A decision-framework for retrofitting or decommissioning hydropower plants in the USA

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Focal Area(s): The proposed white paper focuses on the "water for energy" focal area, with the goal of enhancing the resilience of the complex water-energy system to improve hydropower energy production. We aim to develop a comprehensive framework that integrates upstream hydrology modeling under different conditions with the management of reservoirs and hydropower facilities, actively engaging stakeholders across these sectors to support informed decision-making regarding the retrofitting of aging hydropower plants for continued power generation versus opting for decommissioning.

Existing Challenge: Aging hydropower infrastructure and fluctuating water availability pose significant challenges for the United States energy sector. Most of the approximately two thousand hydropower plants, with a combined capacity of around 80.58 GW, are approaching or have exceeded their designated life expectancy (ORNL, 2023). Decisions regarding whether to decommission or retrofit this infrastructure carry substantial energy, environmental, and economic implications. Retrofitting existing facilities can mitigate the economic and environmental costs associated with constructing new plants (Szabó et al., 2016; Chaudhari et al., 2021) and the installation of advanced turbine technologies may yield efficiency improvements of 3% or more per facility (DOE, 2018). However, the cost of retrofitting—and its impact on the levelized cost of energy—varies considerably from plant to plant, making some sites more economically attractive for retrofitting than others.

While retrofitting and upgrades are essential for extending the life of hydropower plants, they do not fully address the challenges posed by increasing fluctuations in water availability (Broman et al., 2024; Craig et al., 2018) and sediment loading issues (Garrett, 2021; Wisser et al., 2013). Nearly all current estimates of surface water extent upstream of hydropower reservoirs remain highly inconsistent (Rajib et al., 2023); this inconsistency intensifies for smaller reservoirs as seasonality increases and permanent water area diminishes (Khare et al., 2025). In response, the justification for retrofitting is influenced by changing hydrologic flow and their spatial variabilities depending on snow or rain-dominance in watersheds, sediment loading from upstream areas, and dominance of hydropower across different energy grids. Variability in snowpack and melting patterns leads to fluctuations in short- and long-term water availability (Whitney et al., 2023; Wang et al. 2024), causing operational disruptions and inconsistent hydropower output (Mishra et al., 2018; 2022), which further reduces the economic attractiveness of retrofitting existing infrastructure. Additionally, competition for water resources for non-power sectors, particularly during droughts, can significantly increase levelized cost of energy (LCOE) from hydropower systems. Furthermore, if the upstream watershed is prone to erosion, sedimentation can reduce the operational efficiency of a plant, directly impacting the economic return on capital-intensive retrofitting and upgrades.

The primary driver of the retrofit decision is the economic viability of retrofitting – whether the projected revenues and savings from retrofitting exceed the total retrofit costs, short payback period, and reasonable return on investment – considering available resources,

input costs, and energy prices. This economic viability is influenced by a complex interplay of direct costs and revenues, site-specific physical and operational factors, external risks such as water availability and sediment loading, energy prices, and the policies and financial incentives. To evaluate economic viability of restoring these complex facilities, it is critical to design an integrated assessment framework (IAF) that incorporates all these factors and drivers. Therefore, combining insights from the operational, hydrological, and energy landscape components is critical for developing a science-based decision framework for hydropower retrofitting.

Near Term Opportunity: To that end, a near term opportunity is a) developing an integrated assessment framework to evaluate the economic viability of hydropower retrofitting efforts and b) demonstrating the IAF for hydropower fleets (for instance in the western U.S. leveraging on our NASA supported work). The framework could encompass three critical components: the physical and operational factors of the hydropower infrastructure, the inherent drivers of upstream and downstream environments, and the regional energy landscape – which may then feed into cost benefit analysis to populate the financial indicators demonstrating economic feasibility (Figure 1).

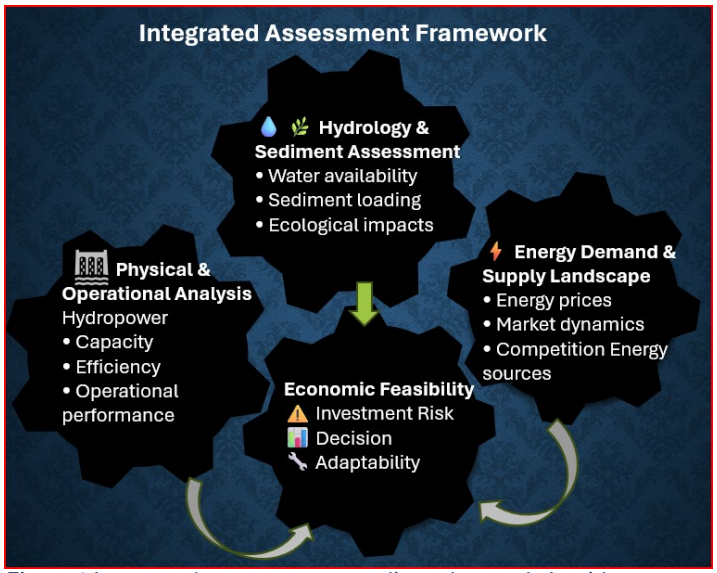


Figure 1 Integrated assessment coupling advanced algorithms to understand the economics and investment risks of decommissioning or retrofitting of hydropower plants in the US

Most hydropower models focus individually on either hydropower efficiency, reservoir operation for optimizing scheduling, or the impacts of water availability on the hydropower sector. Instead of reinventing the wheel, these models can be adapted and integrated to create a new framework that addresses questions regarding the economic viability of retrofitting under various combinations of scenarios involving the physical characteristics of hydropower, upstream and downstream hydrologic and ecological systems, and the energy landscape. We propose to leverage IAF developed by Mishra et al. (2018; 2021) as well as other models including hydrology model developed by Kumar et al. (2006; 2021), Whitney et al. (2023) and Wang et al. (2024); and cost analysis models.

Physical and Operational Analysis: This includes assessing reservoir storage, outlet, and plant capacities, efficiency, operational performance, and the condition of turbines and generators. Evaluation of operating criteria and legal and policy constraints. Additionally, the hydropower plant's adaptability to variable energy demands will be assessed to understand retrofitting requirements and the potential for revenue generation post-retrofit.

Hydrology and Sediment Assessment: This assessment focuses on hydrological changes, streamflow patterns, seasonal and sub-seasonal availability and variability over next few decades, sediment transport, as well as their cumulative effect in moderating downstream floods and droughts. Understanding the impacts of the physical factors driving the long-term availability of water for the power plant and the impacts of

competition from other sectors for water allocation is another important aspect. Conducting such assessment is expected to help identify potential risks, such as declining water levels, sedimentation issues that could limit the operational lifespan of retrofitted turbines, and flood risks that may render investments impractical.

Energy Demand and Supply Evaluation: This includes investigating the current and projected energy demand in the region, which involves analyzing peak load periods and seasonal variations in energy consumption, as well as evaluating the energy supply landscape from various other sources and their competitive advantage. It is important to note that understanding how retrofitted hydropower plants can integrate with traditional and other renewable energy sources, is critical. Furthermore, assessing the existing grid infrastructure and its capacity to accommodate increased energy generation from retrofitted plants will clarify whether the energy produced can be effectively assimilated into the grid without facing curtailment issues, thereby ensuring profitability.

Economic Feasibility Analysis: The outputs from the analyses of the three critical components—physical and operational factors, hydrological conditions, and energy demand and supply—are essential inputs for a comprehensive cost-benefit analysis. This analysis will evaluate the value of retrofitting hydropower systems and provide key financial metrics, including: Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. The economic viability of retrofitting can be evaluated by using the output of the modeling framework – information on the present value of cash inflows generated by the retrofitted system and the present value of cash outflows associated with the investment on retrofitting, the expected annual return on the retrofitting investment (allowing for comparison with other investment opportunities), and the time required to recover the initial investment in retrofitting through the cash flows generated by the enhanced hydropower system (the shorter the payback period, the better).

Uncertainty Analysis: Uncertainty analysis and uncertainty propagation are essential for integrated assessment work due to the variety of data sources and types used in different model components. Additionally, the results from one model often serve as inputs for subsequent models. Assessing uncertainty through simulation ensembles will be a key component.

Relevant existing or new partnerships critical for developing and implementing activities to unlock the opportunity: We will leverage our established partnerships with scientists from following agencies: NASA Goddard Space Flight Center for hydrologic products using the NASA LIS model and Arizona State University, Center for Hydrologic Innovations for streamflow projections; Bureau of Reclamation for multipurpose reservoir operations and planning, NOAA Colorado Basin River Forecast Center for the historic data and models on climatology and hydrology; and Western Area Power Administration for the hydropower fleets. In terms of other DOE national labs, our team includes scientists from Pacific Northwest National Lab, who bring in expertise on reservoir modeling and University of Texas, Arlington, who will support the characterization and modeling of reservoirs and sedimentation.

Success Measure: The decision framework developed adopting this multi-pronged approach is expected to enable decision-makers to assess whether retrofitting selected hydropower plants is economically feasible or poses significant investment risks. This framework will be adaptable, allowing for the evaluation of hydropower sites across the US. The important success measures include quantification of hydropower fleet suitable for retrofit or decommissioning. In addition, the quantification of new capacity that would be available by region based on the analysis.

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