3 HYDROPOWER PROGRAM OVERVIEW

Hydropower has provided clean, low-cost electricity for over a century as the nation's first renewable source of electricity. Today's evolving power system has created new opportunities for hydropower to play an important role in a 100% clean energy future, using existing technologies and infrastructure. In 2019, hydropower provided 6.6% of the electricity on the grid and accounted for 38% of U.S. renewable electricity generation. Pumped storage hydropower (PSH) is the largest contributor to U.S. energy storage with an installed capacity of 21.9 gigawatts (GW), or roughly 93% of all commercial storage capacity in the United States.[19] Hydropower, including PSH, provides flexibility, inertia, storage, and grid services to support the integration of variable renewables like wind and solar energy. Additionally, PSH offers unique flexibility and long-duration storage, and multiple new large-scale PSH projects have started development in recent years.

Hydropower and Pumped Storage: Benefits and Potential Impacts

Enabling a 100% Clean Energy Future

Hydropower and PSH provide flexibility, storage, and other grid services over time scales from seconds to seasons, while facilitating greater penetration of variable solar and wind resources. Development of novel hydropower technologies can also support energy-water infrastructure modernization in irrigation districts and remote communities.

Hydropower Flexibility

The evolving power system creates opportunities for hydropower to serve as a critical asset in a grid served entirely by clean energy. The increased deployment of variable renewable energy sources like wind and solar energy has created a need for resources that can store energy or quickly change their operations to ensure power system reliability and resilience. Hydropower has historically been operated primarily as a baseload-scheduled or predictable peaking resource, generating energy over relatively long time scales. However, the technical characteristics of hydropower and PSH systems make them well-suited to provide a range of storage, flexibility, inertia, and other grid services that can enable increased integration of variable renewables in a future decarbonized power sector.

The ability of hydropower to provide this flexibility across many time scales is often bounded by technical constraints on machines and hydraulics, as well as policies such as limits on water flows to meet environmental requirements. With the evolving grid, hydropower owners and operators face a complex decision-making process in choosing how to operate their plants, balancing trade-offs associated with compensation for services, impact on machines, and meeting license requirements. Therefore, understanding how hydropower can provide the most value in systems that include other types of flexible generation, storage, and load resources is critically important. In addition, technology innovation to enhance hydropower's capabilities—including faster and more frequent ramping, more frequent starts and stops, and enhanced frequency and voltage control—is needed, targeting the highest-value services crucial for the transition to a primarily renewable power system.

Pumped Storage: Cost-Effective, Long Duration Storage Asset

As the largest existing storage resource in the United States and worldwide, PSH will play a unique role as the power system is decarbonized. PSH systems are configurations of two water reservoirs at different elevations that can generate power (discharge) as water moves down through a turbine; this draws power as it pumps water (recharge) to the upper reservoir. PSH systems fall into two primary categories: open-loop (continuously connected to naturally flowing water) or closed-loop (reservoirs not connected to an outside body of water). PSH can provide

[19] Uría-Martínez, R., Johnson, M., and Shan, R., 2021. "U.S. Hydropower Market Report." https://www.energy.gov/eere/water/downloads/us-hydropower-market-report.

services ranging from fast frequency response to 12-hour energy storage, or even longer timescales. By providing large-scale storage, PSH can reduce transmission congestion and serve as a transmission alternative, particularly in an electric grid dominated by renewable energy.

Despite an absence of large-scale PSH deployments in past decades, a resurgence of interest in PSH in recent years has advanced several U.S. projects further in the development pipeline. The number of PSH projects in the U.S. development pipeline increased by 31% in 2019, with 67 new PSH projects in various stages of evaluation or development across 21 states, totaling 52.48 GW. The Federal Energy Regulatory Commission (FERC) issued 14 preliminary permits for PSH in 2019, and an additional 17 preliminary permit applications were pending at the end of the year. PSH has also gained increasing interest internationally, with over 50 GW currently under construction around the world, resulting from innovative policy and market mechanisms to successfully build new PSH projects.

Although PSH comprises 95% of utility-scale energy storage in the United States, one of the challenges to developing new pumped storage projects is potential environmental impacts. However, new closed-loop pumped storage projects are being developed internationally and are expected to produce minimal environmental impacts compared to traditional open-loop designs. Other challenges faced by PSH developers include market uncertainty, permitting challenges, and high capital cost. WPTO focuses on addressing these deployment challenges through improved valuation of proposed projects to account for future market uncertainty, accurate modeling, industry acceptance, and through efforts to reduce permitting timescales. WPTO also funds innovative technologies and construction methods to dramatically reduce capital costs and construction timelines for PSH, which require rigorous testing and demonstration to derisk and ultimately deploy.

Expanding the Value of Sustainable Hydropower

There are more than 90,000 existing dams across the nation, of which about 2,500 have hydropower facilities for electricity generation. Dams serve many roles besides power generation such as flood control, water supply, irrigation, and recreation. At the same time, many dams pose safety risks due to aging infrastructure or have outlived their usefulness. Retrofitting existing dams and adding generation at non-powered dams (NPDs) can increase renewable energy production, while rehabilitating dams can address safety problems, increase climate resilience, and mitigate environmental impacts. WPTO R&D focuses on retrofitting and rehabilitating dams, but also acknowledges that it may be necessary to remove obsolete dams that no longer provide benefits to society, have safety issues that cannot be cost-effectively resolved, or have harmful impacts on the environment that cannot be adequately addressed.

Though hydropower plants were historically built as cost-effective means to provide electricity, it is currently challenging for new hydropower projects to compete with the rapidly decreasing costs of wind, solar, and natural gas on a per-kilowatt-hour (kWh) basis. However, hydropower offers other unique benefits through connections to the water supply and associated infrastructure. For example, cost savings from hydropower project developments have allowed irrigation districts to modernize their irrigation systems. The process of converting unlined, open canals to pressurized pipes saves water, decreases pumping costs for farmers, decreases nutrient loading downstream, and increases on-farm productivity. Other benefits hydropower can enable include targeted aquifer recharge and energy independence. Hydropower combined with water distribution and treatment systems can power behind-the-meter applications for resilience and reliability within water networks or neighboring infrastructure. This energy-water nexus means that new hydropower projects can enable a large suite of benefits by serving multiple social, environmental, and energy needs. Identifying new value propositions—in concert with efforts to drive down costs and improve environmental performance—can enable hydropower to play an even greater role in healthy communities than it has historically.

The opportunity to leverage water supply systems is vast—there are thousands of miles of existing conduits in the United States that are used to transport and distribute water for agriculture, ground-water pumping and injection, water treatment, industrial uses, etc. Energy can be harvested from these existing systems with minimal disruptions, but major technology innovation is needed to do so in a cost-effective, sustainable manner. WPTO supports developing new modular and standardized hydropower technologies to leverage these systems, capitalizing on advanced manufacturing and materials, while preserving and enhancing stream functionality. To commercialize these technologies, WPTO works to develop testing capabilities and facilities to validate hydraulic, mechanical, electrical, civil/structural, and biological performance.

Understanding and Adapting to Climate Change Impacts on Hydropower

While hydropower can play a critical role in decarbonizing the electric grid to mitigate climate change, it will also experience negative impacts due to climate change. Water availability and hydropower generation are fundamentally affected by changes in hydrological patterns and extreme weather events. Hydropower relies on water supplies from streams, rivers, groundwater, and snowpack, which are expected to experience the most acute impacts of climate change. Globally, increasing temperatures are altering regional patterns of precipitation that deliver water to rivers and reservoirs and are intensifying floods and droughts across the United States. Increasingly unpredictable precipitation is already threatening infrastructure, food, and water security. As temperatures continue to rise, changes in hydrologic systems will become harder to predict and predictions will become more uncertain. Because hydropower intersects infrastructure, water, and energy, it will be crucial to national climate adaptation efforts. A significant challenge remains in reimagining hydropower, energy technology development, and resource management to optimize human health and safety, water security, and clean energy.

The cascading hazards associated with climate change will significantly impact utility operations and create a disclosure risk for investors and asset owners. Evaluating these risks requires complex analyses of emerging climate signals, understanding impacts on generation and marketing of hydropower, and the need to develop climate resilience measures. Hydropower utilities need to perform such climate risk analyses and holistic examinations of business operation, value, and adaptation strategies, but not all utilities have the resources or the expertise to do so. WPTO will advance climate and hydrologic science as well as develop hydropower decision-making tools to adapt energy-water infrastructure to the demands of a changing climate. These analytical tools, infrastructure solutions, and adaptation processes can ensure the reliability of our current system and spur the development of adaptive, flexible solutions for a climate resilient future.

Climate change will disproportionally impact regional water supplies across the United States and pose challenges for reservoirs. Most reservoirs are multipurpose and may serve as drinking water supply, flood control, and recreation, in addition to generating hydroelectric power. Reservoirs need to adapt to address evolving demands on water driven by population growth, agriculture, and ecosystem preservation; and hydropower reservoir management can create opportunities to enhance climate resilience and adaptation for remote or socioeconomically vulnerable communities. In the coming years, WPTO will work to advance climate science and adaptation, analyze infrastructure design and water management, enhance environmental sustainability, and ultimately build socioeconomic resilience in communities challenged by climate change.

Building Our Fleet Back Better

As the fleet ages, maintaining efficient and cost-effective operations and ensuring the security of our critical infrastructure becomes increasingly challenging. Modernization of the existing hydropower fleet represents a significant opportunity to restore reliability and performance and add new cutting-edge technologies.

Modernization through Asset Management

Asset management refers to the systematic governance approaches to hydropower systems and includes the mechanical, electrical, civil, and digital structures within the hydropower plant. For the existing fleet, operation and maintenance costs and outage times are increasing, leading to increased system costs. New asset management practices and technologies are needed, including condition-based maintenance than prescriptive maintenance schedules.

Digitizing hydropower plants will allow improvements in maintenance practices, streamline workflows, improve reliability and safety, and reduce costs through holistic monitoring and management of components. The development and integration of digital systems also require appropriate cybersecurity protections to ensure the resilience of these critical infrastructure assets. While a vast majority of potential attacks are prevented, notable exceptions include a successful intrusion into the dam controls of Bowman Dam in 2013 and an interruption of electrical system operation for an unnamed utility in 2019. A recent study of the power sector found that such cyberattacks were increasing in frequency and sophistication. With its range of legacy components and diverse system structure, hydropower plants have unique cyber vulnerabilities. WPTO supports research in operations and information technologies to develop unique cybersecurity solutions for the hydropower industry.

Modernization through Environmental Mitigation and Relicensing

Non-federally owned hydropower facilities require a license from FERC to operate, and license terms typically last for 30-50 years. At the time of licensing or relicensing, the environmental impacts of a hydropower facility are rigorously evaluated. Relicensing provides an opportunity for communities to (1) establish goals for the environment, recreation, energy, and other benefits; (2) evaluate site- and basin-level potential impacts in relation to goals; and (3) define measures to avoid, minimize, or mitigate impacts. In the next decade, approximately 30% of U.S. hydropower will need to go through relicensing. Similarly, federally owned facilities need to provide mitigation measures and ensure compliance with conditions and operational terms set through stakeholder processes to reduce risks to the environment. Environmental measures can account for up to 30% of the federal wholesale rate, and solutions for effective environmental outcomes and cost reductions are essential.

Cost-effective environmental tools and technologies assist hydropower owners and operators in meeting environmental permitting requirements. For existing hydropower assets, new technologies, tools, and data are needed to better understand and improve the environmental performance of hydropower facilities, particularly on issues related to fish passage, water quality, and water release management. Maintaining target levels of dissolved oxygen is crucial to the health of fish and other freshwater organisms. Safe, timely, and comprehensive water-quality data collection supports more accurate predictive, real-time modeling for dissolved oxygen. High priority needs for fish passage at hydropower dams include multispecies management technologies; advancing methods to relate site-level impacts to population responses for sensitive and Endangered Species Act-listed species; fundamental research in fish behavior, movement, and lifecycles; and information and tools to increase fish survival through turbines and other hydropower structures. WPTO-funded technologies, tools, and data support optimization of dam and river operations to maximize power generation revenue with improved operation control. WPTO also enables the development of models and strategies for environmental protection, which reduces FERC and state water quality compliance costs.

Hydropower Program Vision and Mission

To achieve the vision of the Hydropower Program, WPTO conducts research, development, demonstration, and commercial activities to advance transformative, cost-effective, reliable, and environmentally sustainable hydropower and pumped storage technologies; better understand and capitalize on opportunities for these technologies to support the nation's rapidly evolving grid; and improve energy-water infrastructure and security.

VISION

A U.S. hydropower and pumped storage industry that modernizes and safely maintains existing assets; responsibly develops new low-impact hydropower; promotes environmental sustainability; and supports grid reliability, integration of other energy resources, and energy-water systems resilience.

The Hydropower Program comprises five R&D activity areas, which represent the program's strategic approach to addressing the challenges faced by U.S. hydropower stakeholders (Table 10). The Hydropower Program launched a public RFI to solicit feedback from stakeholders on its revised programmatic strategy in FY 2020. Through the revised hydropower strategy, WPTO aims to clearly communicate the rationale for and organization of possible DOE-supported hydropower R&D. Table 10 summarizes the foundation of the revised strategy, and Table 11 describes both the challenges facing the U.S. hydropower industry and the Hydropower Program's approaches to address these challenges.

Table 10. Hydropower Program Overview

HYDROPOWER PROGRAM MISSION		
Conduct research, development, demonstration, and commercial activities to advance transformative, cost-effective, reliable, and environmentally sustainable hydropower and pumped storage technologies; better understand and capitalize upon opportunities for these technologies to support the nation's rapidly evolving grid; and improve energy-water infrastructure and security.		
INNOVATIONS FOR LOW-IMPACT HYDROPOWER GROWTH	GRID RELIABILITY, RESILIENCE, AND INTEGRATION (HYDROWIRES)	FLEET MODERNIZATION, MAINTENANCE, AND CYBERSECURITY
Develop, test, and validate cost-effective, sustainable technologies for non-conventional hydropower applications in new-stream reaches, NPDs, and conduits.	Understand, enable, and improve hydropower and PSH's contributions to reliability, resilience, and integration in a rapidly evolving electricity system.	Develop digitalization, maintenance, and cybersecurity tools and capabilities to enable data-driven decision making, improve system reliability and reduce costs; and enhance infrastructure security.
ENVIRONMENTAL AND HYDROLOGIC SYSTEMS SCIENCE		
Research and develop new technologies to better characterize river systems and evaluate potential impacts; avoid, minimize, or mitigate environmental impacts; and improve understanding of various hydrologic risks and uncertainty.		
DATA ACCESS, ANALYTICS, AND WORKFORCE DEVELOPMENT		
Improve access to relevant hydropower, river, and water information—including hydropower educational and training materials—and develop analytical tools to explore opportunities and weigh potential trade-offs across multiple objectives at basin-scales.		

Challenges and Hydropower Program Approaches

The hydropower industry faces a number of critical challenges. The average hydropower plant is 64 years old,[20] and the aging infrastructure requires fleet modernization. Environmental sustainability is another critical challenge, requiring fundamental research to understand hydropower's effects on the environment, as well as novel monitoring and mitigation technologies. Hydropower's long-term value depends on maintaining a high level of environmental performance across the fleet. Other challenges for hydropower include valuation of grid services, operations optimization, relicensing, climate change impacts, identifying additional value streams, and developing innovative technologies to increase the flexibility that hydropower and PSH can provide.

Through collaboration with the stakeholder community, the Hydropower Program has identified several core challenges that must be addressed to achieve its mission and the ultimate vision for the U.S. hydropower industry. These are similar to and overlap with many of the issues identified in the Hydropower Vision and the Vision Roadmap. However, challenges are not all-encompassing of every difficulty identified by the hydropower industry and other stakeholders; the challenges are focused on those that the program has a direct and government-appropriate role in helping to address. These challenges illustrate the complexities and difficulties that must be overcome in modernizing and maintaining a safe and cost-effective hydropower fleet, developing new low-impact hydropower technologies that can be deployed, improving the ecological resilience of America's rivers and water infrastructure, and improving grid flexibility and integrating other renewables. The wide range of specific challenges and high-level approaches to address them have been organized into five corresponding activity areas that the Hydropower Program aligns its work and efforts to, as discussed in the following sections and summarized in Table 11.

Table 11. Challenges and Hydropower Program Approaches to Overcome Them

Challenges	Approaches
Limited Opportunities for New, Affordable Hydropower Growth Given Existing Technologies • Remaining new hydro resources (including NPDs, new stream-reaches, and conduits) are smaller, lower-energy density and expensive to develop with existing technologies. • Uncertain and complex socio-environmental impacts associated with existing hydropower designs that could require difficult or expensive mitigation measures. • Lack of infrastructure and capabilities to test and validate new technologies and designs.	**Innovations for Low-Impact Hydropower Growth** • Enable the development of new technologies for both existing water infrastructure and new stream-reach applications that incorporate ecological and social objectives. • Leverage new advancements in manufacturing and materials to dramatically lower costs of components and systems designs. • Support testing of new technologies, including development of necessary testing infrastructure. • Explore opportunities for new development in which hydropower is not the principal motivation of the project, but a critical enabler of a larger suite of benefits.

[20] U.S. Energy Information Administration, 2017. "Hydroelectric generators are among the United States' oldest power plants." https://www.eia.gov/todayinenergy/detail.php?id=30312#.

Challenges	Approaches
Untapped Potential for Hydropower and Pumped Storage to Support a Rapidly Evolving Grid • Limited understanding and valuation of the grid services needed to support a rapidly evolving electricity system. • Complex machine, water, and institutional constraints on hydro operations, some of which do not account for evolving grid needs. • Information gaps on how to optimize hydropower operations and planning in coordination with other resources. • Limited capabilities of existing hydropower technologies to provide flexibility and other grid services.	**Grid Reliability, Resilience, and Integration (HydroWIRES)** • Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower and pumped storage. • Investigate hydropower's full range of capabilities to provide grid services, accounting for the machine, hydrologic, and institutional constraints to fully utilizing those capabilities. • Optimize hydropower operations and planning—alongside other resources—to best utilize hydropower's capabilities to provide grid services. • Develop innovative technologies, including new pumped storage system designs, which improve hydropower capabilities to provide grid services.
Maintaining Cost-Competitiveness and Security of Existing Hydropower Assets Given Fleet Age • Longevity of hydropower assets lead to new technologies and upgrades occurring slowly. • Limited information available on the operational and physical characteristics of diverse hydropower facilities. • Increased cybersecurity risks as hydropower and pumped storage plants digitalize and connect to information technology systems.	**Fleet Modernization, Maintenance, and Cybersecurity** • Create mechanisms to classify diverse hydropower plants by mechanical and cyber-physical systems and identify exemplary facilities and best practices. • Research advanced technologies and data evaluation approaches to improve equipment longevity and condition-based repair. • Develop cross-cutting digitalization systems and advanced sensor suites to empower data-driven decisions on operations and maintenance (O&M) and asset management. • Create cybersecurity tools and studies to articulate the cybersecurity target, risk, and recovery landscape in order to enhance the security of critical dam infrastructure.
Addressing Environmental Impacts and Hydrologic Uncertainties • Knowledge gaps remain related to fish and wildlife biology, behavior, and interactions with hydropower facilities. • Limitations in instrumentation and monitoring tools and technologies to understand the environmental impacts of hydropower. • Uncertainties about long-term climate change and hydrologic variations or extreme events and the associated operational and ecological impacts.	**Environmental and Hydrologic Systems Science** • Develop better monitoring technologies to study river systems and evaluate environmental impacts. • Develop technologies and strategies to avoid, minimize, or mitigate environmental impacts. • Support development of metrics to better evaluate environmental sustainability for new hydropower developments. • Assess potential impacts of long-term climate and hydrologic changes to hydropower. • Improve abilities to assess risk of potential methane emissions from water bodies.

Challenges	Approaches
Lack of Access to Information Necessary to Support Decision-Making • Widely dispersed data on technologies, resources, environmental attributes, markets, etc., which is of differing qualities and difficult to gain access to. • Costly and time-intensive regulatory processes and poor information and data available/accessible on regulatory process outcomes and drivers. • • Difficulties in analyzing and evaluating tradeoffs due to the many uses of water, as well as changing and sometimes unclear resource management objectives (e.g., environmental, recreational, irrigation, etc.).	**Data Access, Analytics, and Workforce Development** • Support the development of systems and standards to improve access to integrated water data and information relevant to hydropower stakeholders. • Support development of new educational resources where gaps currently exist, including curricula and training, to support an evolving hydropower workforce and increase awareness of hydropower opportunities. • Create and improve capabilities to analyze multifaceted types of hydropower and water data in order to better identify opportunities and weigh potential trade-offs across multiple objectives at basin-scales.

Limited Opportunities for New, Affordable Hydropower Growth Given Existing Technologies

The development of new hydropower is limited by the customized and the site-specific approach to construction, powerhouse design/installation, and environmental mitigation. New standardized, modular approaches to hydropower project design at NPDs and new stream reaches have the potential to significantly reduce costs and incorporate environmental performance at the initial design stages. The Hydropower Program's R&D efforts focus on areas where hydropower turbine manufacturers and hydropower-owning utilities are unlikely or unable to spend private capital. This typically includes the initial conceptual design, numerical modeling, validation, and testing of technologies that can subsequently be adopted by industry for further development and commercialization. For entirely new and unproven approaches to hydropower development, such as modular hydropower, the Hydropower Program partners with the private sector through competitive mechanisms to perform early-stage research. This research focuses on innovative approaches to hydropower, including design, configurations, and advanced manufacturing, improving DOE's ability to propagate cost-reductions and environmental performance improvements across the industry.

Most new hydropower facilities will be smaller scale than existing systems, since limited opportunities exist to develop new, large-scale conventional hydropower given high costs and environmental concerns. These new facilities—including low-impact, small hydropower or with technologies for existing conduits and canals—can integrate multiple social, environmental, and energy benefits, while realizing value and revenue from a variety of sources. WPTO supports the deployment of these systems to modernize irrigation districts, power NPDs, and provide hydropower to remote communities. Scientific advances can allow developers and operators to more effectively identify and mitigate potential environmental impacts, ultimately allowing for more effective utilization of existing hydropower and reduced regulatory costs.

Untapped Potential for Hydropower to Support a Rapidly Evolving Grid

Traditionally, hydropower was designed to provide optimal performance and value when operating at a constant output level. Both hydropower and PSH, however, are capable of adjusting their output quickly and on demand, providing a highly flexible generation source with critical services that help maintain the reliability and resilience of the nation's power grid. Services include quick response dispatchable power that can be used to meet peak demand and balance variable resources, as well as a discrete set of technical capabilities ranging from sub-second frequency response to black-start (restoration) capabilities that can help the grid quickly recover from an outage. PSH provides many of these same services, in addition to the ability to absorb excess generation during the pumping mode and provide long-term power storage for when it is needed most. The importance of these capabilities and flexibility will increase as the nation's electric grid evolves, however the specific design and operational attributes that will prove most valuable are not well understood and remunerated, which leads to potential inefficiencies in how existing power and ancillary services are procured and compensated. As part of the ESGC, the Hydropower Program under the Hydropower and Water Innovation for a Resilient Electricity System (HydroWIRES) Initiative, continues research to quantify and understand the economic value of the services provided by hydropower and PSH, and the additional costs or technical requirements of operating hydropower systems in a changing grid. This research includes understanding the value of hydropower under future electric system conditions, quantifying the effect of flexibility constraints on plant capabilities and performance (e.g., from variations in water flows, plant designs, or license conditions), addressing critical technical barriers to effective operation of hydropower resources for reliability and economic dispatch, and identifying technology solutions that will preserve or enhance hydropower capabilities to deliver services or system benefits competitively. The Hydropower Program will also continue to assess and drive innovation in hydropower flexibility, as well as new PSH configurations that reduce geographic siting limitations, construction costs and timelines, and environmental impacts. These activities drive needed innovation in the design of PSH, as traditional designs are capital intensive, limited in where they can be sited, and difficult to finance. New transformative designs could reduce capital investment requirements, expand siting possibilities, and shorten development timeframes for new facilities, thus creating incentive for private investment.

Maintaining Cost-Competitiveness and Security of Existing Hydropower Assets Given Fleet Age

The majority of hydropower plants in the United States are more than 50 years old;[21] and as they continue to age, maintaining efficient and cost-effective operations and ensuring the security of these critical pieces of infrastructure becomes increasingly challenging. Efforts in hydropower plant upgrades and modernization will focus on developing tools to better understand the health, mechanical, hydrological, and electrical status of hydropower plants based on operating regimes by means of a fleet condition data analysis and creation of a numerical model capable of predicting hydropower plant system conditions. These tools will play a critical role in maximizing hydropower plant reliability as operation grows increasingly variable and more flexible in the wake of increasing penetration of wind and solar generation into the U.S. grid. In addition, the program will support projects that advance sensor analytics, capitalizing on the range of existing hydropower sensor data, to provide unprecedented insight into hydropower plant operation, maintenance, and environmental interaction. Finally, cybersecurity R&D efforts focus on standardizing cyber-physical typologies to establish a hydropower "State of the Fleet" analysis, highlighting opportunities to improve security, to understand the value of effective cybersecurity, and to understand the risk and consequence sensitivities of hydropower plant cyberattacks. Hydropower has certain unique characteristics, due to the age and diversity of the fleet, that may exacerbate cybersecurity risks, including a widely diverse set of network layouts and 50+ year-old infrastructure. WPTO cybersecurity activities focus on those risks and mitigation activities unique to hydropower.

Addressing Environmental Impacts and Climate Change

Significant knowledge gaps remain related to fish and wildlife biology, behavior, and interactions with hydropower facilities; and there are several critical limitations in instrumentation and monitoring tools and technologies to understand the environmental impacts of hydropower. Hydropower generation is both impacted by climate change and has an important role in climate change mitigation. Climate change impacts on the water system can affect hydropower operations by complicating short and long-term planning, introducing risk and uncertainty, and compounding other challenges such as managing water quality and species protection measures. As a crucial

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[21] Uría-Martínez, R., Johnson, M., and Shan, R., 2021. "U.S. Hydropower Market Report." https://www.energy.gov/eere/water/downloads/us-hydropower-market-report.

component to achieving net-zero emissions by 2050, hydropower dams can help alleviate the extreme impacts of climate change (e.g., flooding and drought) on our nation's river basins, as well as longer-term shifts in regional water availability. Scientific advancements that allow developers and operators to more effectively identify and mitigate potential impacts ultimately allow for more effective utilization of existing hydropower and reduced regulatory costs. The Hydropower Program continues to develop turbine design and evaluation tools based on new biological research. These tools support the efforts of manufacturers to design new turbines, both for new projects and replacements of existing turbines, that simultaneously optimize generation and environmental performance.

Lack of Access to Information Necessary to Support Decision-Making

Throughout the course of its funded R&D activities, the Hydropower Program, its national laboratories, and its awardees identify and aggregate large amounts of data from across the hydropower industry and hydrologic science disciplines. Non-proprietary data are validated and made publicly available through the program-maintained HydroSource data portal.[22] These data are useful to inform R&D, investment, advocacy, and regulatory decisions for researchers, technology developers, conservation advocates, policy-makers and regulatory agencies. These data also underpin the publicly available U.S. Hydropower Market Report, compiled and released by the program and Oak Ridge National Laboratory every two to three years, with select data updates released in intervening years. The most recent full report was published in January 2021, and an update to the 2021 report was published in September 2021. Many different types of data collected by the program are also used to conduct analyses and provide unbiased scientific data to facilitate targeted improvements to regulatory processes.

The Hydropower Vision report included a Roadmap of detailed actions recommended to advance sustainable hydropower in the United States, with potential growth of nearly 50 GW (13 GW of new hydropower and 36 GW of new PSH) by 2050. The Roadmap is intended to function as a guidepost for not only the Hydropower Program but the entire hydropower community. The Hydropower Program, with support from its national laboratories, has used the Roadmap as an evolving plan against which it has tracked progress of its own research and activities throughout the broader hydropower community on the way to realizing the Hydropower Vision. Regular updates to the Roadmap will ensure that the hydropower communities' path to achieving the sustainable hydropower future laid out in the Vision remains relevant and up-to-date.

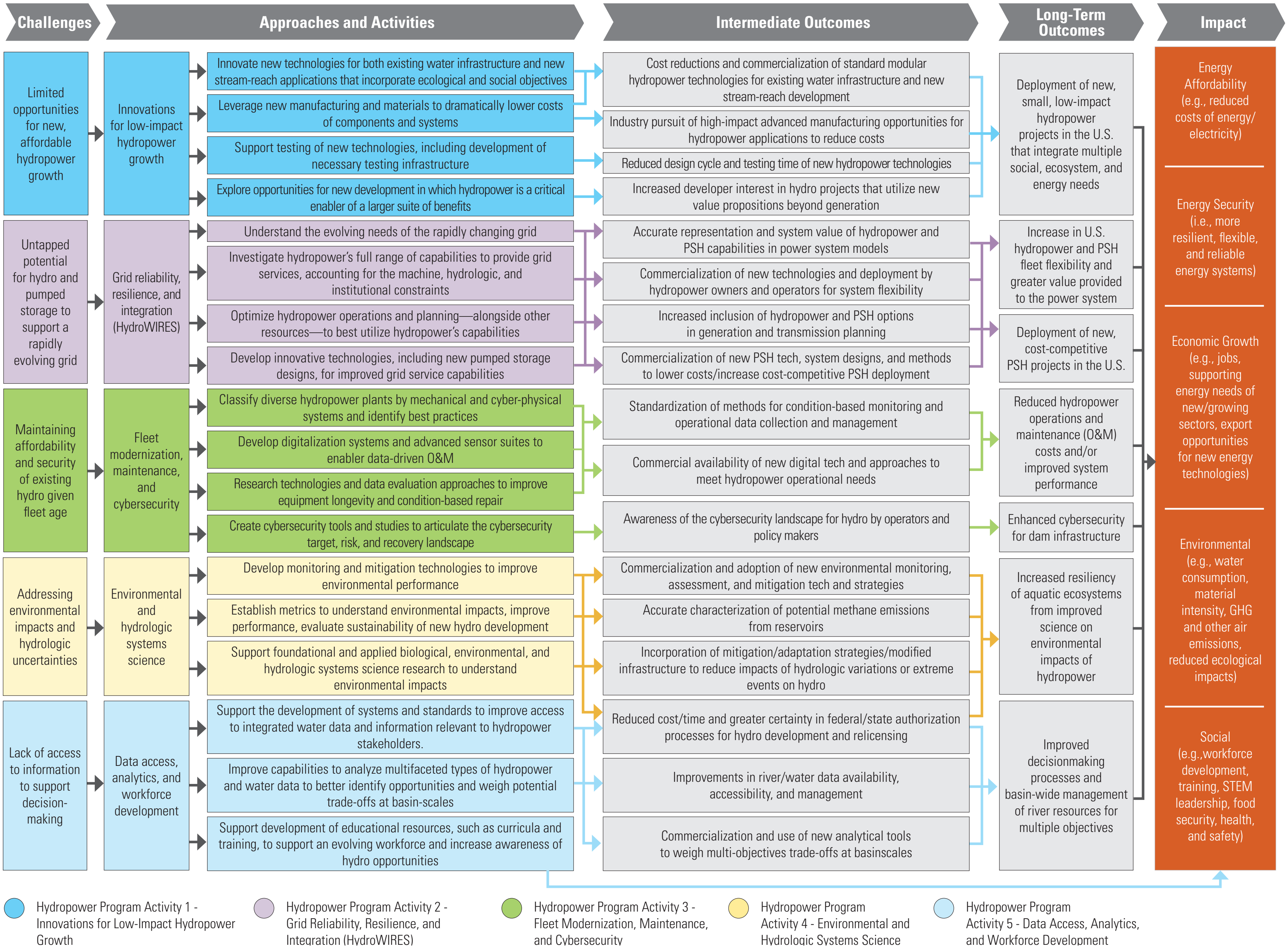
Hydropower Program Goals and Objectives

Hydropower Program Logic Model

Figure 9 illustrates the portfolio-wide logic for the Hydropower Program. The challenges and approaches to addressing those challenges are summarized in Table 11. WPTO's Key Results and Performance Goals for the FY 2021-2025 timeframe are the significant outputs or products that are being targeted within the next five years. Those results and performance goals are critical to achieving the program's 2026-2030 objectives, which are short-term outcomes that are intended to lead directly to one or more of the intermediate outcomes identified in Figure 9 below. Those intermediate outcomes then hopefully influence the identified long-term outcomes, and the ultimate society or economy-wide impacts.

22 HydroSource data portal: https://hydrosource.ornl.gov/.

Figure 9. Hydropower Program Logic Model



Assessing Performance

At the time of publication of this document, the Hydropower Program is engaged in reevaluating baseline modeled cost and performance (for both NPD-relevant technologies and those applicable for low-impact projects in new stream-reaches) and set new long-term targets. This is necessary due to the philosophical shifts in system design approaches for future potential hydropower projects at NPDs or for new developments. Previous cost and performance baselines and future targets for these two categories of projects were originally established with the objectives of reducing costs and improving performance for traditional methods of developing hydropower projects at these types of sites. However, recent work within the Standard Modular Hydropower (SMH) project, led by Oak Ridge National Lab, is shifting the underlying design principles that future R&D and cost/performance targets may be aligned to. To avoid a potential future "apples-to-oranges" type comparison, prior DOE resource assessments and modeled costs for developing sites must be reevaluated to establish a baseline of costs given SMH design philosophies. For more information on this effort see Hydropower Program Sub-activity section 1.1 below.