HydroWIRES Initiative Research Roadmap

January 2022

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Executive Summary

In April 2019, the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) launched the HydroWIRES (Water Innovation for a Resilient Electricity System) Initiative to understand, enable, and improve hydropower and pumped storage hydropower's (PSH) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. The unique characteristics of hydropower, including PSH, make it well-suited to provide a range of storage, generation flexibility, and other grid services and support the cost-effective integration of variable renewable resources. Specific research areas in HydroWIRES (Figure 1) are motivated by pressing industry challenges and have been developed with significant external input from both hydropower industry and power system stakeholders.

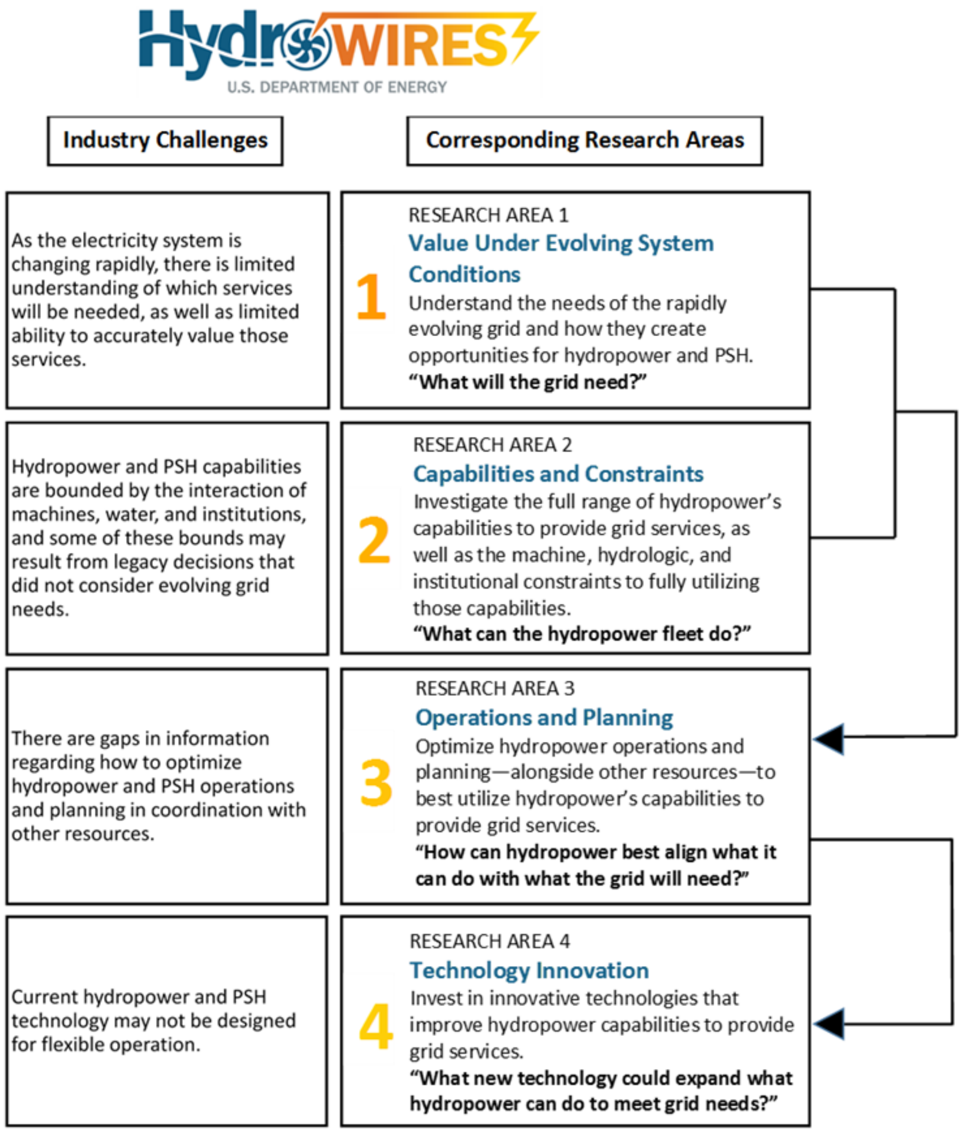

Figure 1. HydroWIRES research areas are aligned with industry challenges. While the research areas are envisioned to flow from 1 and 2 into 3, and then 3 into 4, individual projects and reports may span multiple research areas.

While WPTO has historically focused on technology solutions to drive down the cost of hydropower development and support the expansion of the sector, the HydroWIRES Initiative adds a complementary focus on hydropower's role as an integrator of variable renewables. This is especially important as the U.S. transitions to a more sustainable economy and combats climate change by eliminating its carbon emissions. The central hypothesis of HydroWIRES is that, as the electricity system undergoes rapid changes, the U.S. hydropower fleet is well-positioned to take on this new role as an integrator by offering additional value streams, enhanced flexibility, new operational strategies, and innovative technology solutions. HydroWIRES will support these goals through development of industry- and national lab-led modeling, analysis, tools, and targeted technology R&D for the benefit of the broader community.

The government role of WPTO in executing the HydroWIRES Initiative is essential, as challenges addressed by HydroWIRES related to reliability, resilience, and integration are national in scale and extend beyond the purview of any single utility or industry player. In describing the possible roles for hydropower under evolving power system conditions, HydroWIRES should explore future scenarios, equipment capabilities, operational paradigms, and market structures that reach beyond those considered by most planners and operators today. All of these areas must be considered with respect to their environmental impacts such that any new advances from the HydroWIRES Initiative will be sustainable. Thus the activities under HydroWIRES will productively inform current as well as future actions by industry decision makers.

Major end-users for HydroWIRES include hydropower owners and operators, Independent System Operators/Regional Transmission Organizations (ISO/RTOs), regulators, original equipment manufacturers, and environmental organizations. The HydroWIRES Initiative also coordinates closely with other DOE initiatives and offices, participating in cross-office collaborations like the Energy Storage Grand Challenge (ESGC) and the Grid Modernization Initiative (GMI). The Advanced Research Projects Agency–Energy (ARPA-E), Office of Electricity (OE), the Office of Energy Efficiency and Renewable Energy's (EERE) Strategic Analysis team, EERE's Solar Energy Technologies Office (SETO), EERE's Wind Energy Technologies Office (WETO), and EERE's Geothermal Technologies Office (GTO) are all important partners.

HydroWIRES is envisioned as a 5-year research initiative. In partnership with industry and key stakeholders, research efforts and "outputs" from HydroWIRES will target measurable, real-world outcomes, shown in Table 1.

More information about HydroWIRES is available at energy.gov/HydroWIRES.

Table 1. Simplified version of the logic model in Table 2, showing short-term and intermediate outcomes of the HydroWIRES Initiative. The four research areas (RA) are indicated as RA1-RA4 in Figure 1.

OUTCOMES	
Short-Term *(Earliest intended effects of outputs on target audiences, usually represented by documentable uptake or usage within 1–5 years)*	**Intermediate** *(Follow-on effects intended to result from achieving short-term outcomes, usually within 5+ years)*
• **RA1:** Publish regionally focused roadmaps for maximizing hydropower's value for reliability, resilience, and integration. • **RA2:** Release the first version of an asset-level cost-benefit assessment toolbox for owners and operators of hydropower and PSH plants, which integrates previous model and tool development focused on revenue opportunities, environmental outcomes, and machine impacts to inform asset-level decisions. • **RA3:** Release the first version of a cost-benefit toolbox for system-level decision makers, such as planners and regulators, which integrates system values, system costs, externalities of hydropower, and the abilities of other resources. • **RA4:** Test innovative technology R&D at a small-scale PSH or flexible hydropower demonstration project, potentially including new PSH concepts and/or flexibility enhancement through hybrid controls and advanced operations.	• Understanding across the hydropower community of the value hydropower provides in different regions and system conditions. • High-fidelity modeling of hydropower and PSH that accommodates flexible operations, enhanced market participation, varying water availability, and multi-purpose constraints and benefits while considering potential environmental impacts should become standard practice. • Quantifiable improvement of hydropower plant operations, including coordination or co-location with other resources to increase system flexibility. • Increased inclusion of hydropower and PSH in generation and transmission planning. • Commercialization of new PSH technologies, system designs, and methods that can dramatically lower costs and/or increase cost-competitive PSH deployment opportunities.

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1.0 Introduction: A New Role for Hydropower

The U.S. electricity system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. Increasing deployment of variable renewable resources such as wind and solar photovoltaic have enabled low-cost clean energy in many regions of the United States, while also creating a need for resources that can store energy or quickly change their operations to ensure 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, for some plants, particularly in regions with high variable renewable penetrations, this operational pattern is changing. Hydropower is well-suited to provide a range of storage, flexibility, and other grid services that can enable integration of variable renewables. The U.S. hydropower fleet may therefore be approaching an inflection point—from the classic paradigm of a predictably scheduled resource to a new paradigm of enabling variable renewable integration through more flexible operations.

Industry Challenges

In recent years, WPTO has gathered information from industry, academia, state and local governments, and other stakeholders to understand and map out the core challenges described in this section. In 2018, WPTO issued a Request for Information (RFI) to solicit feedback on developing a new research initiative. The RFI received responses from diverse sample of 39 entities, including market operators, utilities, environmental organizations, research institutions, and hydropower developers (Figure 2). Respondents provided exceptional detail on a range of topics in more than 275 pages of content. Key messages are that hydropower's provision of reliability services and flexibility is important but not well-recognized nor accommodated through incentives nor through balancing with siting objectives; that without such accommodation or alignment, hydropower capabilities will erode and constraints will increase; and that more work needs to be done on a national, long-term outlook to assure hydropower resources will have the capabilities and the right revenue signals to provide those essential grid benefits into the future. These foundational insights have shaped the development of the HydroWIRES conceptual structure and research areas, and HydroWIRES will continue to prioritize engagement with external stakeholders to ensure its research outputs have maximum positive impact for the community.

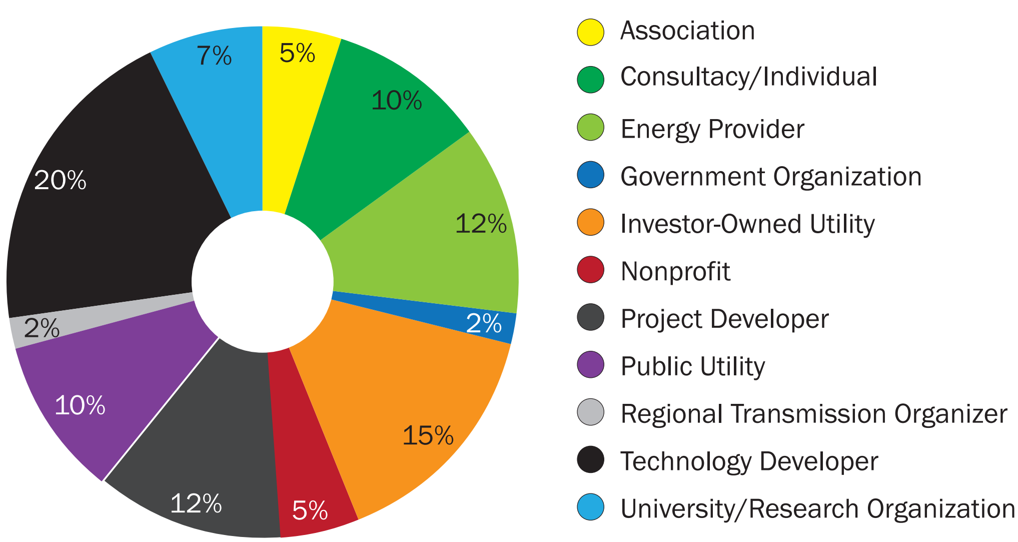

Figure 2. Distribution of respondents to the 2018 Request for Information

Based on this feedback, HydroWIRES is structured around the idea that understanding and mapping out potential new roles for the hydropower fleet requires addressing four main challenges:

1. *As the electricity system is changing rapidly, there is limited understanding of which services will be needed, as well as limited ability to accurately value those services.*

A rapidly changing energy resource mix and market environment can limit our ability to understand grid needs and corresponding value propositions for long-lived assets such as hydropower. If, in a given U.S. region, wind deployment, market prices, transmission constraints, water availability, and other factors could all change significantly over time scales of only a few years, this creates a range of possible futures with which operators and planners must grapple. Even if reasonable sets of scenarios and corresponding needs for generation and grid services can be identified, accurate economic and financial valuation of all the services hydropower can provide is a separate complexity. Some grid services provided by hydropower are monetized in current markets, and others are not. Some services may be provided simultaneously, while others may not be. Furthermore, hydropower facilities generally exist as integral parts of larger river systems, making them inherently multi-use and thus giving rise to costs and values that extend beyond the power system. All of these complexities must be addressed for appropriate valuation of hydropower assets.

2. *Hydropower and PSH capabilities are bounded by the interaction of machines, water, and institutions, and some of these bounds may result from legacy decisions that did not consider evolving grid needs.*

The plant-level operational capabilities of hydropower are constrained by several overlapping factors. The full technical capabilities of the machines may be unavailable in practice because of a lack of water availability for the plant and other plants (e.g., in a cascading system), or because of institutional requirements such as water releases for environmental flows, navigation, and other purposes. Tradeoffs exist among these three broad categories of constraints, where some constraints are flexible and others are not. Crucially, many of the decisions surrounding machine design, water management, and institutional factors were made decades ago when the electricity system looked very different from the system today, resulting, in some cases, in a mismatch between hydropower capabilities and modern grid needs. The ongoing relicensing of a significant fraction of the fleet makes this challenge especially timely. A further complexity lies simply in the diversity of the fleet. The broad range of configurations, equipment, hydrology, and institutional situations across the fleet makes the majority of hydropower projects essentially unique. A more detailed yet still generalizable understanding of the multifaceted capabilities and constraints of the hydropower fleet is a critical need.

3. *There are gaps in information regarding how to optimize hydropower and PSH operations and planning in coordination with other resources.*

A further set of challenges includes the appropriate operations and planning of hydropower to meet changing grid needs. While hydropower can provide many grid services, there is a need to better understand which grid services can be most effectively and economically provided by hydropower, and which are best provided by other resource types, defined broadly to include generation, storage, transmission, and end-use. Uncertainties and challenges associated with capabilities and deployments of other resources compound the challenge of identifying the best “roles” for hydropower to play, but the full-system perspective is nevertheless essential to enable appropriate decision making, particularly for long-term planning. Significant gaps exist in the operational timeframe as well. Like the various constraints on hydropower, the operational paradigms for hydropower are often tied to legacy decisions that may not account for rapidly changing conditions. Moreover, suitable tools and operational strategies for enabling new, more flexible operations may not exist, even if the technical capability is available in the plant.

4. *Current hydropower and PSH technology may not be designed for flexible operation.*

While hydropower is already a widely deployed technology in the United States, many plants in today's fleet are designed chiefly for energy generation with high efficiency at a single operating point, which can make them less suited for flexible operation to serve evolving grid needs. Current technologies may exhibit rough zones that can cause additional machine wear and tear as they are traversed during more frequent cycling or ramping. Beyond technology, hydropower faces significant deployment challenges, particularly in the case of PSH. Despite its capabilities for highly flexible generation, storage, and even transmission equivalence, new PSH has not been deployed at a large scale in the U.S. for decades. Some challenges stem from valuation and financing for a long-lived asset in a time of high market uncertainty, while related but distinct challenges include the long lead time for PSH construction. Large-scale deployment of new PSH will likely require significant reduction in the overall time to commissioning.

The HydroWIRES Research Initiative

In response to the challenges outlined and strong interest from the hydropower community, DOE's WPTO launched a new research initiative entitled HydroWIRES: Water Innovation for a Resilient Electricity System in April 2019. The mission of HydroWIRES is to understand, enable, and improve hydropower's contributions to reliability, resilience, and integration in a rapidly evolving electricity system.

While WPTO has historically focused on technology solutions to drive down the cost of hydropower development and support the expansion of the sector, the HydroWIRES Initiative adds a complementary focus on hydropower's role as an integrator and force-multiplier for integration of variable renewables. The central hypothesis of HydroWIRES is that, as the electricity system undergoes rapid changes, the U.S. hydropower fleet is well-positioned to take on this new role by offering additional value streams, enhanced flexibility, new operational strategies, and innovative technology solutions. HydroWIRES will support these goals through development of industry- and national lab-led modeling, analysis, tools, and targeted technology R&D for the benefit of the broader community.

While HydroWIRES focuses primarily on hydropower's role supporting the electricity system, the changing operations of hydropower can also have impacts—both positive and negative—on other important variables of sustainable energy and water systems. As such, much of the operations and planning work has strong ties to WPTO's Environmental and Hydrological Systems Science (EHSS) program. For example, scientific studies to determine the impact of flexible operations on particular species will be performed in EHSS, while HydroWIRES will incorporate these results into larger flexibility, cost-benefit, and tradeoff tools. Therefore, work may include a scoping study of system-level changes associated with more flexible hydropower operations, including impacts on water end-use, reservoir emissions, river system ecology, and other cross-domain impacts.

The government role of DOE in executing the HydroWIRES Initiative is essential, as challenges addressed by HydroWIRES related to reliability, resilience, and integration are national in scale and extend beyond the purview of any single utility or industry player. In describing the possible roles for hydropower under evolving power system conditions, HydroWIRES should explore future scenarios, equipment capabilities, operational paradigms, and market structures that reach beyond those considered by most planners and operators today. Thus, the activities under HydroWIRES will productively inform both current and future actions of industry decision makers.

The HydroWIRES Initiative builds on and integrates a significant body of previous work within WPTO. The 2016 Hydropower Vision Report provided a baseline for hydropower's technical performance and illustrated challenges to and opportunities for expansion of the hydropower fleet, but this report also highlighted research gaps in understanding the past, present, and future value of hydropower. Such questions motivated two flagship projects in what later became the foundational efforts for the HydroWIRES Initiative. First, the forthcoming Hydropower Value Study describes the current operational landscape of the hydropower fleet, including how flexibility has been valued in the past and what value drivers could be most important in future scenarios. Second, the congressionally directed PSH techno-economic assessment will result in a valuation guidance tool with a comprehensive, rigorous valuation methodology for the grid services that PSH can provide. This methodology will then be applied to two proposed PSH sites competitively selected through a 2017 Notice of Opportunity for Technical Assistance: the Banner Mountain site in Wyoming and the Goldendale site on the Oregon and Washington border. Other foundational ongoing work is shown below in the HydroWIRES Research Areas and Technical Objectives section. More information about the relationship of the HydroWIRES Initiative to the broader hydropower program is described in WPTO's Multi-Year Program Plan.

Aligned with the four challenges described above, the conceptual structure of HydroWIRES includes four interrelated research areas (Figure 3). The research areas are intentionally cumulative, with the first and second research areas feeding into the third and then the fourth research areas. Structurally, the first two research areas establish a critical baseline understanding of what range of services may be most valuable for the future grid (depending on different ways it may evolve), together with what services hydropower can (and cannot) contribute. With a more complete picture of grid requirements facing hydropower resources and the actual ability and limitations of hydropower to respond to grid conditions, the third research area operationalizes this information by developing strategies to take advantage of hydropower's capabilities in order to contribute the services required by the evolving grid. The fourth area continuously integrates the findings from these three research spaces to inform technology needs and target innovation that can expand hydropower's capabilities to provide value to the grid. While the research areas are conceptualized as flowing in sequence, the dependence is not rigid. Work performed on individual HydroWIRES projects can often proceed in parallel, and a given project may span multiple research areas.

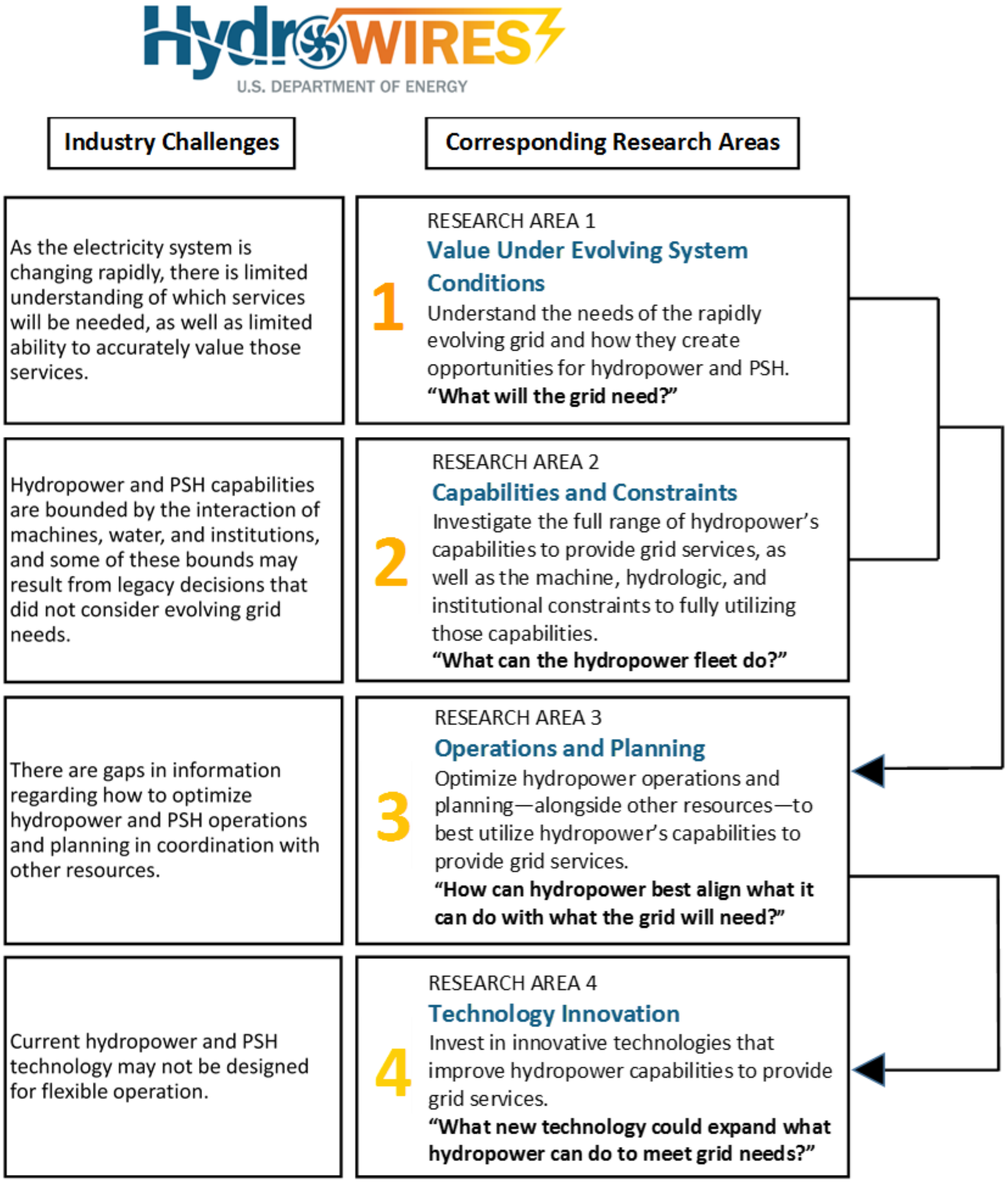

Figure 3. HydroWIRES research areas are aligned with industry challenges. While the research areas are envisioned to flow from 1 and 2 into 3, and then 3 into 4, individual projects and reports may span multiple research areas. Findings from these projects can inform the approach to any applicable research areas.

Innovative Mechanisms for High-Priority Research

HydroWIRES has developed and piloted innovative funding mechanisms for high-priority topics. For example, the "quick win" mechanism enables national labs to propose new research ideas in an ad-hoc fashion as opportunities arise, rather than relying solely on pre-planned lab calls and external funding opportunities that are often timed according to the fiscal year. Quick wins are generally smaller-budget projects (e.g., <$100k), and are envisioned to serve both as one-off low-hanging fruit that can add immediate value, or as seeds for potentially larger areas of research in the future. Ideas for quick wins are proposed by DOE or national lab staff and discussed among the HydroWIRES team for technical feedback and to identify connecting points with other work across the labs. If the team agrees that the concept would provide high value and support the mission of HydroWIRES or broader DOE efforts, the proposer writes a short scope and budget level, and work on the quick win can proceed immediately. Funding is reserved for quick wins throughout the year, enabling a more flexible approach than with funding for large, pre-planned projects. Examples of past and ongoing quick wins include:

- Organizing a production cost modeling technical workshop with owner/operators, model vendors, and other stakeholders to improve representation of hydropower.
- Developing, through a multi-lab effort, methods to use existing state-of-the-art models to inform WECC's representation of hydropower resources in their territory.
- Working with Portland General Electric to characterize different modes of flexible operation currently being used in their plants.
- Planning a technical workshop with the Northwest Hydropower Association to solicit industry feedback on HydroWIRES projects.
- Investigating PSH development and financing in other countries, including case studies of several examples that could offer lessons for the United States.

Strategic Engagement and Building Partnerships

Major end-users for HydroWIRES include hydropower owners and operators, ISO/RTOs, regulators, policymakers, original equipment manufacturers, and environmental organizations, all of which will benefit from HydroWIRES data, analysis, models, and technology R&D that can improve their capabilities and inform their decisions. Gathering stakeholder input from these groups will be an integral part of the research process that will allow HydroWIRES to maximize its positive impact on the community. Furthermore, building partnerships with organizations in the regulatory and operational spheres will be critical to the success of the initiative. Partnerships with regulatory agencies ensure not only that the work done within the initiative considers the most up-to-date regulatory considerations, but will also ensure that these agencies can use the best available information about hydropower and PSH. Partnerships with owners and marketers of hydropower such as the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Tennessee Valley Authority, the Power Marketing Administrations, and utilities, will bring a practical perspective, ensuring that results are useful in real applications.

The HydroWIRES Initiative also coordinates closely with other DOE initiatives and offices, including ESGC, GMI, OE, SA, SETO, WETO, and GTO. HydroWIRES operates in coordination with GMI, and synergies across the Grid Modernization Lab Consortium (GMLC) projects and HydroWIRES projects are leveraged to ensure consistency and avoid duplication. Representatives from GMI, OE, and SA serve on the HydroWIRES Executive Board, providing input into the program's organization and research direction as well as formal and informal review of work products.

HydroWIRES emphasizes the role of DOE national laboratories in providing technical leadership, recruiting subject matter experts from multiple disciplines to advise project and program directions, and coordinating internally and externally with research partners to assure that investments and outcomes can have maximum impact. National laboratories can, by design, tackle multi-disciplinary challenges that require many forms of expertise and specialized capabilities. Thus, HydroWIRES includes close engagement with five national laboratories—Argonne National Laboratory (ANL), Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL)—who work as a team to provide strategic advice and develop connections across the research portfolio.

Finally, HydroWIRES includes collaborative work with international partners through the International Energy Agency's (IEA) Hydropower Technical Collaboration Programme, the International Hydropower Association's Pumped Storage Forum, and a United States-Norway Memorandum of Understanding for Hydropower R&D to contribute to and benefit from technical advances and lessons learned in other countries.

More information about HydroWIRES is available at energy.gov/HydroWIRES.

2.0 HydroWIRES Research Areas and Technical Objectives

Each research area also includes specific technical objectives, 15 in total, shown on the left axis of Figure 4, below. Research Area 1 technical objectives include compiling a standardized grid service taxonomy, understanding value drivers for hydropower, and developing rigorous valuation methodologies. Research Area 2 includes development of a framework for different types of flexibility available from hydropower plants, evaluating tradeoffs involving flexible operation, and improving inflow forecasting and modeling representation of hydropower. Research Area 3 includes evaluating hydropower's contributions to system resilience, comparing hydropower with other available resources (e.g., in planning), optimizing hydropower's operations, and evaluating non-power system-wide effects of hydropower operations. Research Area 4 technical objectives include identification of outstanding technology innovation gaps, improving flexible potential at the unit- and plant-level, and addressing PSH-specific challenges associated with innovation and deployment. The rest of this section provides more detail on each research area and technical objective.

In addition to the sequential relationships within each technical objective—represented as linear tracks in Figure 4—many research efforts will also crosscut, intersect, and inform work in other research areas. For example, work that contributes to improving hydropower's contributions to grid reliability and resilience occurs in most research areas. While not pictured in Figure 4, knowledge and tools from each of these efforts will be shared across research areas.

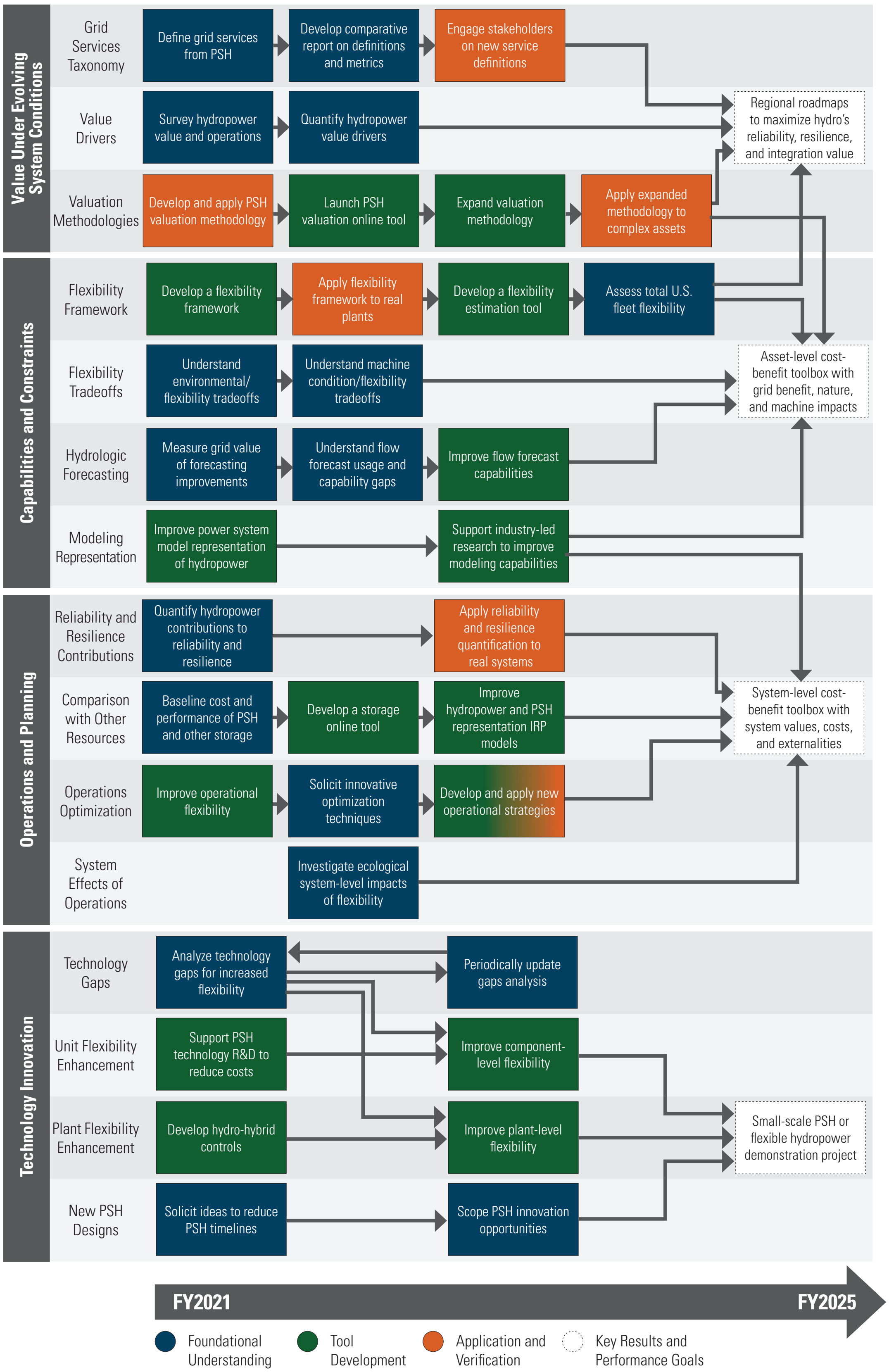

Figure 4. HydroWIRES includes a number of Technical Objectives (shown in orange)

nested under each Research Area.

Research Area 1: Value under Evolving System Conditions

Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower.

"What will the grid need?"

Rapid changes in the power system limit our ability to understand which reliability services and associated technical capabilities the grid will require, and how this will differ from system to system. Likewise, they will limit our ability to accurately value those services. Furthermore, rapid changes in the water sector due to climate change are making regional water availability less predictable. HydroWIRES will provide both the hydropower industry and grid operators the tools, data, and analysis to understand how evolving characteristics of the power system (e.g., levels of wind or solar penetration, distributed generation, market prices, transmission constraints, and industrial electrification) drive grid needs. This will culminate in a set of regional roadmaps to maximize hydropower's contributions to reliability, resilience, and integration. As such, research in this area will include developing a comprehensive valuation methodology to inform hydropower investment decisions that includes all of the costs and benefits of different operational paradigms. An outline of the timeline for potential future work in this research area, divided by technical objective, is shown in Figure 5.

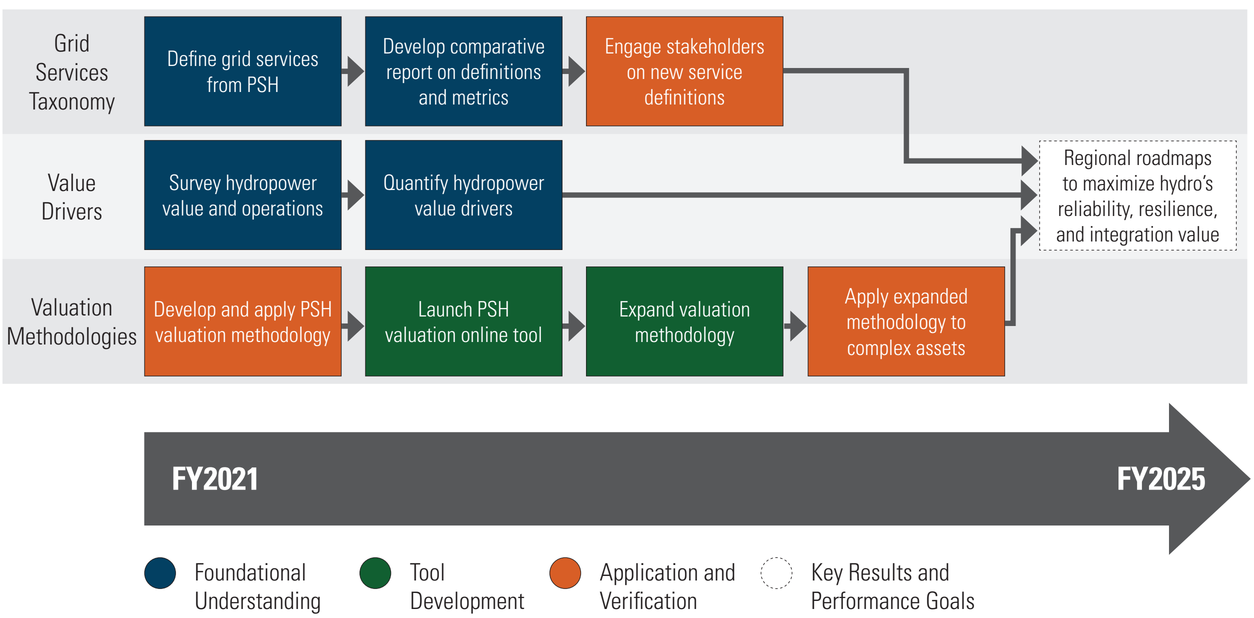

Figure 5. Ongoing and possible future efforts in Research Area 1.

Technical Objective 1.1: Grid Services Taxonomy

Enable unified understanding of grid services and system benefits through consistent taxonomies.

Market operators, utilities, regulators, and researchers use a wide variety of definitions for power system services, and this can create challenges for standardization and shared understanding. Complexities include distinguishing between physical requirements of the system and market products that vary by region and change over time. In addition, physical power system requirements do not depend on the particular resource providing them (i.e., generation, transmission, storage, load), but market products may be resource-specific. Therefore, this objective seeks to develop a comprehensive taxonomy of grid services and system benefits that account for contributions from hydropower and PSH, as well as other technologies. The taxonomy will be initially developed for advanced PSH valuation, which requires discrete established services and supporting methodologies that can be co-optimized and modeled for a specific asset, but follow-on efforts in coordination with other DOE offices will include a more generalized framework that can accommodate other technologies and resource classes. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 5.

- **Define grid services from PSH:** Based on prior work, formalize a standardized set of grid services applicable to PSH in collaboration with industry partners.
- **Develop a comparative report on definitions and metrics:** Understand how different grid services are defined across regions and countries, including how this can inform compensation mechanisms for hydropower and PSH.
- **Engage stakeholders on new service definitions:** Educate stakeholders on metrics and explain new potential grid services that may be required in future systems.

Collaborations with SA and GMI will be leveraged to develop a unified taxonomy of grid services. The IEA Hydropower Technical Collaboration Programme also has significant interest in developing an understanding of service taxonomies that can further understanding of market designs across different countries.

Technical Objective 1.2: Value Drivers

Understand value drivers for hydropower in today's power system and investigate how this value might evolve under different future system scenarios.

Given rapid changes in the power system and water sector, hydropower is, in some cases, changing its operations significantly in response to changing value drivers. Identifying current value drivers for hydropower (e.g., sets of system conditions that enable hydropower to provide value to the power system) is a foundational piece of this technical objective, with the ultimate goal being an investigation of value drivers under hypothetical future scenarios with different sets of system conditions than current ones. Scenarios could be designed to understand how hydropower will be used in different resource mixes, what new system requirements and/or market products will be needed in the future, and what uncertainties will be the most impactful. Further, value drivers will be critical for establishing the spatial and temporal intervals that are most meaningful for hydropower, which will illustrate where planning practices are limited in capturing the full potential contribution of hydropower, and especially for modeling development to support effective resource planning and dispatch. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 5.

- **Survey hydropower value and operations:** Study how hydropower has been valued in the past, using case studies and historical data for different regions across the United States.
- **Quantify hydropower value drivers:** Identify and quantify the factors (generation mix, market design, water availability, load shapes, etc.) that influence the value of hydropower resources to help understand their value under disparate future grid conditions.

Development of future scenarios and sensitivities cannot be only a hydropower-specific activity, but must include consideration of the entire resource mix and corresponding drivers. HydroWIRES activities will therefore include discussion with other offices, including EERE, the Office of Nuclear Energy (NE), OE, and the Office of Fossil Energy and Carbon Management (FECM).

Technical Objective 1.3: Valuation Methodologies

Develop rigorous, widely applicable methodologies that accurately value hydropower assets.

While energy storage valuation capabilities have advanced significantly in recent years, PSH plants present several unique technical challenges. PSH plants are long-lived assets requiring long-term projections of revenue, system characteristics, and demands. Generating capacities are often large enough to change supply-demand curves and influence prices and value of individual services. Pumped storage plants are capable of providing a wide range of different grid services and must manage for operational constraints. All of these elements must be addressed in order to effectively evaluate PSH facilities. Advancing valuation for conventional hydropower resources will be equally important. Hydropower will change operations under different future grid scenarios, and where there are options among operational paradigms, decisions—including adopting or integrating new technologies—should be made on sound economic analysis. Hydropower plants are often operated for other public benefits and purposes beyond electric generation, such as irrigation or flood control. Each benefit (such as energy, water delivery, recreation) requires a different set of valuation approaches, and each are critical to address in any comprehensive valuation of a hydropower project. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 5.

- **Develop and apply PSH valuation methodology:** Finalize and publish a PSH valuation methodology and techno-economic studies for two proposed PSH plants.
- **Launch PSH valuation online tool:** Based on the PSH valuation methodology, develop an easy-to-use online tool that will allow developers, regulators, and other stakeholders to better evaluate diverse value streams from PSH.
- **Expand valuation methodology:** Extend the previously developed valuation methodologies to conventional hydropower, hybrids, and other storage types (in addition to PSH).
- **Apply expanded methodology to complex assets:** In coordination with industry, apply the expanded valuation methodologies to a real-world proposed project with more complex technical, market, or multi-use characteristics.

While initial work in this area has focused on PSH, many of the methodologies are broadly applicable to long-duration storage more generally (e.g., flow batteries), making coordination with other offices such as OE critically important.

Research Area 2: Capabilities and Constraints

Investigate the full range of hydropower's capabilities to provide grid services, as well as the machine, hydrologic, and institutional constraints to fully utilizing those capabilities.

"What can hydropower do?"

While reservoir hydropower plants are some of the most flexible resources on the grid, the full technical capabilities of the individual plants often go unused because of a combination of factors such as water availability (e.g., in a cascading system), or institutional requirements to use water for environmental flows, navigation, and other purposes. Additionally, operators may choose to limit the flexibility of hydro plants to meet competing objectives, such as limiting wear and tear by reducing how often the plant passes through its rough zones. HydroWIRES will provide new and never-before-accumulated data from across the U.S. hydropower fleet to understand the range and limits of hydropower's flexibility and identify opportunities at the plant and fleet level where flexibility and grid services can be increased. An outline of the timeline for potential future work in this research area, divided by technical objective, is shown in Figure 6.

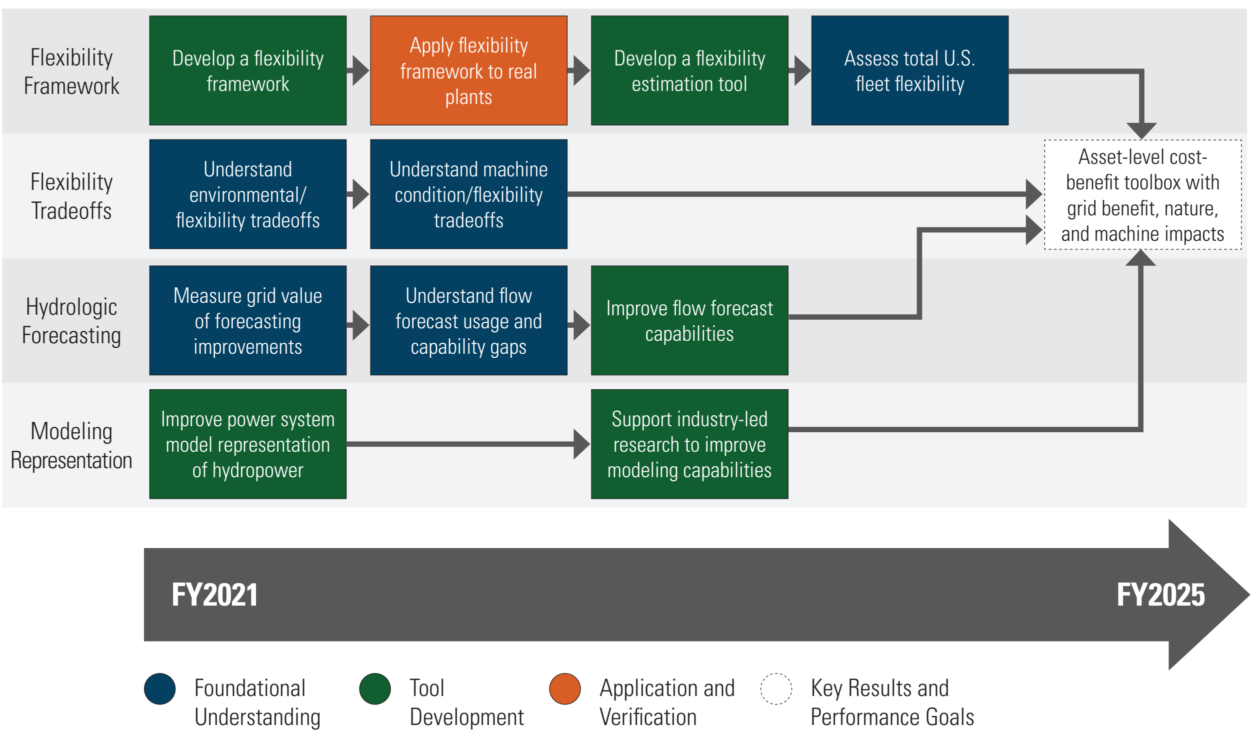

Figure 6. Ongoing and possible future efforts in Research Area 2.

Technical Objective 2.1: Flexibility Framework

Quantify the different types of flexibility available in hydropower plants as a first step to assessing the total flexibility available in the hydropower fleet.

Hydropower is often described as a flexible resource given the range of services it is theoretically capable of providing, but on a site-specific plant basis, flexibility capabilities vary widely. Hydropower plants vary greatly in their impoundments, flow rates, machine capabilities, and other attributes, all of which affect how much flexibility and what types of grid services they can provide. Moreover, an individual plant's flexibility could change depending on the time of year, water demand patterns, and available water resources. Most research to date on this topic characterizes degradation and accounts for effects and costs (i.e., wear and tear, forced outages). Often hydropower flexibility is identified by its utilization—when is it acting in a flexible fashion—as opposed to available plant flexibility. There is a need for a comprehensive and systematic approach to assess the flexibility of the hydropower fleet in a way that allows us to measure total available potential, mark change in potential and utilization, and prioritize areas of work. This objective therefore seeks a comprehensive, national assessment of the potential flexibility available in the fleet. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 6.

- **Develop a flexibility framework:** Establish a broadly applicable framework to estimate the amount of flexibility that a hydropower plant can provide.
- **Apply the flexibility framework to real plants:** Implement the framework into real-world plants in coordination with owners and operators.
- **Develop a flexibility estimation tool:** Launch an online portal that allows for an estimation of the amount of flexibility available from a particular asset, using the flexibility framework previously developed.
- **Assess total U.S. fleet flexibility:** Complete a fleet-wide assessment of the total potential flexibility available in the U.S. fleet.

While this flexibility framework will be hydropower-specific, there could be lessons from other generation types (e.g., natural gas) that could inform the categorization and quantification for hydropower. This work will, therefore, include discussions with FECM and other DOE offices.

Technical Objective 2.2: Flexibility Tradeoffs

Understand the tradeoffs between operating flexibly and meeting other objectives related to environmental performance, revenue opportunities, and machine wear and tear.

Hydropower plants include physical limits on their capabilities as well as requirements to balance multiple objectives. For some aspects of this balancing, operational optimization practices are complex but fairly well-established: rule curves for reservoirs, water withdrawals, and minimum flows, among others. In some cases, the balancing is an economic assessment (e.g., bypassing an immediate dispatch opportunity for a more valuable projected dispatch, providing a high-value response while accepting some compromised performance), whereas, in other cases, factors such as plant equipment durability and risks to meeting other reservoir objectives must be considered. Following from the flexibility capability assessment in 2.1, this objective will identify areas where there is a need for advanced tools, models, or platforms to assess and evaluate tradeoffs within the hydropower facility or set of co-managed facilities. Examples include meeting (or exceeding) environmental objectives under relicensing while maintaining flexibility or other revenue opportunities and capitalizing on short-term revenue opportunities while balancing increased wear and tear to facility components outside of design parameters, which shorten life or increase maintenance and forced outages. Increased flexibility will also have to be balanced against a resulting decrease in capacity value. This objective will prioritize developing areas where tradeoffs cannot be modeled or evaluated without improved techniques and win-win opportunity spaces. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 6.

- **Understand environmental/flexibility tradeoffs:** Comprehensively map the linkages between flexible operations and environmental outcomes through the hub of flow decisions.
- **Understand machine condition/flexibility tradeoffs:** Quantify the impacts of flexible operations on plant equipment, enabling tradeoff quantification.

Hydropower is unique among generation types in the breadth of tradeoffs that must be considered in its operation, but coordination with other DOE offices could offer valuable insights. Tradeoffs involving machine wear and tear, for example, could be informed by work with FECM on increased cycling of the thermal fleet.

Technical Objective 2.3: Hydrologic Forecasting

Quantify and improve the accuracy and resolution of inflow forecasting tools to enable more flexible operation.

Hydropower operators use inflow forecasting tools to estimate future inflows to hydropower reservoirs. These tools vary extensively within the hydropower industry in terms of lead time (short, medium, long term), geographic setting, and complexity. Some forecasting tools are proprietary, but can be purchased from vendors; other tools are in-house, developed by the hydropower facility operator to be fit for purpose. Understanding reservoir inflow is critical to managing multiple water uses and making informed operational decisions. If hydropower plants are required to operate more flexibly, forecasting tools will likely require improvements in accuracy and resolution. For example, there may be some instances where conditions are swiftly shifting, as is the case with low-elevation upper watersheds, snowpack-dependent facilities, and lower latitude facilities. Hydropower flexibility is a function of reservoir capacity; therefore, knowing exactly how much water will be available at a particular time can enable better planning and unlock additional operational capabilities. Work under this objective will first focus on identifying instances where forecasting tools are currently or prospectively insufficient in the context of increasing operational flexibility, and evaluating the degree to which past and current investments resolve those gaps. Future investments will then be aimed at addressing specific gaps that are highly targeted and impactful. Close partnership with utilities, in particular hydropower water managers, will be a fundamental part of this objective. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 6.

- **Measure grid value associated with improved flow forecasting:** Quantify the value of different potential short-term forecasting improvements to increase hydropower flexibility.
- **Understand flow forecast usage and capability gaps:** Working with industry partners, understand forecast usage and identify the forecast model capabilities to prioritize for improvement.
- **Improve flow forecast capabilities:** Support an industry-led effort to make the highest impact in water forecasting model capability improvements (as identified in previous work).

Collaborative work through GMLC on water impacts to various generation resources could inform this work. In addition, there could be overlap in tools and approaches to forecasting solar irradiance, wind, and load, which work in this technical objective could leverage.

Technical Objective 2.4: Modeling Representation

Improve the representation of hydropower and PSH in power system models to more accurately capture its unique capabilities.

There is a growing common understanding that the current representation of hydropower and flexibility in grid models is inadequate. There are fundamental differences in hydropower representation between grid models and water management models, creating a need for appropriate coupling between models. While grid models are improving to capture variable generation profiles, such as wind and solar, and new technologies, such as batteries, the representation of hydropower has remained essentially static. At the same time, hydropower operations have changed to accommodate the increased competition in water uses and associated river regulation, as well as toward providing the complementary power services required to allow the higher penetration of variable renewables. As markets increasingly regionalize and create transfer opportunities for large hydropower, precise models that capture the local operational realities will be critically important. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 6.

- **Improve power system model representation of hydropower:** Improve hydropower and PSH representations in power system models so that they better capture unique capabilities and constraints associated with hydropower.
- **Support industry-led research to improve modeling capabilities:** Participate in an industry-led effort to upgrade targeted power system model capabilities relevant for hydropower and PSH.

This technical objective will be closely coordinated with SPIA and other EERE offices, as modeling improvements for hydropower will need to be incorporated into models used by other offices.

Research Area 3: Operations and Planning

Optimize hydropower operations and planning—alongside other resources—to best utilize hydropower's capabilities to provide grid services.

"How can hydropower operations and planning be optimized for grid needs?"

Given insights on what grid services will be needed as the system evolves (Research Area 1), combined with insights on the specific capabilities of the hydropower fleet, subject to associated constraints (Research Area 2), Research Area 3 brings these areas together by investigating appropriate "roles" for hydropower that align its capabilities with system needs. While hydropower can provide many grid services, there is a need to better understand which grid services can be most effectively and economically provided by hydropower, and which are best provided by other resource types. HydroWIRES will provide data and modeling tools to improve hydropower operations and planning—from both a project and power system perspective—to most effectively utilize hydropower's capabilities to contribute to grid reliability and renewable energy integration. An outline of the timeline for potential future work in this research area, divided by technical objective, is shown in Figure 7.

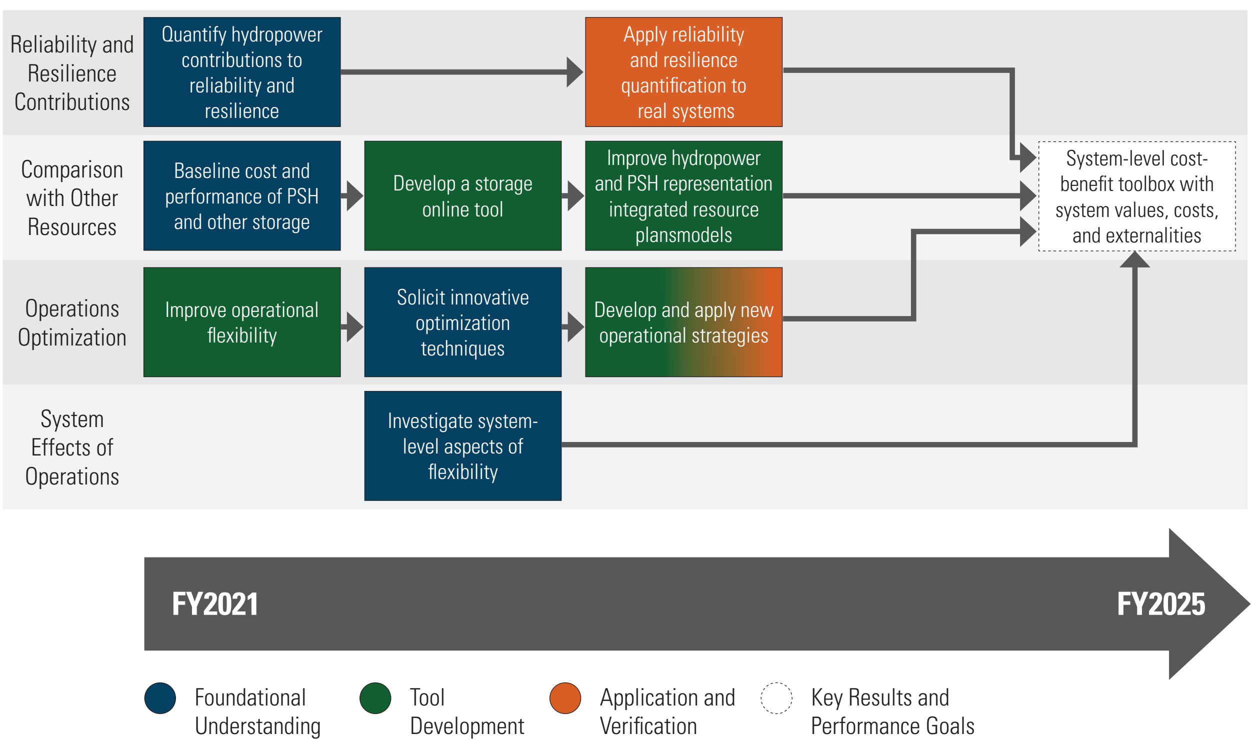

Figure 7. Ongoing and possible future efforts in Research Area 3

Technical Objective 3.1: System Reliability and Resilience Contributions

Quantify hydropower plant- and fleet-level contributions to system reliability and resilience requirements.

Reliability is a measurable, standards-based, and enforceable grid condition. While certain metrics are well-established (i.e., System Average Interruption Duration Index, System Average Interruption Frequency Index) and new reliability metrics are under development, these measurements represent the *system* capability and condition. Recent procurement of reliability services from specific generating resources suggests that there can be not only a quantification, but also valuation for plant-specific contributions. In addition, given observed increases in the variety, intensity, and frequency of potential natural and man-made threats to electricity system reliability, electricity system *resilience* has also become an important system property to measure and to assure. The role of generating assets in contributing to system resilience is still under-developed, but some examples may offer insights, such as hydropower's compensated provision of black start. This objective seeks a quantified understanding of how hydropower as a sector contributes—or could contribute—to system reliability and resilience, such as preventing a contingency event, or recovering from a grid disturbance. Preliminary studies of hydropower responses to frequency excursions illustrate that hydropower units respond differently to the same event, that a single unit will respond differently to different events, and that hydropower units respond differently from thermal units. Methods developed should be technology-neutral and applicable to all regions or major market environments, rather than specific to one balancing authority or interconnection. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 7.

- **Quantify hydropower contributions to reliability and resilience:** Develop a framework to determine the contributions of hydropower to the reliability and resilience of the grid during contingency events.
- **Apply reliability and resilience quantification to real systems:** Work with industry or other external partners on improved contingency strategies supported by hydropower.

Quantifications of resilience under this technical objective will leverage previous work by OE and GMI, as grid disturbances are not necessarily specific to hydropower (although hydropower could have unique water-related challenges and/or opportunities to provide value that should be captured).

Technical Objective 3.2: Comparison with Other Resources

Understand hydropower's unique benefits and costs—in comparison with other resources—to best inform planning decisions.

While hydropower can provide a range of services to the system, there are almost always other resources available that also can provide these services. There is, therefore, a need to distinguish hydropower resources from other comparable technology solutions. In addition to technology characterization—developing precision around performance for hydropower assets—the context of system operations and planning paradigms are also critical to capture technical, economic, financial, and policy aspects of service provision. In some instances, new opportunities for technology cooperation and hybridization may be identified. Rigorous, apples-to-apples comparison of resource capabilities under this objective will enable more informed and effective resource planning. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 7.

- **Baseline cost and performance of PSH and other storage:** Compile the latest data on costs and performance PSH alongside other storage technologies to allow apples-to-apples comparison.
- **Develop a storage online tool:** In coordination with other DOE offices, create and maintain a tool to serve stakeholders that provides them with the latest storage cost and performance data.
- **Improve hydropower and PSH representation in IRPs:** Work with planners to apply modeling tools that more accurately capture hydropower and PSH in integrated resource planning processes.
- By design, this technical objective requires collaboration across DOE. Investigating capabilities, costs, externalities, and other attributes of different generation technologies can only be done in coordination with relevant experts in EERE, OE, NE, FECM, ARPA-E, and other offices.

Technical Objective 3.3: Operations Optimization

Develop operational strategies and associated tools that enable hydropower to better optimize its operations to provide grid services.

Hydropower plants are commonly multi-objective and must manage operations for multiple uses simultaneously. At the plant level, this creates challenging and sometimes competitive purposes at the same time for the same water. In cascading systems, where plants interact with each other to store water and to generate, cooperation is a physical requirement. The dynamic grid state and bid/cost optionality compound the complexity of operational management schemes. This objective seeks to enhance hydropower's potential utilization for the grid through new optimization approaches; an evolution of practice within operations modeling, computational improvements, and real-time sensors; AI and machine learning algorithms; and other plant-based advanced techniques to address constraints or expand capabilities. Practices could include improved, integrated, site-based modeling and controls; advanced multi-unit or multi-plant coordination; or more dynamic system utilization of hydropower. The objective will also tackle structural and analytical challenges that would prevent an otherwise competitive and high-performing resource from selection and utilization. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 7.

- **Improve operational flexibility:** Support industry-led efforts to increase the operational flexibility of hydropower plants.
- **Solicit innovative optimization techniques:** Canvass other fields for cutting-edge optimization techniques to apply to hydropower operations.
- **Develop and apply new operational strategies:** Building on modeling enhancements and prior work, support industry-led efforts to develop new operational strategies that better meet system needs.

Optimization includes hydropower-specific aspects, but work under this technical objective will also be coordinated with relevant DOE partners. Investigating needs of the federal fleet, for example, will be done in close coordination with Power Marketing Administration representatives.

Technical Objective 3.4: System Effects of Operations

Quantify effects of hydropower plant- and fleet-level operations on water availability, emissions, environment, and other system properties.

While HydroWIRES focuses primarily on hydropower's role supporting the electricity system, the changing operations of hydropower can also have impacts—both positive and negative—on other desirable properties of a sustainable energy and water system, such as water availability, emissions, or environmental goals. While these properties are considered at the plant level in Technical Objective 2.2 on flexibility tradeoffs, this technical objective expands the focus to system-level considerations. This objective will seek to catalog and quantify these impacts. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 7.

- **Investigate system-level aspects of flexibility:** Examine the links between increased fleet-scale hydropower flexibility and system-level attributes of ecology, air quality, or water use.

System-level considerations under this technical objective could be informed by GMLC work on water availability impacts, and by broader-scope system-of-systems modeling in DOE's Office of Science.

Research Area 4: Technology Innovation

Invest in innovative technologies that improve hydropower capabilities to provide grid services.

"How can new hydropower and PSH technologies best meet new operational patterns?"

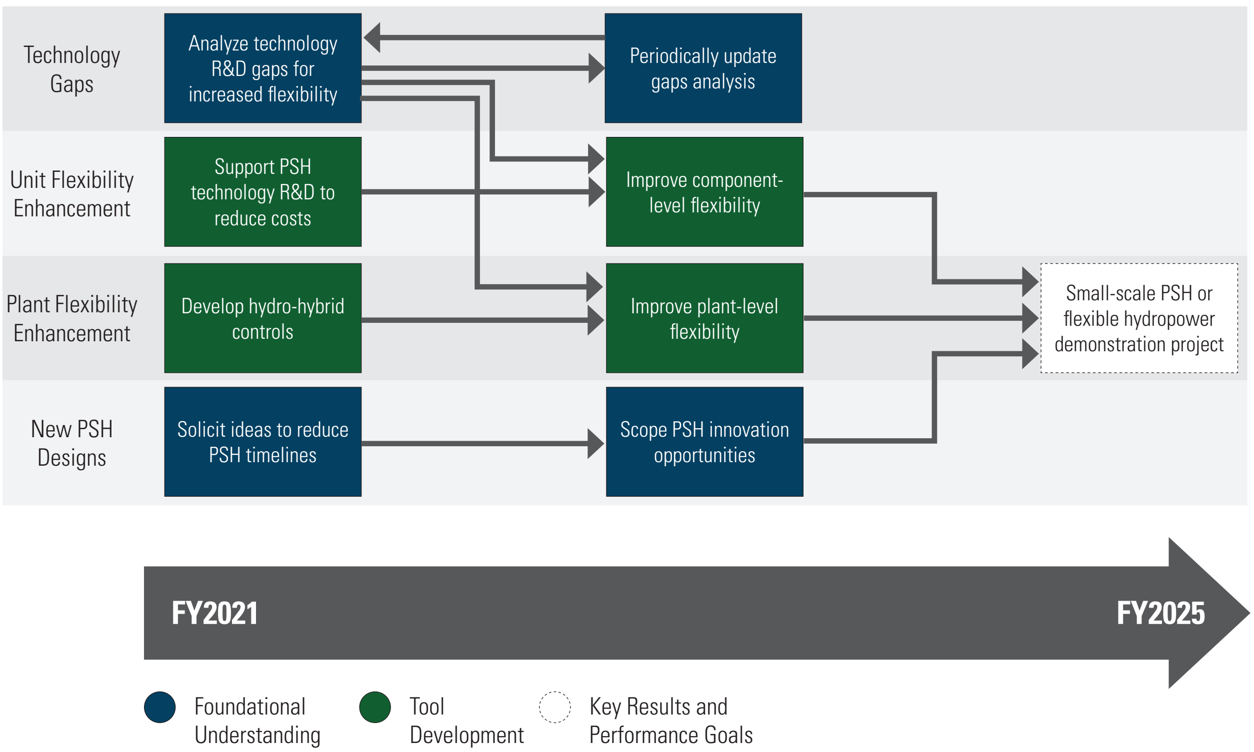

Figure 8. Ongoing and possible future efforts in Research Area 4

While hydropower is already a widely deployed technology, there is still significant need for innovation. Many plants in today's fleet are designed primarily for steady generation in a narrow operating range, which can make them less suited for flexible operation for current grid needs. In addition, new PSH faces significant deployment challenges including high capital costs and long lead-time to commissioning. HydroWIRES will invest in innovative technologies that improve hydropower capabilities to provide grid services. The timeline for illustrative current and potential future work in this research area, divided by technical objective, is shown in Figure 8.

Technical Objective 4.1: Technology Gaps

Identify and map out technology innovations that enable hydropower plants to improve provision of grid services.

While hydropower and PSH have been commercialized for many decades, the fleet is facing changing operational paradigms that can challenge the capabilities of existing machine and plant designs. Major OEMs are already receiving orders for equipment that can ramp and cycle much more frequently than in the past. Work under this objective will take stock of the state of the art in hydropower technology, specifically focused on capabilities for enhanced flexibility or provision of other emerging system needs. This bottom-up assessment of technology gaps will outline opportunities for targeted technology R&D. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 8.

- **Analyze technology R&D gaps for increased flexibility:** Determine what technology gaps at the component- and plant-level could be addressed to enable increased hydropower flexibility.
- **Update gaps analysis periodically:** Periodically update the gaps analysis to ensure that new technology R&D targets new value drivers for hydropower and PSH that may emerge.

Coordination with other DOE offices could inform the design of this bottom-up analysis, as other technologies have developed similar mappings of innovation gaps at various stages of technical maturity.

Technical Objective 4.2: Unit Flexibility Enhancement

Develop technology solutions that enable enhanced flexibility at the unit level.

This objective builds from the technology gaps assessment in 4.1 to support advanced technologies and design innovations that preserve and enhance unit flexibility attributes, including powertrain and peripheral equipment. Possible innovations within this objective could include technologies that enable provision of new services, reduce barriers to dispatching units more quickly, reduce unit downtime, enhance the ability of a unit to achieve environmental objectives, or lead to greater ranges of unit operation. If successful, this objective will achieve outcomes such as faster response, longer duration response to frequency excursions, reduced wear and tear, faster repair methods, and reduced environmental impacts. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 8.

- **Support PSH technology R&D to reduce costs:** Support innovative technology to reduce the cost per kilowatt of new PSH.
- **Improve component-level flexibility:** Develop technology that can improve the flexibility of particular hydropower and PSH components.

While many unit-level enhancements will be specific to hydropower, some might be more generally applicable (e.g., governors) and will be informed by discussions with FECM and other DOE offices.

Technical Objective 4.3: Plant Flexibility Enhancement

Develop technology solutions that enable enhanced flexibility at the plant or cascading system level.

This objective builds from the needs assessment to support advanced technologies and design innovations that preserve and enhance plant flexibility attributes, such as innovations at the level of the powerhouse, dam, and reservoir system. This can include technologies that remove barriers to flexibility, new sensors that improve plant intelligence, structural and civil works enhancements that improve plant responsiveness, artificial intelligence approaches to plant management and maintenance that reduce forced outages, and new environmental technologies that increase the ability of a plant to deliver energy services among others. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 8.

- **Develop hydro-hybrid controls:** Create controls for hybrid hydropower systems that allow for increased flexibility and improved grid services.
- **Improve plant-level flexibility:** Develop technology that can improve the flexibility of hydropower and PSH plants.

Combinations of hydropower and PSH with other generation technologies create an obvious need to work closely with other DOE technology offices. Work under this technical objective will continue in close coordination with SETO, WETO, and OE, and, potentially, with other offices as well.

Technical Objective 4.4: New PSH Approaches

Develop new technology concepts and approaches that overcome barriers associated with PSH deployment.

Pumped storage technologies, with a total of 22 GW of installed capacity in the United States, represent over 95% of the domestic electric energy storage available today and are a transmission-interconnected storage resource. However, no large PSH projects have been commissioned in the last 20 years. Many states' storage policies and regulators prioritize incremental solutions that can be deployed in short timeframes. These often fail to take into account the reduced environmental effect of closed-loop PSH. PSH technology R&D in the United States focuses mainly on adjustable speed technologies (i.e., doubly-fed induction machines and converter-fed synchronous machines) and alternative pump-turbine configurations that have been deployed successfully in other countries (i.e., ternary units) rather than new conceptual designs of pumped storage facilities.

There is little information available in public literature about new designs and alternative mechanisms for utilizing water infrastructure to offer some of the benefits of pumped storage at competitive costs. To investigate such opportunities, this objective seeks radically new designs in pumped-storage hydropower technologies that can meet cost-reduction goals, competitive timelines to commissioning, and enhanced value without requiring the economies of scale and financial structures that make large pumped storage economically viable. Examples of current and prospective work are detailed below, where the bold text corresponds to the boxes in the timeline in Figure 8.

- **Solicit ideas to reduce PSH timelines:** Query other industries and academia on ways to reduce the total time to commissioning for PSH plants.
- **Scope PSH innovation opportunities:** Complete a holistic evaluation of previous PSH technology R&D to identify the most fruitful avenues for future work in technology R&D, as well as for innovative project development.

While many technology concepts may be specific to PSH, there could be advances in excavation techniques, materials, and other areas that leverage work by AMO, GTO, or other offices. In addition, tech-to-market and other commercialization efforts could be informed by ARPA-E's approach.

3.0 Outcomes

HydroWIRES is envisioned as a five-year research initiative, during which time, the initiative is expected to make substantial progress to further its mission of understanding, enabling, and improving hydropower's contributions to grid reliability, resilience, and integration. The research products, or "outputs," resulting from the HydroWIRES Initiative—reports, white papers, model enhancements, tools, and workshops—will be designed to engage appropriate stakeholders. In partnership with these stakeholders, HydroWIRES research outputs will target a number of concrete, real-world outcomes, detailed in the logic model in Table 1. While the success of some of the outcomes is easily measured, the success of others will require more work to quantify. For example, the short-term success of a modeling project might be measured as an accuracy improvement over standard models, but the long-term success hinges on the model's uptake. This is more difficult to measure, but some metrics for this are model views, downloads, and paper citations.

A logic model is a visual representation of the key elements in a "theory of change," or the sequence of activities intended to bring about significant changes across society. The longer-term targeted "outcomes" and "impacts" identified within a logic model are directly linked to the nearer-term results or "outputs" the program is expected to achieve. The "Program Challenge" is the challenge identified by WPTO that HydroWIRES is tasked with addressing, and the "Approaches" correspond to each research area in the initiative. The short term are the significant outputs or products that are being targeted by the initiative, and correspond to the white boxes in Figure 4. Those short-term outcomes are intended to lead directly to one or more of the "Intermediate Outcomes," identified in Table 2, below. Those intermediate outcomes then, ideally, influence the identified long-term outcomes, and the ultimate society- or economy-wide impacts.

Table 2. HydroWIRES Initiative context, outcomes, and impacts

HydroWIRES Initiative Outcomes	OUTCOMES			ULTIMATE IMPACTS
	Short-Term *(Earliest intended effects of outputs on target audiences, usually represented by documentable uptake or usage within 1–5 years)*	Intermediate *(Follow-on effects intended to result from achieving short-term outcomes, usually within 5+ years)*	Long-Term *(Follow-on effects intended to result from achieving intermediate outcomes, usually within 10+ years)*	Impacts *(Biggest-picture changes intended to result from the progression of outcomes)*
	RA1: Publish regionally focused roadmaps for maximizing hydropower's value for reliability, resilience, and integration. **RA2:** Release the first version of an asset-level cost-benefit assessment toolbox for owners and operators of hydropower and PSH plants, which integrates previous model and tool development focused on revenue opportunities, environmental outcomes, and machine impacts to inform asset-level decisions. **RA3:** Release the first version of a cost-benefit toolbox for system-level decision makers, such as planners and regulators, which integrates system values, system costs, externalities of hydropower, and the abilities of other resources. **RA4:** Test innovative technology R&D at a small-scale PSH or flexible hydropower demonstration project, potentially including new PSH concepts and/or flexibility enhancement through hybrid controls and advanced operations.	Understanding across the hydropower community of the value hydropower provides in different regions and system conditions. High-fidelity modeling of hydropower and PSH that accommodates flexible operations, enhanced market participation, varying water availability, and multi-purpose constraints and benefits while considering potential environmental impacts should become standard practice. Quantifiable improvement of hydropower plant operations, including coordination or co-location with other resources to increase system flexibility Increased inclusion of hydropower and PSH in generation and transmission planning. Commercialization of new PSH technologies, system designs, and methods that can dramatically lower costs and/or increase cost-competitive PSH deployment opportunities.	Increase in U.S. hydropower and PSH fleet flexibility and greater value provided to the power system. Deployment of new, cost-competitive PSH projects in the United States.	**Energy Affordability** (reduced costs of energy/electricity). **Energy Security** (more resilient, flexible, and reliable energy systems). **Environmental** (e.g., water consumption, material intensity, GHG and other air emissions, reduced ecological impacts).

4.0 Appendix A: Glossary

Capability: The technical ability of a resource to perform a specified function. Generally, resources are designed with capabilities that enable them to provide services to the system. A resource may utilize only a subset of its total capabilities to provide services.

Electricity System: The interconnected network of electricity generation, transmission, storage, distribution, and end-use, including physical, market, and institutional aspects. Informally, the terms "grid" and "power system" or "system" are also used in this document.

Flexibility: The ability of a system or component to adapt to changing grid conditions while providing electricity safely, reliably, affordably, and in an environmentally responsible manner.[1] Often used in this document to refer broadly to operational responses of individual resources to system needs, such as by ramping, load-following, or providing other grid services, but may also refer to longer time scales and/or system-level capabilities.

Grid Service: A specific requirement of the electricity system that supports reliability, resilience, economic efficiency, or other system attributes, the provision of which may or may not be compensated. Examples include energy, capacity, frequency regulation, other reserves, ramping, voltage support, black start, and transmission deferral. In a market context, performance characteristics are monetized through the procurement of select services via market products. However, not all services (e.g., inertia) currently have market products and subsequently remain unmonetized.

Reliability: The ability of an electric power system to meet the electricity needs of end-use customers, even when unexpected equipment failures or other conditions reduce the amount of available power supply. Reliability is a measure of the capability of the electric system to withstand sudden disturbances or unanticipated losses in system components, whether caused by natural or man-made events.[2, 3]

Resilience: The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.[4]

System Conditions: Aspects of the physical system, market environment, institutional environment, or other system properties, which are often dynamic. Examples of system conditions include generation mix, enacted policy, and water availability.

Valuation: The process or methodology for defining, cataloging, evaluating, and co-optimizing the value streams that may be created by a resource. Valuation in this context includes both financial and economic value, and may thus include market-compensated values and non-market-compensated values that are more difficult to quantify.

[1] Electric Power Research Institute (2014), Metrics for Quantifying Flexibility in Power System Planning, 3002004243, epri.com/#/pages/product/3002004243/?lang=en US

[2] International Energy Agency (2017), The Economic Value of Energy and Water Management Services provided by Hydropower Project s with Storage, ieahydro.org/media/54b38044/IEA%20Hydro%20Annex%20IX_Summary%20Report_Final%20Draft_Nov_2017.pdf

[3] North American Electric Reliability Corporation (2013). Frequently Asked Questions. nerc.com/AboutNERC/Documents/NERC%20FAQs%20AUG13.pdf

[4] Federal Energy Regulatory Commission (2018), Grid Resilience in RTOs/ISOs AD18 7 000, ferc.gov/Calendar-Files/20180607073820FERC%27s%20Presentation%20on%20Resilience%20 --%20Ramlatchan.pdf

5.0 Appendix B: Bibliography of Relevant Past and Current Work

Selected projects in the HydroWIRES program are listed below. Please check energy.gov/HydroWIRES for the most updated information.

HydroWIRES New National Laboratory-Led Projects (started in 2022):

Hydro+Storage: Accelerating Industry Deployment of Hydropower Hybrids

This project seeks to develop tools and tactics that will advise current and future hydropower hybridization efforts. Hydropower hybrids—or the combined operation of hydropower with other energy generation or storage technologies—have the potential to increase value for hydropower owners while also leveraging hydropower's non-power benefits. The project team aims to provide deployable solutions to accelerate the potential of hydro-storage hybrids.

Laboratory(s): INL, ANL, NREL

Additional Partner: American Governor

Developing Tools to Evaluate Environment-Flexibility Tradeoffs

This project will build on previous research led by the labs to understand the flexibility and environmental tradeoffs involved in hydropower operation. Researchers will develop a user-friendly tool that helps operators analyze the flexibility-environmental tradeoffs of hydropower operations. This is expected to lead to improved support of variable renewable generation without sacrificing river ecosystem health.

Laboratory(s): ORNL, PNNL, ANL, NREL, INL

Improving Hydropower Representation in Power System Models

This project will provide a critical update to dynamic models of hydropower generators that were developed in the 1960s and 1970s. Researchers will also develop tools that provide an accurate, updated representation of water availability and hydropower generation constraints in different models. These accurate representations will allow will give system planners and operators a more realistic understanding of operating reserves, resulting in fewer unexpected outages.

Laboratory(s): PNNL, NREL, INL

Additional Partner: V&R Energy

Electricity Market Design in Zero Marginal Cost Systems–Experiences and Insights for Hydropower in the United States and Norway

The overall goal of this project is to provide insights to market design changes that will smoothen the transition to a decarbonized power system. To obtain these insights, this project will analyze the market design initiatives in the U.S. and Norway. Since hydropower is a likely to be a strong driver of price formation in zero marginal cost systems, the team will focus on areas with high penetrations of hydropower and renewables to identify best practices to that will guide future collaborations. The final deliverable will be a whitepaper on the efficacy of different market design measures in future decarbonized systems. This work will be pursued under the framework of DOE's memorandum of understanding with Norway's Royal Ministry of Petroleum and Energy.

Laboratory(s): ANL, PNNL

Additional Partners: The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, Norwegian University of Science and Technology

Grid and Market Integration of Hydropower and Wind Energy: Challenges and Opportunities

This project seeks to build an archive of case studies documenting the co-existence of hydropower and wind turbines across the U.S. and Norway, while also investigating challenges and opportunities for hydropower resources as wind penetration increases. This work will be instrumental in identifying locations in both countries that may be prone to facing these challenges in the future. This project will increase foundational understanding of the combination of hydropower and wind turbines, in turn helping to advise future projects of this nature. This work will be pursued under the framework of DOE's memorandum of understanding with Norway's Royal Ministry of Petroleum and Energy.

Laboratory(s): ANL, INL

Additional Partners: The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, Norwegian University of Science and Technology

Real-Time Inertia Monitor Based on Pumped Hydro Operation Signatures

This project seeks to develop a real-time, low-cost, accurate inertia monitoring system for pumped storage hydropower plants. Monitoring inertia is essential for stable system operation, especially in high-renewable grids, but traditional inertia estimation approaches do not work in systems with high penetrations of inverter based resources. Researchers will demonstrate and deploy their monitoring system by the end of the two-year project.

Laboratory(s): ORNL

Additional Partners: University of Tennessee, North American Electric Reliability Corporation, Dominion Energy, Tennessee Valley Authority

Emulating Hydropower in a Controlled Real-world Environment at ARIES for Rapid Prototyping of Next-Generation Hydro-Controls

This project aims to solve the industry problem of risky, expensive, and time-consuming field validation of new hydropower governor controls by developing a controlled lab environment for evaluation. In this environment, researchers will be able to easily plug in real controller hardware to test under various grid conditions. This effort will utilize a variety of ARIES' tools, including digital real-time simulation, actual hardware grid controllers, digital governors, variable speed hydro-generator, and more.

Laboratory(s): NREL

Evaluating Options for Non-Powered Dams to Provide Grid, Community, Industry, and Environmental Benefits

This project aims to create a ranking framework that weighs various hydropower and energy storage options for non-powered dams (NPDs). With about 600 NPDs in the U.S. identified as having potential to generate hydropower, NPDs are a high impact option for new hydropower development. To evaluate and justify investment in NPDs moving forward, researchers will develop a system to evaluate costs and benefits of various NPD projects to their communities, the environment, and the grid. The ranking system will include standardized criteria to compare various options against one another.

Laboratory(s): INL, PNNL

Additional Partners: Sapere Consulting

Hydro-Based Microgrids to Support Grid Resiliency during Wildfires

As wildfires are becoming more severe and commonplace in the U.S., researchers are evaluating how to mitigate the impacts from west coast wildfires on the grid since power is often critical for life-saving services. This project will create a framework to leverage hydropower resources to ensure grid resilience during and after wildfire events.

Laboratory(s): PNNL, INL

HydroWIRES Ongoing National Laboratory-Led Projects (started in 2020):

Value Drivers

The U.S. power system has undergone a number of changes over the past decade driven in part by increasing penetrations of variable renewable energy, distributed energy resources and grid-scale battery storage, as well as increasing consumer participation and shifting load profiles to name a few. These changes are anticipated to continue in the coming decade and beyond, likely accompanied by others—technological, socio-political, and market-oriented—that may substantially change the operational requirements of the power grid. The varying degrees to which these changes manifest will drive changes in the value that hydropower resources can provide to power systems. Many hydropower resources have technical capabilities to provide a range of grid services that have traditionally been largely untapped due to either low system requirements for these services, or a lack of clear price signals for the value that they provide to the grid. We will establish a framework for quantifying the system value generated by conventional hydropower and PSH through the provision of grid services, as well the system factors that may augment these value streams in the future as power systems continue to evolve. The outcomes of this work will help stakeholders make prudent decisions regarding changes in operating practices and directing capital investments to improve resources' abilities to provide various grid services.

Laboratory(s): ANL, PNNL, NREL

HIPPO-HS: A Tool for Planning and Assessing Hybrid Resources at System Level

The benefits of utilizing and integrating large-scale hydropower into grid operation are multi-faceted. Run-of-river (RoR) hydropower by itself has limited dispatchability, but RoR and energy storage hybrid resources have much more flexibility and controllability in their operations. At the system level, these hybrid resources will impact electricity market operations, and the full benefit will depend on how these resources are configured, controlled and represented in market models. The project team will develop a RoR and energy storage hybrid resource representation model to represent the new combination of resources in the day-ahead market. This model will be used for security-constrained unit commitment and for siting and sizing of energy storage paired with RoR in an independent system operator size system. The objective of this project is to assess the benefits of co-located and/or co-optimized hybrid RoR hydroelectric generators and energy storage resources from a system operator perspective.

Laboratory(s): PNNL

Integrated Variable Renewable Generation and Battery Energy Storage: Value of Predictability in the Financial Performance of Hybrid Systems

Increased deployment of variable renewable generation (VRG) assets and lower costs of grid-scale battery energy storage have led to increased deployment of hybrid generation and storage systems. The objective of this work is to compare the technical and financial value of integrating battery energy storage with ROR hydropower, wind, solar, and tidal generation resources. The Revenue, Operation, and Device Optimization (RODeO) model will be used to account for the financial value of capacity, energy sales (including arbitrage), and ancillary services from a VRG-battery hybrid system. Addressing this is important to understand the value of hybridizing resources and which types of resources to prioritize. In this work, at least two resource profiles will be selected for each generation type, and corresponding forecast uncertainties will be analyzed. These resource profiles will be normalized based on total energy produced per year and used as input to RODeO for market conditions corresponding to two different U.S. Independent System Operators. Two of the key considerations that this work will address are: (1) How will forecast uncertainty affect the financial performance of a VRG-battery hybrid system?; and (2) Is hybridization financially advantageous compared to operating the VRG and battery storage independently? This work will provide a quantitative comparison to help motivate enhancement of the industry's perspectives on "hydro-hybrids" (i.e., ROR hydropower + batteries and tidal + batteries).

Laboratory(s): INL, NREL

Hydropower as a Signal Processor

The Hydropower Signal Processor project will develop a data-driven methodology for classifying and comparing the water-to-energy and energy-to-water "transfer functions" that succinctly characterize the essential regulating and converting behavior of hydropower facilities. If one considers the time series of flow (and the specific energy conveyed by that flow) in a river as the signal, insight may be gained by examining how this "inflow" signal, with its myriad and periodic fluctuations, is lagged, filtered, and otherwise converted into an outflow signal by a hydropower facility, with a corresponding electric power output signal. By taking advantage of analytics from the signal processing and information flow domains, this effort will develop an efficient method for encapsulating the complex and facility-specific behavior of many hydropower facilities.

The hypothesis of the project is that the transfer functions of facilities, derived from time series data, in the same archetype ("run-of-river," "ponding storage," and "long-term storage" for example) will exhibit similarities and features that can be used to classify facilities and model facilities more coherently and consistently in river and power system models, and understand which hydropower project archetypes warrant more detailed study and effort to improve their representation in models. These hydropower facility transfer functions and their facility-specific parameters derived from historical time series data will ultimately be intuitively and quantitatively linkable to hydropower parameters production cost modeling (e.g., modes of operation for hydropower facilities) and water balance modeling, routing, and scheduling. This research and proposed methodology is not intended to create yet another model for how hydropower participates in power systems; it will provide an analysis tool, lexicon, and set of concepts that enable river system and power system decision makers and modelers to mutually convey the functionality and value of hydropower to electric power systems.

Laboratory(s): ORNL

Data-Driven Approach for Hydropower Plant Controller Prototyping Using Remote Hardware-in-the-Loop (DR-HIL)

Real-time prototyping of hydropower plant controls is important for reducing the cost and the risk of field deployment. In this project, we propose to 1) collect design and operational data from actual hydro plants and 2) use a physics-informed machine learning approach for real-time emulation of hydropower plants, including the hydro turbine and hydrodynamics. The data-driven models will be interfaced with digital real-time simulation at NREL's Flatirons campus for hardware-in-the-loop (HIL) testing of the governor hardware device or controller-HIL (CHIL). The proposed approach will also establish the connectivity-based remote CHIL testing capability using real-time data streams from an actual hydro plant. This integrated data-driven hydro-plant emulation with CHIL will be used to prototype hydro-governor controls and, in the future, provide an opportunity to test hydropower integrated with various technologies (e.g., conventional and renewable generation, energy conversion, etc.) as HIL.

Laboratory(s): NREL

White Paper Series on the Role of Hydropower in Changing Electricity Markets

The main objective for this project is to develop a series of forward-looking and technically rigorous white papers intended to motivate discussion of hydropower capabilities across the broader power system community. The project team will develop three white papers, focusing on topics such as evolving trends within electricity markets, contractual arrangements for hydropower, future grid requirements for a changing resource mix and how hydropower can contribute to meet these needs. Each white paper will contribute to the HydroWIRES goal of increased awareness and buy-in from the energy community for hydropower and pumped storage hydro to be part of the conversation about flexible, renewable electricity resources and a cleaner power grid. Overall, the project will lead to an increased understanding of hydropower's role in evolving power systems and electricity markets.

Laboratory(s): ANL, PNNL, NREL

Hydropower Storage Capacity Dataset

Hydropower operations are closely linked to requirements and capacity of reservoir storage. In hydropower and multipurpose reservoirs, managing storage is critical to controlling floods, providing water supplies throughout the year, and producing suitable hydraulic head for power generation. Recognition of the potential for existing hydropower reservoir storage to improve grid resilience and reliability has led to a growing interest in understanding existing storage capacity for conventional hydropower facilities. An understanding of the storage capacity (volume, timing, and variability of storage), and how it translates to benefits to the grid (potential generation), is essential for more strategic and effective exploitation of existing hydropower infrastructure. The creation of a national dataset of attributes related to storage capacity will ultimately help inform flexible plant operation and management strategies and will enable more effective support of the grid as it continues to evolve.

Laboratory(s): ORNL

Power Flow and Stability Models

Operational needs of U.S. power systems are changing due to increasing penetration of variable renewable energy (VER) resources and retirement of conventional fossil fuel-based generation. The nature of grid services, such as inertia and primary frequency response, may also change as more of these services are likely to be provided by inverter-based VERs and batteries. Consequently, the role of hydropower is also expected to change, as it relates to provision of these grid services. Modeling of hydropower plants in power systems analysis has been studied for decades but there are still modeling gaps that are being acutely realized due to the changing nature of power system operations. For instance, the modeling of hydropower resource capabilities in short-term power flow and dynamic stability models, which are used for analysis of system (and resource) response to contingency events, such as loss of a large generator. These modeling gaps need to be addressed urgently to create better opportunities and challenges for hydropower resources in a changing power grid landscape. The project will produce a report on a list of hydro units modeling gaps in steady-state power flow and dynamic stability models, developed through an extensive stakeholder engagement process.

Laboratory(s): PNNL, NREL, INL

Life Cycle Assessment of Pumped Hydropower Storage

Life cycle assessment (LCA) is an internationally accepted method for making consistent comparisons among technologies providing the same service based on environmental metrics. LCAs utilize similar inputs as techno-economic analysis (TEA). Traditionally, energy generation technologies have been evaluated through LCA, and in recent years, some energy storage technologies have likewise been evaluated, like pumped storage hydropower. However, with newer forms of energy storage being built, like closed-loop PSH, there is a need for detailed assessment of life cycle environmental impacts of them in a consistent manner to other storage technologies and to TEAs. With advice from an expert review panel, NREL will develop a novel LCA of closed loop pumped storage hydropower leveraging extant TEAs to inform stakeholders and decision makers such as DOE, ISOs, non-government orgainizations, and other researchers on credible, objective environmental indicators such as life cycle greenhouse gas emissions, material demands, and net energy that can be fairly and commensurately compared to other storage technologies.

Laboratory(s): NREL

Flexible Ops

A review of hydropower operations across market regions has revealed that they are changing in many parts of the country due to grid conditions. In particular, system operators are increasingly relying on hydropower's capabilities—such as inertia, primary frequency response, spinning reserves, and regulation reserves—to support grid reliability. Provision of these services depends on the plant's technical capabilities, but there are often other constraints that limit full utilization of those capabilities, which could be of electro-mechanical, environmental, and regulatory nature. Research has also shown that operating regimes associated with flexible operations can also have a detrimental effect on equipment condition that translates into higher operations and maintenance (O&M) costs. Technology innovation is needed to address these challenges and improve hydropower's capability as a fast-acting and flexible resource. ORNL, in partnership with INL and PNNL, is performing a comprehensive assessment to describe the current flexibility capabilities of hydropower components, establish existing constraints to fully utilize them, and identify novel opportunities for improvement.

Laboratory(s): ORNL, PNNL, INL

PSH Portfolio Evaluation and Innovation Study

PSH, with a total of 22 GW of installed capacity in the United States, represent over 95% of the domestic electric energy storage available today. However, no large PSH projects have been commissioned in the last 20 years due to challenges associated with the magnitude of project costs and financing interest during development and construction; the length of time from project investment until project revenue; permitting challenges and construction risks; competition from other storage technologies; and unrecognized energy storage valuation. To address these challenges, research and development efforts have focused on radically new designs and technologies that can dramatically reduce costs and commissioning timelines. In this study, Argonne National Laboratory will perform a landscape analysis to establish the current state of the art of PSH technology, identify promising new concepts and innovations, and highlight technology gaps that have yet to be addressed.

Laboratory(s): ANL

HydroWIRES Ongoing National Laboratory-Led Projects (started in 2019):

Improving Hydropower Benefits by Linking Environmental Decisions and Power System Trade-Offs Through Flow Release Decisions

Hydropower has a new and potentially important role in enhancing resilience of the electric system due to its ability to generate power without inputs from the grid. It is imminently important to understand if hydropower can have the necessary operational flexibility to provide these services given environmental flow requirements placed on the fleet. Environmental flow requirements included in Federal Energy Regulatory Commission (FERC) hydropower licenses are an important component to preserving and, in some cases, restoring ecological function and services provided by riverine ecosystems. While environmental flow requirements in a FERC license may improve outcomes such as water quality, fish habitat, or recreation, they may limit the operational flexibility of hydropower plants, narrowing their ability to respond to the grid. Defining linkages between flow requirements and specific environmental outcomes is essential to not only producing favorable environmental outcomes, but also to enabling greater operational flexibility within a given hydropower facility. This project will provide pathways for this co-optimization in hydropower systems by quantitatively linking power system and environmental outcomes through the common hub of flow decisions. It is anticipated that the co-optimization framework created in this project will provide a guide for designing environmental flow requirements that create value propositions for a diversity of stakeholders in FERC licensing proceedings.

Laboratory(s): ORNL, PNNL, ANL, INL, NREL

Enhancing the Representation of Conventional Hydropower Flexibility in Production Cost Models

Hydropower is in high demand from a power grid coordination perspective because of its operational and economic characteristics. But production cost models (PCMs)—a tool traditionally used to plan and optimize power generation sources to meet demand within security constraints at the lowest cost—currently oversimplify hydropower operations. As part of the HydroWIRES Initiative, researchers from PNNL, ANL, and ORNL are teaming with the Center for Advanced Decision Support for Water and Environmental Systems to improve the representation of hydropower operations in PCMs across regional power grids. The PNNL-led team is leveraging large-scale, integrated water-modeling tools and unit commitment models to build a module that characterizes potential hydropower operations based on daily hydrologic conditions, regulatory water management compliance rules, and economic signals. This module, referred to as "dynamic classification" by PCM modelers, will support more robust PCM-based studies. The dynamic classification will be developed over the western United States as proof of concept. Results from this effort will guide future model development and research to improve generator fleet dispatch, scheduling, and planning, toward the goal of better co-optimizing water and energy systems.

Laboratory(s): PNNL, ANL, INL, ORNL

Improving the Representation of Hydrologic Processes and Reservoir Operations in Production Cost Models

Although there have been many advances in PCM techniques over the past decade, the representation of hydropower operations has remained relatively rudimentary. Hydropower operational constraints (e.g., equipment, water use priorities and rules, environmental constraints) are not easily characterized in unit commitment and economic dispatch models. Uncertainties involved with hydropower planning also do not align well with grid operation methodologies. These misalignments make it difficult for grid operations models to comprehensively value and make best use of the flexibility available with hydropower generation. To address these challenges, NREL will lead integration of intraday and day-ahead grid operations models with a river basin model, enabling a global optimization across both grid and reservoir operations. The lab will also use stochastic hydropower forecasts combined with progressive hedging to perform multi-stage, multi-time period optimization. This allows the combined grid and water model to value multiple timescales and uncertainties in a single optimization, enabling more accurate value of real-time flexibility to help balance supply and demand under different scenarios while enforcing precise, long-term water level constraints. In essence, the project will help to improve both grid and water system resilience while making better use of the water throughout the season.

Laboratory(s): NREL

Characterization of Hydropower Generation Attributes Relevant to Grid Reliability and Resilience

The U.S. power system is continuing to evolve both in terms of system composition, as well as the definition of and requirements for attributes related to reliability and resilience of operations. While conventional contributors to system reliability are being replaced by as-available and variable renewable energy resources, extreme events (e.g., man-made [cyberattacks] and natural) continue to afflict the power system on a more routine basis, causing damage and potential disruptions to the grid. Hence, the role of hydropower in meeting reliability and resilience needs will become even more important. This project will develop frameworks, evaluation methodologies, and tools to identify hydropower's contribution to grid reliability and resilience. These methods will be demonstrated through various use cases representing a variety of future grid conditions and extreme event scenarios. The project will also provide insights into the specific operational and design attributes of hydropower resources that may need to be adapted to ensure that resources are best equipped to meet the power system's reliability and resilience needs.

Laboratory(s): PNNL, INL, NREL, ORNL, ANL

Improving Hydropower and PSH Representations in Capacity Expansion Models

Long-term planning tools have difficulty representing detailed hydropower operating characteristics, which depend not only on technological specifications but also on water management practices and regulations. As a result, the value of hydropower is incompletely characterized, and the potential role of hydropower in the performance and resiliency of the future electric grid is not fully understood. This work will fill that gap by developing new ways to represent hydropower resource, technology, and operational characteristics in electric sector capacity expansion models and implementing them in the open-source version of the NREL's Regional Energy Deployment System (ReEDS) model. ReEDS is a well-established, national-scale planning tool used since 2003 by DOE and others to explore the evolution of the U.S. electric sector. Improvements will include a comprehensive national resource assessment for pumped storage hydropower and methods for modeling multiple hydropower technology categories characterized by technical, regulatory, and economic characteristics. The project will provide guiding principles and strategies for improving hydropower modeling in capacity expansion models and deliver a first-of-its-kind versatile PSH dataset. All data, code, and methods will be publicly available, allowing the industry to better identify the value of hydropower in the future electricity system and make more informed planning decisions.

Laboratory(s): NREL

Addressing Barriers to Energy Storage in Transmission Planning and Operations

A complex set of technical and regulatory issues creates significant barriers that prevent PSH and other forms of energy storage from accurate representation in transmission planning and operational processes. These barriers are numerous and complex, and a full evaluation of them has not yet been done. As a result, current transmission planning, deployments and operations may be inefficient and, ultimately, may result in higher costs for customers. This project will identify those barriers, create a proposed participation model for PSH to provide transmission and market functions, and conduct a techno-economic analysis of PSH that fully quantifies its technical capability and economic value as a transmission asset.

Laboratory(s): PNNL, ANL

Value of Flow Forecasts to Power System Analytics

Hydropower operators use weekly water inflow forecasts to optimize reservoir releases and unit commitment and to meet power grid needs. The accuracy of inflow forecasts, combined with related scheduling adjustments, contracts, and market opportunities, are reflected in a utilities' revenue. One of the goals of the HydroWIRES Initiative is to quantify the flexibility of hydropower operations and understand its adaptability to changes in water supply, regulation, markets, and power grid needs. In partnership with North Carolina State University and the National Corporation of Atmospheric Research, researchers from PNNL and INL will use inflow forecasts, reservoir and power system models, and case studies to demonstrate the contribution of flow forecast to provide hydropower services to the grid. Flow forecast accuracy metrics, combined with regional power system analytics (including regional economics and generation portfolios), will help detangle the value of incremental improvement in flow forecasts. This research supports DOE in developing strategic partnerships with other institutions to invest in information products and decision-support practices for meeting power grid needs.

Laboratory(s): PNNL, INL

HydroWIRES External and Industry-Led Projects (2016-present):

Predicting Unique Market Pumped Storage Significance

While no new PSH plants have been developed in the past two decades, there is renewed interest in the technology due to increases in VRE penetration. The objective of this project is to develop a framework and outline the parameters needed to analyze the energy and ancillary services PSH provides to the electricity grid currently and how that value may change as the generation asset mix—especially as it relates to increased penetration of VRE—changes over time. A key focus will be to develop understanding of the trends that impact PSH value so that utilities can determine strategy for further development of PSH.

Awardee: EPRI

Hydropower Flexibility Framework

As the generation mix on the grid shifts towards VRE, flexibility services are increasingly in demand. Maintaining reliability and resilience in this context requires operators and regulators to be able to accurately assess exactly how much flexibility exists in the hydropower fleet. This project will develop an industry-recognized methodology and framework for calculating the flexibility that hydropower assets can provide, demonstrate the validity of the approaches and the viability of comprehensive application across the fleet, and establish a platform for future flexibility assessments.

Awardee: EPRI

Modeling and Optimizing Pumped Storage in a Multi-Stage Large Scale Electricity Market under Portfolio Evolution

PSH plants have been traditionally designed and used for large scale, daily energy arbitrage, but technological developments and changes to grid needs are making flexible operation more prevalent. Market participation models for PSH have not kept up with these changes, which means that the range of energy and ancillary services that PSH plants can provide are not being optimally allocated. The proposed work aims to develop a prototype enhanced PSH model for incorporation into MISO's multi-stage market clearing process with proper consideration of the unique characteristics of PSH.

Awardee: Missouri University of Science and Technology

Value and Role of Pumped Storage Hydro under High Variable Renewables

While advanced PSH technologies like variable speed units have existed for some time, none have been installed in the United States. As such, market and operations models do not capture the capabilities of these technologies. The overall goal of this project is to overcome a range of market barriers for PSH by helping utility companies understand benefits of PSH that are not well understood or quantified, by demonstrating the capabilities of new PSH technologies such as variable speed PSH, and by helping developers improve PSH revenues with development of a new scheduling optimization tool.

Awardee: GE Global Research

Increasing Operational Flexibility of Francis Turbines at Low-Head Sites Through Analytical and Empirical Solutions

As operation of turbines outside the operational range recommended by the original manufacturer is more demanding for the machine, significant operational ranges are not included in typical operations planning. Enabling a broader operational range (even temporarily, for a few minutes or hours) offers an opportunity to upgrade dispatch strategy, increase flexibility, and increase support for the grid reliability and resilience. The overall goal of this project is to demonstrate the potential to increase the operational flexibility of installed low head Francis turbine driven hydropower-plants.

Awardee: GE Global Research

Exploring Multidimensional Spatial-Temporal Hydropower Operational Flexibilities by Modeling and Optimizing Water-Constrained Cascading Hydroelectric Systems

One barrier to the optimal operation of hydropower plants is a lack of accurate inflow forecast information. This is true for both seasonal inflow expectations, which affects long-term planning for bulk energy production, and daily inflow expectations, which affects flexibility, and is further exacerbated in the case of cascading plants. The proposed work aims to develop: 1) accurate machine-learning based closed-loop forecast models for seasonal and day-ahead water inflows; and 2) enhanced cascading hydroelectric system (CHE) modeling and data-driven optimization approaches to explore multidimensional spatial-temporal hydropower operational flexibility potentials with proper consideration of unique characteristics of CHE systems.

Awardee: Stevens Institute of Technology

Identifying Hydropower Operational Flexibilities in Presence of Streamflow and Net Load Uncertainty

Hydropower plants have been traditionally designed and used for base-load bulk energy production, but technological developments and changes to grid needs are making flexible operation more prevalent. Still, hydropower's flexibility capabilities and constraints are not well understood. The goal of this project is to develop an accurate model representation of hydropower operations that allows for a detailed specification of various constraints and captures the underlying uncertainty from both inflows and net load.

Awardee: University of California, Irvine

Cost-Effective Small-Scale Pumped Storage Configuration

Since 2000 only one new pumped storage hydropower project has been constructed in the United States. In order to increase the future opportunity for pumped storage development, reductions in cost and scale are necessary. Historically, pumped storage projects have required large capacity to overcome the fixed costs associated with custom engineering of complex underground structures with associated geological risk. The Obermeyer Hydro submersible pump-turbine offers a standard, scalable solution which reduces underground construction and risk. Learn more.

Awardee: Obermeyer Hydro

Furthering Advancements to Shorten Time (FAST) Commissioning for Pumped-Storage Hydropower Prize

Today's electricity system is changing rapidly and hydropower and PSH have an essential role in contributing to the resilience, reliability, and affordability of the U.S. power system. PSH is by far the largest source of energy storage on the grid, and it will play a key role in supporting increased integration of variable generation resources. But large capital investments and long lead times for PSH commissioning are deterrents to would-be developers and utilities. The goal of the prize is to catalyze new solutions, designs, and strategies to accelerate PSH development by reducing the time, cost and risk to commission PSH. In fall 2019, four technology developer teams were selected to receive cash prizes as well as national lab technical assistance to further develop their ideas. Learn more at: www.americanmadechallenges.org/fast/.

HydroWIRES Foundational National Laboratory-Led Projects (2016-present):

Integrated Hydropower and Energy Storage: Providing Essential Reliability and Ancillary Services Using Individual or Coordinated Hydropower Plants

Macro-trends in the grid—increased penetration of variable generation resources and decommissioning of thermal generators in some regions of the United States—are increasing the need for flexibility in the grid. Hydropower as a generation class can provide most grid needs, but the level of a given service it can provide varies significantly between plants. The objective of this project is to increase the value of both hydropower and energy storage and improve provision of grid requirements from existing hydropower plants by examining the synergies of integrating hydropower and energy storage.

Hydropower Value Study

This project's main objective was to perform foundational work to understand recent trends in hydropower operations, future expected changes, and technical abilities of hydropower resources to adapt their operations in the future. The work products included a landscape review of the recent trends in provision of various power grid services by hydropower resources. The project was also designed to identify high-impact research questions to lay the foundation for future research. Learn more.

Valuation Guidance and Techno-Economic Studies for Pumped Storage Hydropower

The objective of this project is to advance state of the art in the assessment of value of PSH plants and their role in the power system. The goal is to develop a detailed step-by-step valuation guidance and apply it to two competitively selected PSH sites to test the valuation methodology and assist the developers in understanding the value streams available from their projects. The project outcomes are:

- Develop a comprehensive, repeatable, and transparent valuation guidance that will allow for consistent valuation assessments and comparisons of potential new PSH projects or project design alternatives.
- Test the PSH valuation guidance and its underlying methodology by applying it to two selected PSH projects.
- Transfer and disseminate the PSH valuation guidance to the hydropower industry, PSH developers, and other stakeholders.

Learn more.

Energy Storage Technology and Cost Characterization Report

As part of the "Valuation Guidance and Techno-Economic Studies for Pumped Storage Hydropower" project, this report defines and evaluates cost and performance parameters of six battery energy storage system (BESS) technologies and four non-BESS storage technologies. Data for combustion turbines are also presented. Cost information was procured for the most recent year for which data were available based on an extensive literature review, conversations with vendors and stakeholders, and summaries of actual costs provided from specific projects at sites across the United States. Detailed cost and performance estimates were presented for 2018 and projected out to 2025. Learn more.

Ground-Level Integrated Diverse Energy Storage (GLIDES)

GLIDES—invented at ORNL—is a cost-effective, scalable, and flexible storage system that can provide a broad range of ancillary services and mitigate many of the market and regulatory barriers faced by PSH. This project aims to quantify the value proposition, identify cost reduction opportunities, and prioritize future research directions for the newly invented GLIDES modular PSH technology. This analysis identifies the most promising market segments to target for commercializing GLIDES as well as the cost and performance targets necessary to reach commercial competitiveness. Learn more.

Hydro Battery Systems Catalog Development

Apart from limited studies, there exists no technology advancements in the field of modular systems for use in water storage for pumped storage projects. In this project, a 5MW pumped-storage system including a floating reservoir option will be developed and analyzed. The advantages of the proposed technology are innovative modularity and scalable application. To reduce environmental footprints and costs, and accelerate pumped storage project deployment, the modularity of this floating reservoir serves specific beneficial purposes: faster and safer deployment, maintenance, and removal. Learn more.

Transforming the U.S. Market with a New Application of Ternary-Type Pumped Storage Hydropower Technology

The U.S. electrical grid is seeing a huge increase in new renewable energy (RE) generation and, at the same time, a huge amount of thermal generation retirements. This dynamic is changing the traditional operation of the grid and is placing a premium on assets that can provide fast-ramping flexible capacity. Addressing this need, the study's goals were to assess & quantify how innovative, fast-acting advanced PSH systems can economically solve these grid integration challenges during future high RE contribution scenarios. Project focused on ternary PSH (T-PSH) and quaternary PSH (Q-PSH), coupling them with sophisticated transmission monitoring/control equipment (i.e., dynamic transmission) as a proposed solution. Learn more.

Pumped Storage Hydropower FAST Commissioning Technical Analysis

This report was developed in tandem with the Furthering Advancements to Shorten Time (FAST) to Commissioning PSH Challenge and represents the underlying technical analysis that informed the competition. Lead by Oak Ridge National Laboratory, the report is designed to address barriers and solutions to PSH development by establishing baseline project development knowledge, defining key aspects of project development, and identifying opportunities to reduce project timelines, costs, and risks. The document's scope includes post-licensing activities and excludes factors related to permitting or licensing. Learn more.

A Comparison of the Environmental Effects of Open-Loop and Closed-Loop Pumped Storage Hydropower

This report compares the potential environmental effects of open-loop PSH projects with those of closed-loop PSH projects; describes how existing projects in other countries are avoiding, minimizing, or mitigating these effects and how proposed U.S. projects will address them; and discusses the relative significance of the environmental issues. Learn more.

Hydropower Plants as Black Start Resources

This report identifies the advantages of using hydroelectric power for black start and compares hydropower with other types of power plants for providing this valuable service to ensure the resiliency of the power grid. The report provides an overview of the critical role of black start capability to ensure timely restoration of grid operation after a major power grid outage. Learn more.

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