Innovative and Advanced Technology Can Improve Environmental Performance, Increase Generation Efficiency, and Integrate Variable Solar and Wind Generation with Hydropower While Also Improving Technologies Associated with Dam Safety and Dam Removal

The Uncommon Dialogue on U.S. Hydropower: Climate Solution and Conservation Challenge," represents an important opportunity to help address climate change by both advancing the renewable energy and storage benefits of hydropower and the environmental and economic benefits of healthy rivers. Through the Uncommon Dialogue, the participants involved are addressing hydropower advancements, improved dam safety and dam removal as part of the 3 Rs to:

- Rehabilitate both powered and non-powered dams to improve safety, increase climate resilience, improve operational efficiency, and mitigate environmental impacts;
- Retrofit powered dams and add generation at non-powered dams to increase renewable generation; develop sustainable pumped storage capacity at existing dams; and optimize dam and reservoir operations for water supply, fish passage, flood mitigation, and grid integration of solar and wind; and
- Remove dams that no longer provide benefits to society, have safety issues that cannot be cost-effectively mitigated, or have adverse environmental impacts that cannot be effectively addressed.

Addressing the 3Rs will chart hydropower's role in a clean energy future in a way that also supports healthy rivers.

This white paper focused primarily on innovations and technologies to advance hydropower. However, there are also concepts provided on innovations and technologies to advance dam safety and dam removal.

Background: ***The U.S. Hydropower Industry and Dams in the U.S.***

With a U.S. installed base of over 100,000 megawatts (~8.5% of total U.S. electricity capacity in 2018[1]), hydropower and pumped storage hydropower (PSH) can supply substantial low-carbon, secure and affordable electricity generation and storage capacity that can help address climate change, integrate increasing amounts of variable solar and wind power, and enhance grid reliability and resiliency. [1],[2]. Additional new hydropower generation in the U.S. will not come from developing large new impoundment hydropower dams, but instead from identifying and implementing innovative sustainable solutions such as: retrofitting existing dams with higher efficiency and output turbines; powering non-powered dams, canals, and conduits; developing new technology for low-impact capacity that can simultaneously enhance watershed restoration and climate adaptation; and identifying novel approaches for dam inspection and removal when needed or required. To capitalize on this opportunity, increased public and private investment and well-designed policies, such as federal tax credits and clean energy standards, are critical to reduce emissions and ensure a timely transition to a clean energy grid.

This document focuses on highlighting innovative opportunities targeted at modernizing the approach to support a 21st century hydropower industry and dams in the U.S.

Opportunities for Hydropower and Dams in the 21st Century

There is an array of opportunities that can increase the output, provide operational flexibility, and lower the impacts of the existing U.S. hydropower generation and storage facilities. Much of this opportunity reflects innovative technology and system design concepts aimed at improved performance, reduced environmental effects and lower costs.

Progress with any of these innovations may require performance testing and validation at relevant scale at existing or future testing facilities, such as academia, national labs, and private institutions. Modern technologies will also need to accommodate demands for greater operational flexibility with the growing need to integrate variable solar and wind into the electric grid, more extreme weather, and increasingly competitive electricity markets.

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[1] EIA figure of 1098 GW of utility scale generation for US in 2018
https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

Most importantly, development and installation of modern technologies must consider environmental and cultural impacts prior to implementation to avoid the potential risk that can be created by new development damage to these values at the proposed project site.

Promising opportunities include:

- Innovative technologies and solutions aimed at unlocking large market opportunities at non-powered dams (NPDs), canals and conduits. These include: high efficiency variable-speed turbines and generators, modular designs that reduce need for complicated and costly civil works, with a focus on overall increased system efficiency, reliability, and safety[2];
- Environmentally focused designs, such as fish-friendly turbines, aerating turbines[3], environmentally acceptable lubricants and innovative oil-free-designed machinery, and selective water withdrawal and release systems[4] to better manage and mitigate potential damage to downstream water quality and temperature;
- Improved passage technologies for water, fish, sediment, and recreation such as "nature-like" downstream passage structures, new alternatives to traditional "trap and haul" transport methods and 'conventional' fish passage structure design for more cost-effective upstream fish migration[5];
- Standardized modular hydropower[6] approaches that involve off-river construction of separate modules – for power generation, fish passage, stream connectivity, water quality improvement, streambed interface, and grid interconnection – and their integration into facility configurations that maintain ecological and social functionalities of rivers;

[2] https://www.ferc.gov/industries/hydropower/gen-info/guidelines/10-17-19-notice.pdf
[3] http://www.cubehydropartners.com/news/ge-aerating-turbine-commissioning/
[4] https://www.portlandgeneral.com/corporate-responsibility/environmental-stewardship/water-quality-habitat-protection/deschutes-river/our-story
[5] https://www.fws.gov/northeast/fisheries/fishpassageengineering.html
[6] https://www.energy.gov/eere/articles/funding-selections-announced-innovative-design-concepts-standard-modular-hydropower

- New advanced PSH technologies that can help with grid integration of increasingly large quantities of variable wind and solar power by providing operating reserves, grid flexibility, and system inertia,
- A number of existing hydropower plants could potentially be converted to “pump-back” PSH plants. This conversion would not require the construction of new dams or reservoirs and would consist of either replacing the turbines with reversible pump-turbines or adding a pumping station to an existing hydropower plant. The pump back PSH makes better use of the existing water inflows by pumping the water from below the dam back to the existing reservoir.

- Emerging technologies for hybridization with hydropower units or plants that provide opportunities to co-optimize investments and operations, either for the benefit of the grid or specific end-uses. Hybridization provides diverse opportunities for increasing profitability of hydropower assets. Examples include, but are not limited to, integration with batteries and other emerging storage technologies that can enable hydropower to provide frequency regulation and energy shifting better than hydropower on its own[7], while also potentially helping to reduce hydropower peaking to improve environmental performance decreasing flow fluctuations from peaking plants, co-location with other renewable sources such as solar, and co-generation of green hydrogen. Hybridization with energy storage can also provide opportunities for small hydropower to serve as backup power for local communities during emergency events[8]. Increasingly, there may also be opportunities such as hydrogen production. Hybridization can directly produce products used as input to industry[9], while the oxygen byproduct can help maintain the

Innovative Example: Closed-Loop PSH

An important sustainable alternative to today's existing "open-loop" systems, is a closed-loop system. A strategically planned closed-loop pumped storage plant does not necessarily involve a new river-based dam and reservoir, or the continual use of river water. New PSH technologies, such as adjustable-speed, ternary, and quaternary units have a potential to provide even more flexibility to power system operations and, thus, enable high penetrations of variable renewables into the grid. At present, PSH is the only commercially proven long-duration energy storage (LDES) technology that has capabilities to provide large quantities of energy storage that are needed to support transition to carbon-free power systems. LDES is the key to providing resiliency to power systems with remarkably high penetration of variable renewables, especially in cases of extreme weather and other events.

Other emerging forms of energy storage include battery and advanced compressed air storage systems. Pumped storage and other energy storage systems will be a valuable tool for integrating the rapidly growing fleet of variable renewable wind and solar projects as well as providing flexibility for existing hydropower projects that are constrained by limited storage capacity and currently unable to fully participate in a dynamic market.

[7] "Something Old, Something New America Electric Power", https://emarketplace.energystorage.org/wp-content/uploads/2021/05/463466767.pdf
[8] "National Laboratory, Municipal Power Utility Test Energy Storage Tech for Small Hydropower Generation," https://inl.gov/article/national-laboratory-municipal-power-utility-test-energy-storage-tech-for-small-hydropower-generation.
[9] "The green hydrogen revolution: hydropower's transformative role," International Hydropower Association, May 2021.

dissolved oxygen levels in water required to support aquatic life.

- The primary cause of slower PSH development in the U.S. is related to high costs associated primarily with civil works. The cost associated with civil work can at times be up to 60% of the total project's costs, despite geotechnical analysis being conducted prior to breaking ground. DOE has initiated and published a study to address the FAST commissioning of PSH, reducing time, cost, and risk. Additional research in technology is needed to further reduce the time and cost in areas, including, but not limited to, excavation, tunnel boring, pumphouse, and powerhouse civil design.
- Adding adjustable-speed pumps to closed-loop pumped storage systems provide an additional advantage in their ability to vary power consumption during the pumping mode of operation, thereby providing frequency regulation during pumping. Other innovative pumped storage approaches use more cost-efficient geotechnical and commissioning practices, existing water tanks for smaller distributed electricity storage systems, and improved tools to better schedule pumped storage to maximize system values[10].
- New sensors and controls architecture that take advantage of large data sets and machine learning that can co-optimize for control, monitoring and prognostics of hydropower assets, enhancing operational flexibility for hydropower to better integrate increasing amounts of variable renewable resources, including solar and wind to improvements in O&M. Integration of these resources typically entails increased cycling (starts, stops, and ramping), increased flexibility and response time, and more adjustments in shorter time periods, which can affect maintenance schedules and upgrade decisions. Improved monitoring and prognostics can inform asset owners on the impact of these changes in operation. Updated controls can help adapt operations to integrate renewables, mitigate the associated potential changes in wear and tear, and minimize unplanned outages.
- New software that will enable optimal dispatch for a variety of hydropower assets, while balancing revenue, environmental requirements, and water availability. Today, water flows and hydrological patterns are changing due to climate change, challenging the

[10] https://energystorage.org/why-energy-storage/technologies/pumped-hydropower/

historical water availability curves and approaches. There is an urgent need for better tools to balance competing demands in making dispatch decisions, coupled with increasing demands for grid services that support integration of variable renewable generation. Machine learning that can take advantage of rapidly growing imagery and physical data from remote sensing is suited to address this problem, particularly when combined with the wide availability of low-cost, high performance cloud computing. Application of digital twin concepts and software technology will also assist in improving optimization of hydropower for its multiple needs while reducing operational costs.

Progress with these innovations may require performance testing, validation, and demonstration to maximize the adoption by the owners, the stakeholders, and the community at large.

Actions & Next Steps:

The following actions are needed to maximize the contributions that low-carbon hydropower and dam safety and removal technologies can provide the U.S. energy and dam systems to minimize their impacts and cut costs. To be most effective, these technologies should also be responsive to fast-rising demands for integrating variable solar and wind generation, operating in increasingly extreme weather in conjunction with aging infrastructure, and competing in increasingly competitive electricity markets, while also achieving the mutual goals of improved hydropower and healthy rivers. There are multiple actions that can better position hydropower and pumped storage, dam safety and dam removal to address these opportunities and challenges:

1. Increase research, development, demonstration, and deployment (RDD&D) funding at key agencies, including the Department of Energy (Office of Science, ARPA-e and the Water Power Technologies Office), the U.S. Army Corps of Engineers Hydropower Office, the National Oceanic and Atmospheric Administration, and other key research agencies (e.g., Bureau of Reclamation and DOI [USGS and USFWS] Fish Passage Research Centers).
2. Adopt policies such as well-designed federal tax credits and clean energy standards, to match the scale of the climate crisis and take advantage of technical opportunities to enhance the efficiency and environmental performance of existing and new hydropower facilities.

3. Demonstrate and validate the performance and reliability of new hydropower and energy storage technologies to increase developer and investor confidence. Demonstration activities should span lab-to-full-scale. Specific actions include:
    - Developing and validating hydropower technologies that improve environmental monitoring, mitigation, and protection, with advancements such as fish-friendly turbines that reduce fish injury and mortality, fish passage structures to facilitate upstream and downstream fish movements, auto-venting turbines to ensure availability of adequate oxygen levels in outflows, as well as water temperature controls.
    - Developing and demonstrating scalable modular civil structure designs for new generation at existing non-powered dams, i.e., precast, pre-assembled civil structure components that can reduce overall costs and the environmental impact of constructing civil structures in a river system.
    - Demonstrating closed-loop pumped storage projects that are located off-stream and provide energy storage that minimizes impacts to aquatic habitats and related species, cuts evaporation and water loss, and minimizes impacts to historical and cultural sites. Include collaboration and consultation with Tribes and the local communities. Modular design of closed-loop storage systems, using commercial off-the-shelf pumps, turbines, piping, tanks, and valves, may cut investment costs, reduce development risk, and improve implementation. Additionally, small, modular closed-loop PSH systems could be a competitive option for distributed energy storage applications.
    - Developing and demonstrating emerging and existing storage technologies that can provide increased flexibility for existing hydropower and other forms of renewable generation. Examples of the work needed in this area include, proving the breadth of value propositions that hybridization can provide, ways these technologies can be stacked in practice, and approaches to integrating the operations of hybridized plants with existing asset owner / utility practices.
    - Developing and demonstrating information software and hardware to improve the operational flexibility of hydropower facilities, thereby providing the flexible capacity needed to integrate greater amounts of variable wind and solar generation.

- Demonstrating increased operational flexibility of existing federal and non-federal hydropower assets through the development and implementation of cost-effective control, monitoring and prognostic tools, such as digital twin technologies.
- Demonstrating innovative approaches to small-scale and/or distributed hydropower that integrate low-head, fish-friendly technology into strategically sited structures, both built and natural, that can potentially generate multiple environmental co-benefits. These potential benefits include, restored watersheds, habitat creation, improved water quality, and sustained increases in groundwater recharge rates.
- Development of advanced software tools to optimize the operations and reservoir management of multiple hydropower and PSH plants in a cascade or for the entire river basin system, while satisfying all operational and environmental constraints.
- Development of forecasting tools to predict precipitation patterns. Research to date has shown that water patterns are changing, additional research and tools are needed to predict the varying water patterns in the way the precipitation is falling (snowpack versus rain), the length of time of precipitation flow and regionality.
- Develop research and demonstration programs for low-cost sediment removal. The U.S. hydropower system is aged, and sediment buildup decreases efficiency and lessens the lifetime of the project. This will in turn improve project efficiency and environmental performance.
- Develop and promote standardized testing for advanced materials that increase durability of machines while operating flexibly as part of variable renewable energy integration.
- Perform research and demonstration of increased operational flexibility aimed at improving the integration of variable renewables onto the grid. This operational flexibility comes at a cost to the equipment, which may not be adequately captured or compensated, and must be further understood and quantified.

4. Increase research and development in technologies that address dam safety and dam removal.
    - Expand and develop methods and criteria for the use of remotely sensed data, including data collected by UASs, for the assessment of dams. For example, LiDAR

data collected from both traditional and unmanned aircraft has been used to map small changes in the surfaces of dams and the adjoining terrain.

- Conduct research to assess how changing rainfall intensity and frequency may affect the risk of flood-induced failures of dams. Develop methodologies to incorporate anticipated climate trends in the hydrologic design of dams.
- Conduct research and methodologies for sediment removal and management as it relates to dam removal. Buildup of sediment occurs through the life of a dam. Once a decision has been made to remove a dam, a determination must be made on how to address sediment with minimized impact to downstream areas. Research and methodologies are also needed related to the movement of undesirable aquatic species in dam removal.