Innovative and Advanced Hydropower Technology Can Improve Environmental Performance, Generation Efficiency, and Grid Resilience

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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. Uncommon Dialogue participants are working to address U.S. hydropower, dam safety, and dam removal through the "3Rs":

- **Rehabilitate** both powered and non-powered dams to improve safety, increase overall 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; and optimize dam and reservoir operations for water supply, water quality, fish passage, flood mitigation, and grid integration of solar and wind; and
- **Remove** dams that no longer benefit society, have safety issues that cannot be cost-effectively mitigated, or have adverse environmental impacts that cannot be effectively addressed.

Addressing the 3Rs will enhance hydropower's role in a clean energy future while also supporting healthy rivers and climate mitigation and adaptation efforts in response to the increase in flooding, droughts, dam failures and other challenges related to the climate crisis.

This white paper highlights innovative approaches to a climate-ready, river-friendly hydropower industry that operates safe and resilient U.S. infrastructure. The paper focuses primarily on opportunities for innovations and technologies in hydropower, as well as dam safety and dam removal. This is followed by proposed actions and next steps to advance two of the 3Rs: Rehabilitate and Retrofit, while highlighting the need for continued research into the third R: Removal. The white paper targets institutions focused on research, development, demonstration, and deployment (RDD&D) in hydropower, river restoration, and public safety.

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

The U.S. has an installed base of more than 103,000 megawatts (~9% of the total U.S. electricity capacity in 2021 [1]) of hydropower and pumped storage hydropower (PSH) capacity, and pumped storage provides 90 percent of U.S. storage capacity. This resource can supply substantial renewable, secure, and affordable electricity generation and storage capacity that helps address climate change by reducing fossil fuel-based emissions, integrating increasing amounts of variable solar and wind power, and enhancing grid reliability and resiliency. [1],[2] Additional new hydropower generation in the U.S. is not expected to come from developing large new impoundment hydropower dams, but instead from identifying and implementing innovative, sustainable solutions. These include, but are not limited to:

- Retrofitting existing hydropower dams with higher efficiency and higher output turbines;
- Powering non-powered dams, canals, and conduits;
- Developing new hydro-based solutions for low-impact sustainable capacity that can simultaneously enhance watershed restoration and climate adaptation; and
- Identifying and removing unsafe and/or outdated dams to benefit the environment and climate resilience.

To capitalize on this opportunity, increased public and private investment and energy policies that advance both healthy rivers and hydropower generation (e.g. federal tax credits for the 3Rs and clean energy standards) are critical to reduce emissions and other environmental impacts, improve dam safety, and ensure a timely transition to a clean energy grid.

[1] EIA figure of 1098 GW of utility scale generation for US in 2021https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

Opportunities for Hydropower and Dams in the 21st Century

An array of opportunities, including innovative technology and system design concepts, could increase the renewable energy generation output, provide operational flexibility, and lower the environmental impacts of U.S. hydropower generation and pumped storage facilities.

Progress with any of these innovations may require performance testing and validation at relevant scale at existing or future testing facilities, which are operated by academia, national labs, private institutions or in cooperation with equipment suppliers. New technologies will also need to be operationally flexible due to the growing need to integrate variable solar and wind into the electric grid, address extreme weather events through advanced forecasting, and be successfully developed in increasingly competitive electricity markets.

Future adoption and deployment of technologies is outside the scope of this white paper and the authors acknowledge that collaboration and free, prior and informed consent with key groups, such as Tribes and local communities will be an integral component of future project development. Understanding and addressing these effects prior to implementation will avoid potential negative impacts from new development on these resources and affected communities.

Promising opportunities include:

- **Innovative technologies and solutions aimed at unlocking large market opportunities at existing non-powered dams (NPDs), canals, and conduits**. These include high efficiency variable-speed turbines and generators, or modular designs that reduce the 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 and fish deterrent methods, aerating turbines[3] and systems, environmentally acceptable lubricants and

[2] https://www.ferc.gov/industries/hydropower/gen-info/guidelines/10-17-19-notice.pdf
[3] http://www.hydroppi.com/uploads/3/4/5/6/34564986/hvi2015_industry_experience_with_aerating_turbines.pdf

innovative oil-free machinery design, and selective water withdrawal and release systems[4] to better manage and mitigate potential harm 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 fish passage structures designed for more cost-effective upstream and downstream fish migration.[5]
- **Approaches that involve off-river construction** of modules for pre-assembled equipment, fish passage, stream connectivity, water quality improvement, streambed interface, and grid interconnection; and their integration into facility configurations to maintain or enhance ecological and cultural functionalities of rivers.
- **New advanced PSH technologies** do not require building new dams on rivers and can increase energy storage and integrate increasingly large quantities of variable wind and solar power into the electrical grid over longer timeframes than other storage technologies, while providing operating reserves, grid flexibility, fast ramping, and system inertia (see the box below).
- **Converting existing hydropower projects to "pump-back" PSH plants** would not require constructing 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. These pump-back PSH conversions would improve the use of the existing water inflows by pumping water from below the dam back to the existing reservoir with design considerations to protect downstream river ecological and cultural benefits.

[4] https://portlandgeneral.com/about/rec-fish/deschutes-river/our-story
[5] https://www.fws.gov/northeast/fisheries/fishpassageengineering.html

- **Emerging technologies for hybrid hydropower units or plants to co-optimize investments and operations**, either for the benefit of the grid or specific end-uses. Hybridization provides diverse opportunities to increase the value of hydropower assets. Examples include, but are not limited to:
    - Integration with batteries and other emerging storage technologies that can further enable hydropower to expand on its ability to provide frequency regulation and energy shifting[6].
    - Improved environmental performance by decreasing flow fluctuations, co-location with other renewable sources such as solar, and co-generation of green hydrogen.
    - Hybridization with energy storage for small hydropower to serve as backup power for local communities during emergency events.[7]
    - Increasingly, there may also be opportunities such as green-hydrogen production. This type of hybridization can produce byproducts that can improve water quality[8] by re-injecting the oxygen

Innovative Example: Closed-Loop PSH

An important alternative to today's existing "open-loop" systems is a closed-loop system. A strategically planned closed-loop pumped storage plant does not 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, could provide even more flexibility to power system operations and, thus, enable high penetrations of variable renewables into the grid. PSH currently provides the majority of the nation's long-duration energy storage (LDES) capacity and can provide large quantities of energy storage that are needed to support the transition to low-carbon power systems. LDES is the key to providing resiliency to power systems with remarkably high penetrations of variable renewables, such as wind and solar, 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 to integrate the rapidly growing fleet of variable renewable wind and solar projects, as well as to provide flexibility for existing hydropower projects that are constrained by limited storage capacity and currently unable to fully participate in a dynamic market.

[6] "Something Old, Something New America Electric Power", https://emarketplace.energystorage.org/wp-content/uploads/2021/05/463466767.pdf

[7] "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.

[8] "The green hydrogen revolution: hydropower's transformative role," International Hydropower Association, May 2021.

in the river to improve dissolved oxygen levels.

- **Technology to further reduce the time and cost of civil works**. This includes, but is not limited to, coffer dams, excavation, tunnel boring, pumphouse, and powerhouse civil design. The primary cause of slower PSH development in the U.S. is related to high costs and time associated with civil works (e.g., geotechnical surveys, construction), which can represent up to 60% or more of total project costs, not including pre-construction geotechnical analysis. DOE published a study to address the Furthering Advancements to Shorten Time "FAST" commissioning of PSH, reducing time, cost, and risk.
- **Adding adjustable-speed pumps to existing pumped storage systems** provides the ability to vary power consumption during the pumping mode of operation, thereby regulating frequency 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 scheduling tools to maximize system values.[9]
- **New sensors and controls architecture** can analyze large data sets and machine learning to co-optimize for control, monitoring, and prognostics of hydropower assets. These technologies can enhance operational flexibility for hydropower to better integrate increasing amounts of variable renewable resources, such as wind and solar, and result in improvements in maintenance frequency and scheduling. Integration of variable energy resources typically entails increased cycling (starts, stops, and ramping), increased flexibility and faster response time, and more adjustments in shorter time periods, which can affect the frequency of maintenance equipment useful life, and upgrade decisions. Improved monitoring and prognostics can inform asset owners of the impact of these changes to operations. Updated controls can help operations integrate renewables, mitigate the associated potential changes in wear and tear, and minimize unplanned outages.
- **New software to enable optimal dispatch for a variety of hydropower assets,** while balancing resources, environmental requirements, and water availability. Today, water flows and meteorological patterns are changing due to climate change, challenging the

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

historical water availability assessment techniques 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 well-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 adoption by owners, stakeholders, and the community at large.

Actions & Next Steps:

The following actions are desired to maximize the contributions that hydropower and dam safety and removal technologies can provide to the U.S. energy supply, to minimize their impacts, and to and cut costs. To be most effective, these technologies should be responsive to fast-rising demands to integrate 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.

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. **Demonstrate and validate the performance, environmental sustainability, and reliability of new hydropower and energy storage technologies** through public-private partnerships, to increase developer, investor, and stakeholder confidence. Demonstration activities should span from laboratory scale to commercial scale. Collaboration and free,

prior, and informed consultation with key groups, such as Tribes and local communities is an integral component of future project development. 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, and auto-venting turbines to ensure availability of adequate oxygen levels in outflows.
- 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-river and provide energy storage that minimizes impacts to water quality, aquatic habitats and related species, cuts evaporation and water loss, and avoids impacts to historical and cultural sites. Demonstrate that modular design of closed-loop storage systems using commercial off-the-shelf pumps, turbines, piping, tanks, and valves cuts investment costs, reduces development risk, and improves implementation. Additionally, small, modular closed-loop PSH systems could be a competitive option for distributed energy storage applications.
- Developing and demonstrating the combination of emerging and existing storage technologies that can increase flexibility with existing hydropower and other forms of renewable generation. Examples of the work needed in this area include proving that hybridization can provide ways that projects can stack these technologies 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 of hydropower generation and integrating greater amounts of variable wind and solar generation.

- Demonstrating increased operational flexibility of existing federal and non-federal hydropower dams 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 facilities that integrate economic, low-head, and fish-friendly technology into strategically sited structures, both built and natural, with multiple environmental and cultural benefits. Benefits include restored watersheds, new habitat, improved water quality, increased recreation, protection of cultural resources, and sustained increases in groundwater recharge rates.
- Developing advanced software tools to optimize the operations and reservoir management of multiple hydropower and PSH plants in a cascade or for an entire river basin system, while satisfying operational constraints and reducing environmental impacts.
- Developing forecasting tools to predict meteorological patterns. Research to date shows that water patterns are changing, and that additional research and tools are needed to predict the varying water patterns in the form of precipitation (snow versus rain), the duration of precipitation events, and regional patterns.
- Developing research and demonstration programs for low-cost sediment management, recognizing that sediment buildup in reservoirs decreases efficiency and lessens the lifetime of the project. This would improve project efficiency and environmental performance.
- Developing and promoting standardized testing for advanced materials that increase durability of machines while operating flexibly as part of variable renewable energy integration.
- Performing research and demonstration of increased operational flexibility to improve 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.

3. **Increase research and development of technologies that address dam safety and dam removal**. Specific actions include:

- Expanding and developing methods and criteria for the use of remote sensing data, including data collected by Unmanned Aircraft Systems (UASs), for the assessment of civil structures and dam safety inspection. For example, LiDAR data collected from both traditional and unmanned aircraft can be used to capture high-resolution images of changes to structures and/or adjoining terrain that may signal dam safety issues.
- Conducting a study on how climate change will impact dam safety. Recognizing the complexity of such a study, the focus could be on those watersheds that include the riskiest dams. The study can model different climate change scenarios to understand how precipitation and rapid snow melt, among other impacts, might affect the risk of dam failures.
- Conducting research on methodologies for sediment removal and management as it relates to stream restoration associated with dam removal. Buildup of sediment occurs through the life of some dams. Once a decision to remove a dam is made, a program must be developed to address sediment management while minimizing impacts to downstream areas. Research and methodologies are needed on controlling or managing undesirable aquatic species in dam removal.