillways or downstream travel. Spill for upstream migration (i.e., fish ladders) can account for 10 percent of the flow rate, resulting in lost power generation potential. Noting that attraction flows to fish ladders need not spill constantly, the seasonality and perhaps even time of day of fish migration activity can allow for banking of energy benefits through energy storage, which can then be exported when spills do need to flow in correlation with fish activity.

A facility may also operate under specific flow rates for fish spawning benefits, which may require spilling water that cannot be used to generate electricity and may lower the annual energy production of a hydropower facility. However, just as spawning does not happen through all seasons and at all hours of the day, water can be released when needed for environmental benefit and the restriction may be relaxed at other times, thereby allowing a net energy production increase. When the timing of energy increases does not align with power system needs, there is an opportunity for energy storage systems to shift the available energy and make use of the surplus.

4.3 Operational Shifts and Requirements for Fish in the Eastern U.S.

In addition to operational shifts and flow management for western U.S. fish (in particular salmon) as indicated above, eastern U.S. hydropower plants also adjust operations for fisheries including resident, anadromous (e.g., American shad), and catadromous (e.g., American eel) fish. We discuss examples below related to fish specifically, because fish are often the driving factor of dam operational changes; however, we understand that many other aquatic species (e.g., mussels) as well as aquatic ecosystem health benefits are gained from these operational changes.

Operational shifts to ensure safe fish passage through hydropower plants is a precedented activity dating back to the early 1900s—particularly in the northeastern U.S., where migratory anadromous and catadromous fish use rivers highly developed with hydropower projects. For example:

- The Holtwood Hydroelectric Project on the Susquehanna River in Pennsylvania uses a tailrace lift with two entrances and a spillway lift for upstream fish passage and a pipe system for downstream fish passage.
- The York Haven Dam, also on the Susquehanna, uses a vertical slot fishway to support upstream passage of anadromous fish, primarily American Shad.
- In Maine, along the Penobscot River, the Milford Hydroelectric Project uses a 4 ft by 4 ft bottom entrance for American eels to pass through the dams slowed to 70 cfs into the plunge pool and an upstream fish lift capable of passing up to 300 cfs.
- The Orono Hydroelectric Project uses a similar system with an 8 ft wide downstream diadromous fish-passage floor screen chamber into the plunge pool and a lower-level 4 ft by 4 ft entrance designed to pass at 150 cfs.
- The Holyoke Dam, on the Connecticut River, uses two elevator fish lifts that carry migrating fish, including American Shad, Sea Lamprey, Atlantic Salmon, and American eel, up and over the dam.

In these cases, operational flows are altered to meet fish-passage needs. Storage augmentation at these facilities could allow increased flexibility to meet both the electrical demands of the grid as well as the site-specific fish-passage requirements.

4.4 Managing Spill for Habitat Benefit

Habitat benefits for the aquatic ecosystem as a whole may also extend to spill. Many river ecosystems rely on sediment that passes downstream in the absence of dams. Sandbars have been depleted by long-term dam presence, to the detriment of endangered species on the Colorado and Missouri Rivers. The Department of the Interior has shown success in rebuilding sandbars through controlled flood operations through the Glen Canyon Dam since 2012 (USGS 2015). Energy storage may enable a means for making up for some of the lost energy value associated with controlled flood events, or even increase their frequency to maximize the habitat benefit.

4.5 Preserving River Flows to Improve Water Temperature and Dissolved Gases

River water temperatures directly affect aquatic ecosystem health, and energy storage may allow more flexible operation to control downstream temperatures for environmental benefits. Extreme high temperatures, such as those that occurred in 2015 in the Columbia River, were associated with significant salmon and sturgeon fatalities;[1] in these situations, water temperatures may be able to be cooled by further operational flexibility at hydropower dams to release deeper and cooler hypolimnetic waters. Conversely, unnaturally cold water temperatures, such as in a dam tailrace when a thermally stratified reservoir releases the colder/deeper water through deep-draw turbines or spill, can also have detrimental effects such as creating unnatural temperatures that may allow, for example, an invasive species to increase predation on native warmwater fishes (Ward and Bonar 2003). To keep temperatures within acceptable ranges, the added operational flexibility that batteries paired with hydropower may provide could allow hydropower operators to be more selective about mixing upper warmer waters (using surface spillways) with deeper cooler waters (using deep-draw turbines or deep spill).

Similarly, oxygen and/or total dissolved gas (TDG) levels can be directly affected by hydropower operations to the detriment of fish and the larger ecosystem. For example, in the Coosa River in Alabama, low oxygen levels in tailrace waters are directly linked to operation of the turbines drawing low-oxygen water from deep water, which ultimately negatively affected ecosystem health and resulted in the operator's FERC licenses being vacated.[2] High dissolved gas levels above 100 percent also have detrimental effects on aquatic organisms. Dissolved gas levels above 110 percent can cause fish to lose their ability to sense (hear) encroaching predators (Weber and Schiewe 1976), and increasing gas concentrations up to 130 percent result in high mortality of some species (Mesa et al. 2000). An energy storage device may provide additional flexibility for hydropower generators to adjust operations as a function of oxygen/TDG level, or to allow some degree of spill from a considerable elevation to restore oxygen content. Operations to control dissolved oxygen and/or TDGs occur throughout the U.S., but, to our knowledge, the ability of batteries to improve the environmental outcomes has not yet been evaluated.

5.0 Considerations for Studying Storage Applications for Environmental Outcomes

Given the potential benefits, what is the best approach to determining whether a storage device could allow for operational changes that offer environmental benefits at hydropower projects?

[1] https://www.nwcouncil.org/news/warm-water-wreaks-havoc-columbia-river-fish
[2] https://www.gadsdentimes.com/news/20180827/alabama-power-loses-coosa-river-dam-licenses

This paper highlights key components of a *conceptual* methodology to evaluate potential environmental benefits of deploying storage systems in cooperation with hydropower facilities. The following example shows how the deployment of energy storage at a peaking hydropower facility can yield win-win outcomes, i.e., maintain the power generation requirement, while simultaneously allowing for less severe changes in water flows.

5.1 Conceptual Example to Illustrate How Storage May Be Used to Enhance Environmental Benefits for a Peaking Hydropower Plant

Figure 1 presents a stylized example of a utility that operates its hydropower plant to maximize generation during the morning and afternoon peaking periods. In this example, it is assumed that plant operations reach the upper limit of available water (ramp up in water flow – cubic feet per second per hour [cfs/hr]), which is required to ramp up power generation. With the addition of a storage system, plant operators can employ alternative operational strategies, in general charging the storage system when fuel (water) is available and operations are more flexible, and discharging electricity during peak hours or when operational and water (storage) limitations have been reached. Such a strategy could allow the hydropower plant to operate above normal operating levels during off-peak hours and operate at a lower level during peak periods. Water flow to support such an operational strategy would change as well (i.e., increase during off-peak periods and decrease during peak periods). The implied benefits of a less severe ramp up and ramp down of water would include less severe variations in tailwater elevations, and reduced time of running with water flows close to the maximum limit. Depending on the plant configuration and operating conditions, such an operational strategy might also enable coincident benefits, such as longer periods of operating the turbines near their peak efficiencies. It should be noted that the primary benefit associated with market-facing operations—either revenue capture or more efficient generation portfolio stack—is not adversely impacted, because the effective power supply is identical to the baseline.

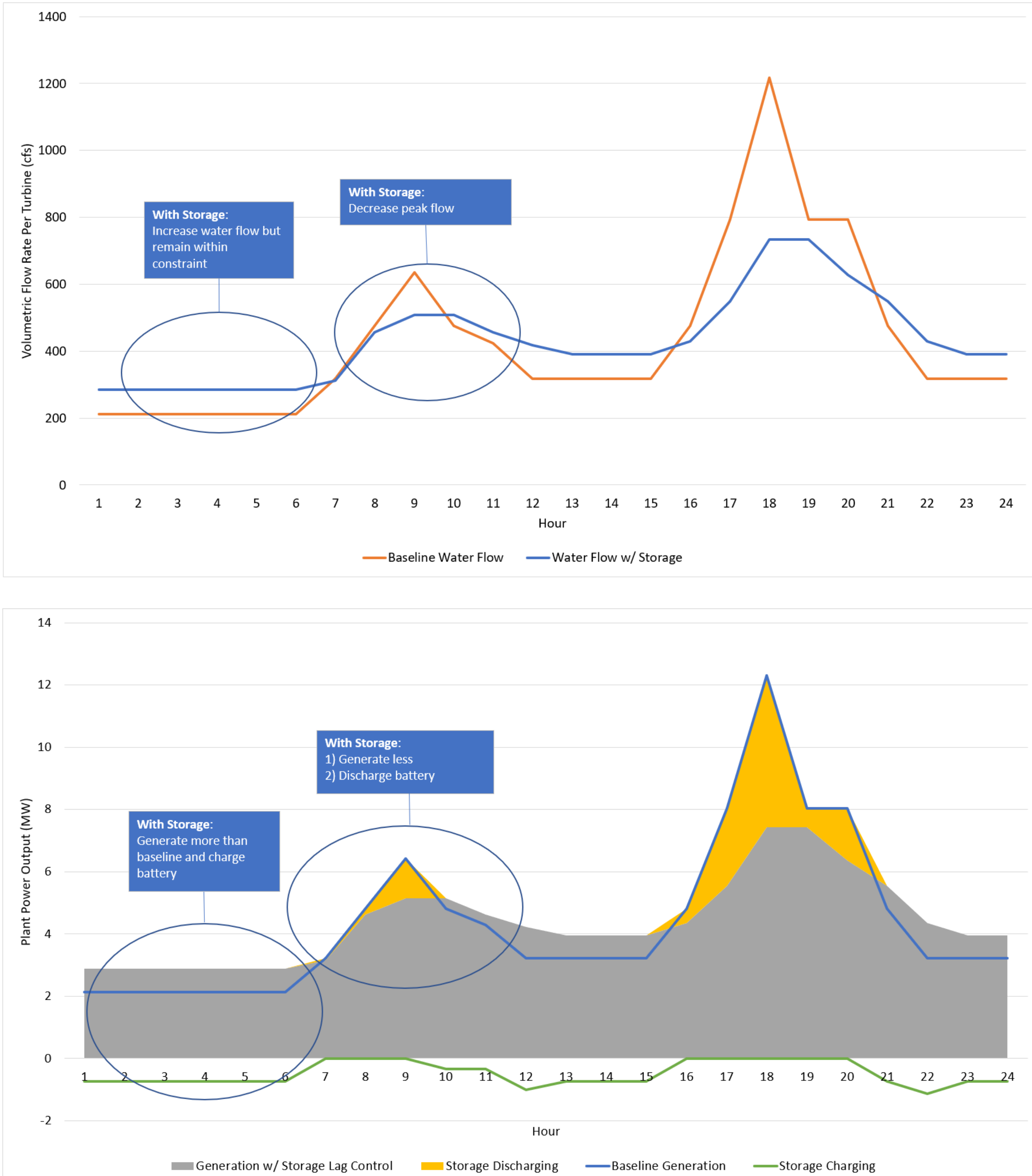

Figure 1. Conceptual example to illustrate alternative water flow regimes (top) and plant operations (bottom) based on deployment and use of energy storage technology.

5.2 General Process of Studying Storage Solutions for Environmental Outcomes

The hydropeaking example can be used to generalize the process one might use to study storage applications for environmental benefits. As highlighted in the example, the decision process requires an understanding of the relationship between environmental and power generation outcomes at a given location. Fundamentally, these outcomes are connected through water flow regimes at that location. Water flow regimes, characterized by min/max flow rates in units of cubic feet per second, daily fluctuations (cfs/24 hr), flow ramp rates (cfs/hr), and duration of sustained flows at increased or decreased levels, directly affect power generation possibilities at the location as well as the health of associated aquatic and riparian ecosystems. These regimes may need to be controlled in time, on hourly or seasonal bases, to balance positive environmental outcomes with power production. Any changes in water flow decisions, due to environmental or other objectives, will directly affect the power generation capabilities at that facility,[1] and hence, affect the choice of whether to install storage technology and if so what size. Figure 2 depicts the decision-making process that is encapsulated in the ensuing numbered steps.

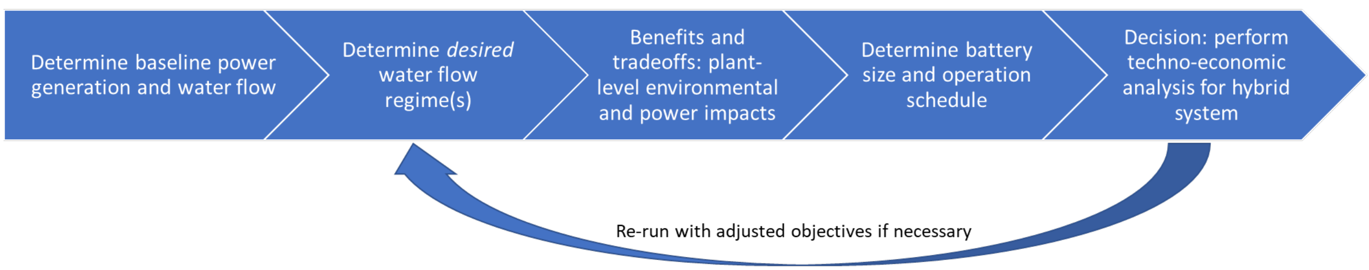

Figure 2. Energy storage sizing methodology.

1. Baseline: Ascertain the existing operational baseline regime (i.e., generation and water flow patterns at a given location) by considering baseload, load following, and peaking.
2. Determine desired water flow regime(s):
   a. Flexibility: Identify the operational flexibility, in both power generation and flow patterns, relative to the baseline operational regime.
   b. Alternatives: Identify the alternative set of water flow regimes that help enhance environmental outcomes at the location based on the flexibility assessment.
3. Benefits and tradeoffs: Assess the environmental benefits, changes in power generation outcomes and other tradeoffs, if any, due to the alternative flow regime(s) (e.g., hydropeaking can limit the opportunities for whitewater recreation).
4. Determine the energy storage size and operation schedule: Perform analysis to optimize energy storage size, including identifying a suitable location, and identify an operational schedule for the hybrid system.

[1] A current, ongoing research project stewarded by the U.S. Department of Energy's Water Power Technology Office, called "HydroWIRES Topic A," will provide a comprehensive mapping of environmental objectives and power operations at a facility, which could be used to supplement the proposed methodology.

5. Decision: Perform techno-economic analysis to ascertain economic outcomes of the optimization.
6. Adjust objectives, if needed, and repeat Steps 2 through 6.

While knowledge of the baseline operational regime—generation and water flow profiles and the inherent flexibility therein—may be known, the identification of alternative flow regimes requires thorough understanding of local environmental needs. These needs will inform how and when hydropower operations must be restricted, and when they can be relaxed, to achieve desirable environmental outcomes.

5.3 Alternative Water Flow Regimes to Enable Environmental Benefits

In the hydropeaking example, a threshold analytical understanding of the relationship between flow rates, power outcomes, and environmental outcomes must first be established. Data related to water elevations in locations of potential fish spawning habitat, flow rates at various river locations, and correlations of these data with flow rates through hydropower facilities must be collected to determine more precisely where and when maximum flow rates should be reduced. Additional measurements will be needed in various locations within a specific river to understand the efficacy of specific restrictions on ramp rate and successive ramping events in attaining meaningful environmental benefits of hydropeaking reduction. These requirements reach beyond hydropeaking reduction; the same can be said for any environmental gain associated with modifications of hydropower operations. The changes in operations, such as minimum and maximum flow limits, etc., will require precise determination of enhanced environmental benefits.

Table 2 presents a *hypothetical* set of values for maximum flow rates, ramp rates, and successive ramps per day that (1) are standard in baseline operations, before hydropeaking avoidance, and (2) will be required to achieve the environmental benefits associated with eliminating or reducing hydropeaking. The additional restrictions on power operations that come with changes in the values of these constraints directly correlate with either reduced or increased power generation potential. In the case of hydropeaking reduction, maximum flows must be reduced within time periods spanning several hours. In the consideration of whether energy storage can yield environmental benefits while maintaining power benefits, it is equally important to know where and when power operations can exceed the baseline. Minimum flow rates at off-peak times serve to limit the ramps associated with hydropeaking as well as provide a means for additional power generation to charge the energy storage asset. In this way, the information pertaining to the new flow regime, as well as the trade-off in power generation timing and scale, can be used to approximate the size, type, and location of a useful energy storage technology application.

Dispatch of the energy storage asset to shave hydropeaking is conceptually demonstrated in Figure 1, which demonstrates how flows can be reduced while energy is exported from the storage asset to maintain power system benefits. In this way, energy storage dispatch is directly linked to benefits to downstream fish populations during various life stages, as described in Table 2. To provide greater precision, an optimization problem can be formulated that treats the new flow regimes as constraints to ascertain the appropriate size, location, and type of storage technology. Hydropeaking avoidance is just one conceptual example. Appendix A presents two tables that repeat this methodology for the potential benefits associated with spill for safe fish passage downstream and upstream, and water quality benefits.

Table 2. Operational shift requirements to enable environmental benefits of hydropeaking reduction (hypothetical metrics).

Operational Constraint	Baseline	Flows to Meet Environmental Objectives (limit impacts from hydropeaking)	Potential Benefit	What data are needed?
Spawning flow range (cfs)	No limit	2,500–5,000	Conducive to spawning activity for spawning fish. Species and river dependent.	Habitat use – including water elevation of spawning habitats and larval fish behavior and habitat use. Life stage phenology.
Minimum flow release (cfs)	1,000	1,500–2,600	Protect larval fish incubating in gravel or developing during larval drift phase.	
Downramp amplitude limit (cfs)	None	4,000	Limit fish from getting trapped in pools that are disconnected from the main channel.	
Maximum downramp rate (cfs/hr)	No limit	3,000	Limit fish from getting trapped in pools that are disconnected from the main channel.	
Daytime downramping	Allowed	Not allowed	Limit fish being trapped; site- and species-specific differences	

5.3.1 Case Study: Glen Canyon Dam

Prior to 1991, Glen Canyon Dam (GCD) operated under fewer environmental restrictions. Table 3 shows that power plant water releases could range from 1,000 cfs to 30,500 cfs, with no limit regarding the daily fluctuations or ramp rates. Such flexibility caused significant environmental damage, such as the endangered species listing of native fishes and changes in the overall ecosystem due to changes in downstream water temperatures and decreased sediment load. From August 1991 to January 1997, temporary restrictions called “Interim Flow Restrictions” were put in place before the release of a final environmental impact statement. Since 1997, the water release range has been reduced to a range from 5,000 to 25,000 cfs, and daily fluctuations and ramp rates have been limited. More recently, in January 2017, a new Record of Decision (ROD, DOI 2016) mandating the preferred alternative prescribed by the Long-Term Experimental and Management Plan has been adopted and was first implemented in October 2017.

Table 3. Evolution of Glen Canyon Dam operating constraints.

Operational Constraint	Historical Flows (before 1991)	1996 ROD Flows (from 1997 to 2017)	2016 ROD Flows (after 2017)
Minimum flows (cfs)	3,000 (summer) 1,000 (rest of year)	8,000 (7 a.m. - 7 p.m.) 5,000 (at night)	8,000 (7 a.m. - 7 p.m.) 5,000 (at night)
Maximum non-experimental flows (cfs)[(a)]	31,500	25,000	25,000
Daily fluctuations (cfs/24 hr)	28,500 (summer) 30,500 (rest of year)	5,000, 6,000, or 8,000 depending on release volume	Equal to 10 X monthly water release (in thousands of acre-feet) during June-August, and equal to 9 X monthly water release the rest of the year, but never exceeding 8,000 cfs
Ramp rate (cfs/hr)	Unrestricted	4,000 up 1,500 down	4,000 up 2,500 down

(a) Except during experimental releases.

Because water flow rate and power are closely related, peaking capability at GCD has been also significantly reduced (Figure 3). Power generation is dependent on available head and flowrates. Before the environmental restrictions, during the week from July 19 to July 25, 1987, GCD was able to produce a peak power of 1,164 MW, that is, 89 percent of the potential peaking capacity of this period. After the 1996 ROD, during the same week of year 2015, this peak generation dropped to 746 MW, that is, only 68 percent of its potential available capacity. The limitation on the peak capacity is due to the maximum daily fluctuations imposed above.

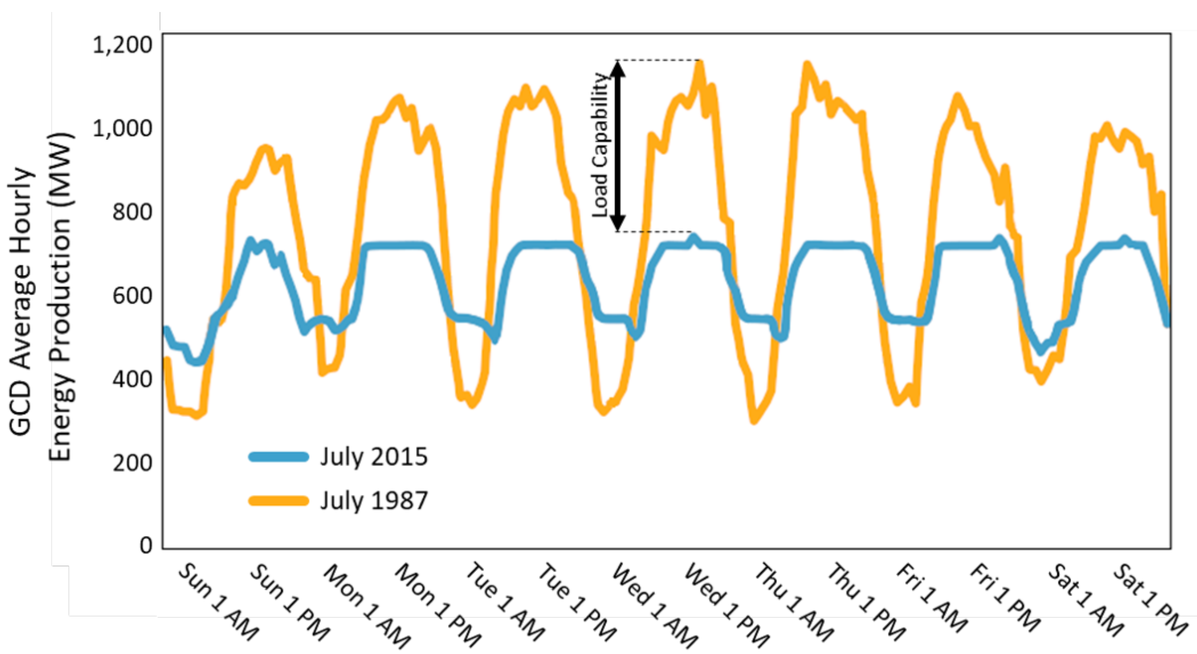

Figure 3. Hourly energy production at the GCD powerplant during a July week in 1987 and 2015.

5.3.2 Case Study: GCD Potential Improvements

The GCD case illustrates the potential benefits of implementing energy storage to improve environmental outcomes. Though the peaks vary significantly due to flow restrictions, the overall power generated relative to potential available power during the case periods is quite similar. Potential available power considers differences in head and assumes the maximum flowrate of 31,500 cfs can be achieved at the differing heads. If 31,500 cfs cannot be achieved during the lower head period of 2015, the convergence is increased. The July 1987 flow data generated at approximately 58 percent of the potential available power, whereas the July 2015 performance is approximately 54 percent of the potential available power. The convergence of these values is due to minimum flows being required during the night for 2015, increasing the generation over this period.

The imposed flow requirements resulting in night generation occur during a period of low demand. Increased power demands begin in the morning, taper through the day, then peak in the evening. Demand drops significantly at night. Implementing an energy storage system to capture the generation at night and discharge during the day would allow the average hourly energy productions from the environmentally restricted 2015 period to behave similarly to the less regulated 1987 period.

5.4 Process of Deciding the Storage Size, Type, and Location

Industry,[1] academia, and national labs have developed several tools and methodologies to assist with the sizing of energy storage for site-specific installations. Most of these tools and methodologies (Wu et al. 2017) focus primarily on maximizing revenues or cost-savings from power operations, either for the stand-alone storage technology or for a hybrid solution, such as a traditional solar or wind facility with the integrated addition of a storage system. To the best of our knowledge, currently there are no tools and methodologies that can assist with making decisions about the sizing of storage technologies for environmental benefits. However, existing methodologies can be adapted for this purpose. All that the methodologies require is a sufficiently precise characterization of the technical attributes of the resource being analyzed—whether a stand-alone storage system or a hybrid solution—and its intended functions. In the case of energy storage for environmental benefits, the technical characteristics of a hybrid hydropower resource with integrated storage will likely be based on the flow regimes, both baseline and alternative ones.

The changes in flow regimes may be required for a variety of reasons:

- FERC licensing or relicensing process, where the federal authorization for the facility requires a new flow regime or alternate water budget, such as maintaining upstream reservoir levels, or flow requirements to meet a downstream objective including human uses such as fishing or boating;
- operational strategies for asset management purposes, where the facility must adjust the hydraulic capacity of the system in order to maintain useful equipment life;
- new market opportunities, such as a change in the price of ancillary services, or changes in underlying regulatory and policy constructs, and market designs; and

[1] Det Norske Vitas (DNV)-GL's ES-Select tool compares energy storage technologies for different use cases; Pason Power Inc., and Energy Toolbase LLC., have designed a tool called Energy Toolbase to assist with sizing and controlling residential solar PV plus battery systems.

- mitigation of environmental issues, where water flows must be adjusted ~~provided~~ to match a water quality, fish, or other ecological objective.

In all but the last case, environmental benefits are not likely to be the primary drivers when making decisions about deploying an energy storage technology. Even so, the deployment of energy storage, whether for operational flexibility or asset management, will provide options for alternative operating practices and, by extension, alternative water flow regimes. The choice of storage technology in such cases will need to consider the appropriate combination of power generation and environmental outcomes, weighed against the cost of the storage technology itself. This process could be designed as a multi-objective optimization problem consisting of an appropriately weighted combination of objectives—(maximize) power generation responsiveness, operating limit, and flexibility, (minimize) asset management costs, (maximize) environmental compliance, and (minimize) technology costs. This process, essentially, uses a range of water flow regimes to construct the *pareto frontier* to analyze tradeoffs between different objectives.

Alternatively, one or more of the objectives may be treated as constraints in the design process. For instance, to avoid lost generation opportunity and attributes in the hydropeaking example, the baseline generation profile may be treated as a fixed requirement that the combination of storage and hydropower generation (with altered flow regime) must attain. Hence, the first step in the decision-making process is to determine the attributes of lost generation capacity—energy and power ranges, ramp rates, and so forth. The required set of attributes will help determine the choice of energy storage technologies. The next step in the process is to conduct techno-economic analyses based on understanding and knowledge of market conditions, water availability, and other critical considerations. The techno-economic analysis can be based on detailed time-series simulations and optimization of the hybrid resource, modeling its operations and dispatch in an actual market. Pacific Northwest National Laboratory's (PNNL's) energy storage evaluation tool (ESET), for instance, has been used extensively to create a sizing space for storage, based on known or assumed use cases (such as hydropeaking), deterministic or stochastic information on market conditions (prices, demand, and so forth), and storage technology specific considerations.

5.4.1 Storage Sizing Methodology for Maximizing Revenue of a Storage Hybrid System

The ESET tool formulates a linear programming problem to maximize the annual economic benefits of the energy storage or hybrid system. In this case, the benefits would include any identified hydropower use cases as well as any other market services that could be provided. The tool co-optimizes identified services to be provided subject to energy storage power and energy constraints, state-of-charge dynamics, and the coupling of different use cases. The ESET formulation dispatches the system on an hourly basis, first formulating a look-ahead optimization to determine a system operating point, and then dispatching the system on an hourly (or more granular) basis, to determine the number of hours the system would be actively engaged in the provision of each service. In addition, a storage system cost formulation can be added to the objective function to optimally size the storage system within the model. This cost formulation includes the equivalent system capital cost as a function of power and energy, which consists of investment, installation, and operations and maintenance costs for the storage device and associated inverter. The optimal sizing approach maximizes investment return for a given time frame. ESET then provides the maximized benefit, optimal size, and dispatch for the system under the given use cases and subject to the other variables (Wu et al. 2016). A *Monte Carlo type* analysis can then be conducted, varying one or more input variables of the formulation, including use case requirements, market prices, and storage technology types and costs, to generate a decision space. Within this space, present-value benefits and costs can be calculated to find optimal energy storage parameters that return the largest net-benefit.

The following sequence of steps presents a simplified version of the methodology:

1. Determine initial energy storage size.
2. Maximize revenue from hybrid plant operations subject to:
    - Plant electro-mechanical constraints,
    - Energy storage capacity limits.
3. Adjust energy storage size and re-initiate Step 2.

Figure 4 below, borrowed from Wu et al. (2016), presents an example decision space generated by the ESET tool across energy storage capacity and energy for different locations (i.e., San Francisco [SF], Chicago [CHI], Houston [HOU], and New York City [NYC]) and technology price points (i.e., high, medium, and low).

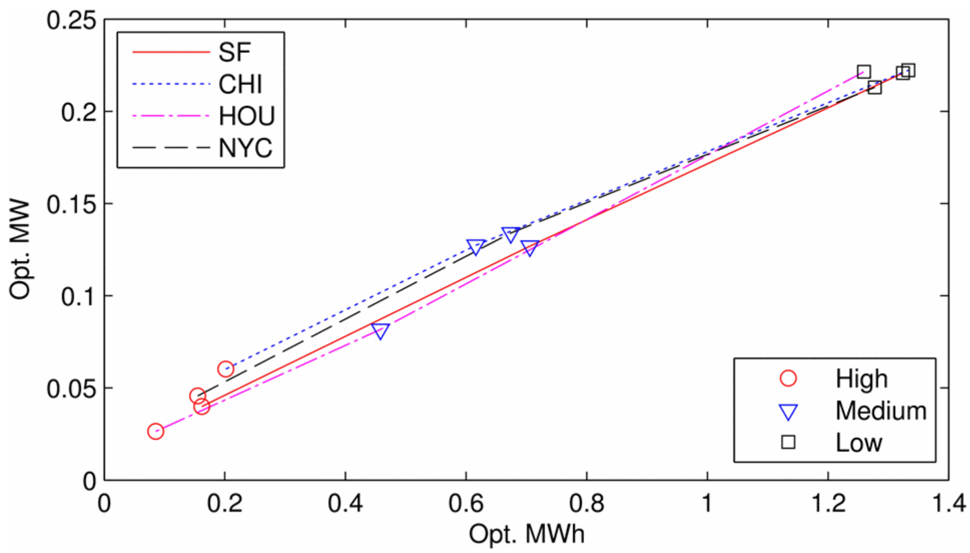

Figure 4. Optimal (Opt.) energy and power capacity in different battery cost scenarios and energy markets (San Francisco [SF], Chicago [CHI], Houston [HOU], New York City [NYC]).

Such tools and methodologies can be extended to study the suitability of different storage technologies for environmental benefits. The above methodology can be adapted to include desired environmental outcomes as additional constraints in the optimization problem. For instance,

1. Determine initial energy storage size.
2. Maximize revenue from hybrid plant operations subject to
    - Plant electro-mechanical constraints,
    - Energy storage capacity limits,
    - Environmental objectives:

  - Flow >= Min flow limit
  - Flow <= Max flow limit.

3. Adjust energy storage size and/or environmental objectives and rerun Step 2.

The min and max flow limits are derived from alternative flow regimes that correspond to desired environmental outcomes. In this way, the sensitivity of energy storage sizing relative to desired environmental outcomes can be determined by adjusting the water flow constraints.

6.0 Co-optimization vs. Co-location of Storage

There is a useful distinction here for when a storage system should be directly interconnected and integrated with a hydropower facility ("co-location") and when it should be operated in a coordinated fashion ("co-optimization"). Generating resources are already coordinated to operate as a portfolio, to serve load, to transmit energy, to balance control boundaries. Advanced control and communication can allow networked operation of electricity system assets across multiple systems. So, when does it make sense to site a storage system within a hydropower facility footprint? This section explores the contextual conditions that lean toward co-location or co-optimization of storage and hydropower assets.

6.1.1 Why Co-optimize?

Hydropower plants operate within a system context and their operation is coordinated with other resources to assure that load and generation are matched. In vertically integrated utilities or system-level coordination, the power tradeoffs for managing environmental objectives may be most cost-effectively dealt with by adjusting the merit order or dispatch of other plants, rather than co-siting storage at a specific project. For example, if a hydropower plant is limited in how fast it may ramp flows up and down, then the faster ramping requirement could be replaced by a gas unit or by other ramping resources already available elsewhere in the system.

For utility-owned plants, operating in organized markets, there may be locational considerations for siting energy storage systems based on geographical patterns of energy and ancillary service prices. One technique for identifying optimal siting of storage systems is to run a system-wide analysis using production cost models. These models enable co-optimization of the entire fleet of resources under a utility's ownership, with explicit consideration of certain locational aspects of its resources.

6.1.2 Why Co-locate?

Co-location of storage at the hydropower plant may allow additional local benefits. To achieve these locational benefits, utility-owned projects may be motivated to enhance the resource eligibility of a larger plant, or to maintain operational simplicity in response to a signal.

The case for co-location is notably broader for merchant (contracted resources) or market-facing plants. These plants are remunerated and environmentally governed independently from other resources, so there is greater motivation to demonstrate higher performance at the facility to be eligible for higher contractual rates, market products, or greater compensation.

Where avoiding harm to facility and unit components is a priority, integration of on-site storage solutions may help avoid detrimental use of existing equipment, such as low-loading units or frequent or sudden movement across hydraulic and efficiency ranges. Hydroelectric projects are uniquely capable of a suite of flexibility characteristics, including motoring units[1] and dispatchability using on-site water (energy) storage in reservoirs. Augmenting or preserving this flexibility with batteries could be very useful, because their characteristics are highly complementary to the flexibility of hydropower. Storage systems can increase the instantaneous responsiveness of units or avoid unit start-stop or rough zone utilization, thereby bolstering the case for on-site power value. They can also support local power needs, such as managing reactive power for voltage control, or assisting in the automatic generation control function for the management of area control error. Another factor is the speed of interconnecting a storage system to the grid, which is substantially more straightforward within the footprint of a large power plant (Kougias 2019).

In addition to the proximity benefits, it is typical for hydropower facilities to own a large parcel of land, or have overarching real-estate agreements for the surrounding land and its use, that may provide a suitable footprint for the location of the energy storage system. Locating energy storage on-site at the hydropower facility may eliminate the need for additional land acquisitions.

Aside from interconnection of the energy storage system, co-location is supported by existing transmission rights. The purpose of the energy storage being proposed provides operational flexibility rather than increased capacity beyond current peak demands. This allows the rights of the existing transmission system, sized for the existing generation, to be suitable for continued load transmission with the added energy storage system.

Many hydroelectric projects are located within a cascading operation, meaning that there are plants upstream or downstream between which there is a hydrologic link. Under these conditions, the project owner may operate the plants in a coordinated fashion, sequencing flows to an optimal outcome. Or if ownership is varied, there may be a coordination agreement regarding flow schedules or communication between plants to assure operational parameters are met at each plant. In these cases, energy storage, when integrated with a particular facility, such as a facility that acts as a hydrologic constraint, may permit additional flexibility to accrue to other plants in the same cascading system.

There also may be instances in which storage co-location is motivated by load tied directly to the water source, and the timing of the load does not align with hydropower production. Examples of this load include environmental restoration through active water treatment, oxygenation or cooling processes, hydrogen production, desalination, sensing, communications, and control and power backup. Loads of these types could be served by merchant resources as well as utilities under various arrangements. To the extent that these loads can be deferred in time and follow business-as-usual hydropower production patterns, the need for on-site storage to serve these loads and thus the requirement for co-location of energy storage assets may be reduced.

[1] Motoring of hydroelectric generators corresponds to an extreme idle state of running the turbines with insufficient pressure head to run the (interconnected) generator at synchronous speed. Under this condition, electrical generators act as synchronous motors and pull power from the grid to drive the turbines.

7.0 Next Steps

This paper outlines the potential for deriving improved environmental outcomes by integrating energy storage systems with hydropower plants. This idea is an exciting one, because it suggests that through technology investments, improvements in both river health and the financial future of hydropower plants can be achieved. Quantifying the mutual benefits is an important step in realizing storage adoption by privately and publicly owned hydropower projects.

Throughout this paper, existing knowledge and practical gaps in data, controls, and methodologies for evaluating this potential are indicated. The next steps, summarized below in order of action and scale, will help inform the industry and shape the discussion:

- Determine the full taxonomy and prioritization of the opportunity space for environmental benefits.
- Specify the practical considerations for retrofitting dams with energy storage, related to physical size, electrical interconnection, and charging mechanisms.
- Develop new techniques, based on multi-objective optimization, to support and evaluate the feasibility of hybridization for environmental benefits.
- Adapt or design a decision-support process to evaluate and inform the size, location, and type of energy storage technology.
- Simulate real hydropower plants and energy storage-informed operational models to design hybrid system controls and interactions of mutual benefit.
- Perform data-rich demonstrations of the relationships between environmental benefits and energy storage-augmented operations, in partnership with dam operators.

Several avenues are being explored to realize the data gaps listed above and to enable a demonstration project to serve as a foundation for integrating energy storage with hydropower projects for environmental benefits. Other use cases including the integration of energy storage with other electricity-dependent water infrastructure, such as water conveyance pumps, may offer similar potential for environmental benefits and will be additionally explored. Once a foundational use-case project is identified and implemented, the ultimate goal is to leverage this environmental use-case framework and apply it across the U.S. to other hydropower projects where energy storage could enable more cost-effective ecosystem improvements.

8.0 References

Alam MS, Mosier MT, Bennett B, Gevorgian V, and Stark G. 2019. *Integrated Hydropower and Energy Storage Systems: Current Use Cases and Future Potential.* Internal Report, Idaho National Laboratory, National Renewable Energy Laboratory: unpublished.

Auer NA. 1996. Response of spawning lake sturgeons to change in hydroelectric facility operation. *Transactions of the American Fisheries Society* 125: 66–77. doi:10.1577/1548-8659(1996)125<_x0030_066:ROSLST>2.3.CO;2.

Becker CD, Neitzel DA, and Fickeisen DH. 1982. Effects of dewatering on Chinook salmon redds: tolerance of four developmental phases to daily dewaterings. *Transactions of the*

American Fisheries Society 111: 624–637. doi:10.1577/1548-8659(1982) 111<_x0036_24:EODOCS>2.0.CO;2.

Bunn SE and Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30: 492–507. doi:10.1007/s00267-002-2737-0. PMID:12481916.

Chapman DW, Weitkamp DE, Welsh TL, Dell MB, and Schadt TH. 1986. Effects of river flow on the distribution of Chinook salmon redds. *Transactions of the American Fisheries Society* 115: 537–547. doi:10.1577/1548-8659(1986)115<_x0035_37:EORFOT>2.0. CO;2.

Clarke KD, Pratt TC, Randall RG, Scruton DA, and Smokorowski KE. 2008. Validation of the flow management pathway: effects of altered flow on fish habitat and fishes downstream from a hydropower dam. *Canadian Technical Report of Fisheries and Aquatic Sciences* 2784.

Connor EJ and Pflug DE. 2004. Changes in the distribution and density of pink, chum, and Chinook salmon spawning in the upper Skagit River in response to flow management measures. *North American Journal of Fisheries Management* 24: 835–852. doi:10.1577/M03-066.1.

Cushman RM. 1985. Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fisheries Management* 5: 330–339. doi: 10.1577/1548-8659(1985)5<_x0033_30:ROEEOR>2.0.CO;2.

DOE (U.S. Department of Energy). 2018. U.S. Utility-scale photovoltaics-plus-energy storage system costs benchmark. Technical Report NREL/TP-6A20-71714, DOE National Renewable Energy Laboratory, Golden, Colorado.

DOI (U.S. Department of Interior). 2016. Record of decision for the Glen Canyon Dam long-term experimental and management plan final environmental impact statement. U.S. Department of the Interior. https://ltempeis.anl.gov/documents/docs/LTEMP_ROD.pdf

Fisk JM, II, Kwak TJ, Heise RJ, and Sessions FW. 2013. Redd dewatering effects on hatching and larval survival of the robust redhorse. *River Research and Applications* 29: 574–581. doi:10.1002/rra.2561.

Geist DR, Murray CJ, Hanrahan TP, and Xie Y. 2008. A model of the effects of flow fluctuations on fall Chinook salmon spawning habitat availability in the Columbia River. *North American Journal of Fisheries Management* 28: 1894–1910. doi:10.1577/M07- 074.1.

Gislason JC. 1985. Aquatic insect abundance in a regulated stream under fluctuating and stable diel flow patterns. *North American Journal of Fisheries Management* 5: 39–46. doi: 10.1577/1548-8659(1985)5<_x0033_9:AIAIAR>2.0.CO;2.

Halleraker, JH, Saltveit SJ, Harby A, Arnekleiv JV, Fjeldstad H-P, and Kohler B. 2003. Factors influencing stranding of wild juvenile brown trout (Salmo trutta) during rapid and frequent flow decreases in an artificial stream. *River Research and Applications* 19: 589–603. doi:10.1002/rra.752.

Harnish RA, Sharma R, McMichael GA, Langshaw RB, and Pearsons TN. 2014. Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population. *Canadian Journal of Fisheries and Aquatic Sciences* 71: 602–615. dx.doi.org/10.1139/cjfas-2013-0276.

Haro A, Castro-Santos T, and Boubée. 2000. Behavior and passage of silver-phase American eels *Anguilla rostrate* (*LeSueur*), at a small hydroelectric facility. *Dana* 12: 33–42.

Hydro Review. 2018. Fortum fits Nordics ‘biggest battery’ at hydro plant.” Hydro Review. 29 November. https://www.hydroreview.com/2018/11/29/fortum-fits-nordics-biggest-battery-at-hydro-plant/#gref

Kern JD, Patino-Echeverri D, and Characklis GW. 2014. The impacts of wind power integration on sub-daily variation in river flows downstream of hydroelectric dams. *Environmental Science & Technology* 48: 9844–9851. doi:10.1021/es405437h

Kougias I, Aggidis G, Avellan F, et al. 2019. Analysis of emerging technologies in the hydropower sector. *Renewable and Sustainable Energy Reviews,* Volume 113, 109257, ISSN 1364-0321.

Li X, Deng ZD, Brown RS, Fu T, Martinez JJ, McMichael GA, Skalski JR, Townsend RL, Trumbo BA, Ahmann ML, and Renholds JF. 2015. Migration depth and residence time of juvenile salmonids in the forebays of hydropower dams prior to passage through turbines or juvenile bypass systems: implications for turbine-passage survival. *Conservation Physiology* 3: 1–17.

McMichael GA, Rakowski CL, James BB, and Lukas JA. 2005. Estimated fall Chinook salmon survival to emergence in dewatered redds in a shallow side channel of the Columbia River. *North American Journal of Fisheries Management* 25: 876–884. doi:10. 1577/M04-168.1.

Mesa MG, Weiland LK, and Maule AG. 2000. Progression and severity of gas bubble trauma in juvenile salmonids. *Transactions of the American Fisheries Society* 129:174–185.

Muir WD, Smith SG, Williams JG, and Sandford BP. 2001. Survival of juvenile salmonids passing through bypass systems, turbines, and spillways with and without flow deflectors at Snake River dams. *North American Journal of Fisheries Management* 21: 135–146.

Nagrodski A, Raby GD, Hasler CT, Taylor MK, and Cooke SJ. 2012. Fish stranding in freshwater systems: Sources, consequences, and mitigation. *Journal of Environmental Management* 103: 133–141. doi:10.1016/j.jenvman.2012.03.007. PMID: 22481278.

Pyper J. 2017. “Tesla, Greensmith, AES Deploy Aliso Canyon Battery Storage in Record Time.” *Greentech Media.* 31 January. https://www.greentechmedia.com/articles/read/aliso-canyon-emergency-batteries-officially-up-and-running-from-tesla-green

Roy GR, Uchida E, de Souza SP, Blachly B, Fox E, Gardner K, Gold AJ, Jansujwicz J, Klein S, McGreavy B, Mo W, Smith SMC, Vogler E, Wilson K, Zydlewski J, and Hart D. 2018. A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost. *Proceedings of the National Academy of Sciences* 115:12069-12074.

Shumkov I. 2020. “Cummins to supply 5-MW electrolyzer for green hydrogen project. *Renewables Now.* 7 September. https://renewablesnow.com/news/cummins-to-supply-5-mw-electrolyzer-for-green-hydrogen-project-712708/

USGS (U.S. Geological Survey). 2015. Rebuilding sandbars in the Grand Canyon. https://www.usgs.gov/news/rebuilding-sandbars-grand-canyon

Ward DL and Bonar SA. 2013. Effects of cold water on susceptibility of age-0 flannelmouth sucker to predation by rainbow trout. *The Southwestern Naturalist* 48:43–46.

Weber DD and Schiewe MH. 1976. Morphology and function of the lateral line of juvenile steelhead trout in relation to gas-bubble disease. *Journal of Fish Biology* 9:217–233.

White D, Chang M, and Odem C. 2020. *Battery Storage and Hydro Power: Storage Options for Run-of-River Hydro for Vernon*. Synapse Energy Economics, Inc. https://www.ctriver.org/wp-content/uploads/CRC-letter-to-FERC_battery-analyses-alternatives_4.24.20.pdf

Wu D, Kintner-Meyer M, Yang T, and Balducci P. 2016. Economic analysis and optimal sizing for behind-the-meter battery storage. *Proceedings of the IEEE Power and Energy Society General Meeting*, Boston, MA, pp. 1-5.

Wu D, Kintner-Meyer M, Yang T, and Balducci P. 2017. Analytical sizing methods for behind-the-meter battery storage. *The Journal of Energy Storage* 12:297-304.

Young PS, Cech JJ, Jr, and Thompson LC. 2011. Hydropower-related pulse flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. *Reviews in Fish Biology and Fisheries* 21: 713–731. doi:10.1007/s11160- 011-9211-0.

Zhong Y and Power G. 1996. Environmental impacts of hydroelectric projects on fish resources in China. *Regulated Rivers: Research & Management* 12: 81–98. doi:10.1002/ (SICI)1099-1646(199601)12:1<_x0038_1:_x003a_AID-RRR378>3.0.CO;2-9.

Appendix A – Methodology Crosswalk

Table A.1. Operational shift requirements to enable environmental benefits of spill for safe fish passage (*hypothetical* metrics).

Operational Constraint	Baseline	Flows to Meet Environmental Objectives (limit impacts from not spilling)	Potential Benefit	What data are needed?
Minimum spill discharge (cfs)	7,000 (late summer) 30,000 (spring) Unrestricted (rest of year)	17,000 (summer smolt passage season) 100,000 for 16 hours daily (spring)	Route downstream-migrating fish from the powerhouse to the spillway to improve passage survival	Hourly passage routing of downstream-migrating fish
Passage flow rate (cfs)	Unrestricted	500 (upstream fish-passage season)	Provide adequate flow rate to attract for upstream fish passage	Seasonal and diel timing of upstream fish passage

Table A.2. Operational shift requirements to enable environmental benefits of Spill for Water Quality (*hypothetical* metrics).

Operational Constraint	Baseline	Flows to Meet Environmental Objectives (limit impacts on water quality)	Potential Benefit	What data are needed?
Minimum flows (cfs)	3,000 (summer) 1,000 (rest of year)	3,000 (summer) 1,000 (rest of year)	Reduce dissolved oxygen and total dissolved gas to at/near 100% for aquatic organism health	Water elevations near spawning habitat, correlation of elevations with flow rates as a function of river hydrology
Maximum non-experimental flows (cfs)[a]	31,500	31,500	Increase dissolved oxygen and/or total dissolved gas to increase under-saturated (<100%) water to avoid fish kills.	
Daily fluctuations (cfs/24 hr)	28,500 (summer) 30,500 (rest of year)	28,500 (summer) 30,500 (rest of year)	Manage spill to optimize oxygen and gas levels for aquatic system health.	
Spill flow rate (cfs)	No requirement	1000 (3-7am)	Spilling warmer surface water downstream may warm the river. Spill from higher elevations re-oxygenates the river but can be too much. Must be carefully planned.	

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov