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RENEWABLE ENERGY

WATER POWER TECHNOLOGIES OFFICE

Multi-Year Program Plan

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Executive Summary

This Multi-Year Program Plan (MYPP) is published as a response to the requirement for a Water Power Technologies Office (WPTO) Strategic Plan as directed under the Energy Act of 2020 (Title 3, Subtitle A, Sec. 3001).

WPTO, which is part of the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE), enables research, testing, development, and commercialization of emerging technologies to advance marine energy[1] as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid. To reduce marine energy costs and fully leverage hydropower's contributions to the grid, WPTO invests in early-stage research and technology design, validates performance and reliability for new technologies, develops and enables access to necessary testing infrastructure, and disseminates objective information and data for technology developers and decision makers. WPTO is also increasing its focus on shorter-term water power technology application and adoption, particularly considering the specific needs of diverse sectors and communities.

People and their communities are deeply reliant on and connected to their water systems as part of their economies and culture. Recognizing and respecting these factors, WPTO has endeavored to build stronger connections to an increasingly diverse set of stakeholders, particularly in remote, tribal, and disadvantaged communities. There is an opportunity to reimagine how to harness water and power by building more resilient infrastructure, producing clean water in new ways, unlocking the full potential of all ocean resources, and better aligning technology development with end users and community needs. WPTO continually strives to leverage evolving innovation ecosystems by incorporating end-user requirements in solicitations and by partnering directly with community-based organizations.

The United States has vast marine energy and hydropower resources, and the continued development of new technologies and modernization of existing assets are critical to furthering the nation's near-term electricity sector decarbonization goals and longer-term, economy-wide objectives. But for those who are not familiar with the specific opportunities these resources hold, the societal and economy-wide benefits that could be unlocked with continued research and innovation may be less obvious. Hydropower is the oldest form of renewable electricity generation in the country; commercially mature systems have been in operation for many decades in some cases. In contrast, marine energy systems are the newest suite of potential technologies, with little more than a decade of significant research having been conducted in the United States and abroad (compared to more than four decades for other renewable technologies) and much work left to do. The following two sections summarize the major benefits and opportunities for continued and sustained investment in water power technologies.

Hydropower—the oldest form of electricity generation in the United States—remains an important energy resource for the country and is critical to long-term decarbonization goals, warranting additional innovation and research.

Hydropower has provided clean, low-cost electricity for more than a century as the nation's first renewable source of electricity. Today's evolving power system has created new opportunities for hydropower to play an important role in a 100% clean energy future using existing technologies and infrastructure. In 2020, hydropower provided 7.3% of the electricity on the grid and accounted for 37% of U.S. renewable electricity generation.[2]

[1] The Energy Act of 2020 (Sec 3001) defines marine energy as "energy from waves, tides, and currents in oceans, estuaries, and tidal areas; free flowing water in rivers, lakes, streams, and man-made channels; differentials in salinity and pressure gradients; and differentials in water temperature, including ocean thermal energy conversion."

[2] U.S. Energy Information Administration (EIA), 2021. "Electricity in the U.S." https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php#:~:text=Hydropower%20plants%20produced%20about%207.3,from%20renewable%20energy%20in%202020.

Numerous recent studies have shown hydropower to be one of the most reliable, predictable, and flexible clean energy generation resources available, and the United States has a sizable existing fleet with more than 80 gigawatts (GW) of generating capacity. While some hydropower plants will reach the end of their useful or economic lives and be retired in coming decades, many others can continue to be valuable energy assets for decades to come. To avoid accelerated or unnecessary losses of U.S. hydropower, which would then need to be replaced by additional low-carbon generation, the existing fleet must be modernized to continue providing clean, flexible power and ensure a 100% clean energy future for the United States.

Firm and flexible hydropower can be expanded by modest amounts by upgrading existing hydropower plants and utilizing other existing infrastructure like non-powered dams and other constructed waterways without building large, new dams and reservoirs. In the past decade in the United States, several dozen new projects of these types have been developed that utilize new technologies and regulatory regimes. For example, the use of new hydropower technologies as part of irrigation modernization projects is an important opportunity to help advance water-system sustainability and agricultural decarbonization goals. As the country continues to upgrade and modernize its water infrastructure, there are also new opportunities for hydropower innovations to be integrated into projects focused on water distribution and groundwater recharge, invasive aquatic species management, and water quality monitoring and improvement. The potential to develop new hydropower from these various opportunities could add another 20 GW of generating capacity.

Pumped storage hydropower (PSH) is the largest contributor to U.S. energy storage with an installed capacity of 21.9 GW or roughly 93% of all commercial energy storage capacity in the United States.[3] PSH could provide tens to hundreds of gigawatts of additional long-duration storage, with projects designed to store energy from days to weeks or months. Many other countries continue to innovate and develop new pumped storage projects, and the global market for pumped storage development is currently larger than it has been in decades. Continued investments to drive down costs, shorten construction timelines, demonstrate and de-risk new types of pumped storage technologies, and reduce market and other deployment barriers for PSH in the United States will ensure that as many low-cost and complementary options for energy storage are available as possible as other energy storage technologies continue to mature.

Work to reduce any existing environmental impacts of hydropower is also important for advancing ecological and environmental justice goals, particularly in the face of greater climate-driven pressures on river systems. As less than 3% of the nation's 90,000+ dams have hydropower, research in this area also has impacts far beyond powered dams for issues like fish passage, recreational access, and water quality improvement. It is important to note that many of the largest and most significant hydropower projects are also multipurpose and serve many other critical societal missions (like flood control, water supply, and navigation) that are unlikely to diminish in importance. Even if hydropower operations ceased, these multipurpose dams will remain, and continuing to innovate new solutions to mitigate environmental impacts is important.

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

Hydropower can also be utilized and upgraded to directly mitigate some of the effects of climate change and improve the ecological resilience of our river basins. For example, hydropower operations can help to mitigate high water temperature events by increasing the ability to release cold water from deep within reservoirs,[4] monitoring and controlling the spread of invasive species,[5] and mitigating the impacts of more intense floods.[6] Because of the complex and uncertain threats posed by climate change to hydropower and broader dam and water infrastructure, there is also a need for new analytical tools and monitoring technologies to ensure our water systems are adaptable and climate resilient.

Finally, there is a significant domestic workforce and U.S. supply chain that supports the existing hydropower and pumped storage industry, with a diverse footprint across many states and regions. The 2016 Hydropower Vision study showed that the U.S. hydropower and pumped storage industries could add more than 100,000 jobs by 2030 under various scenarios analyzed in addition to continuing to support a workforce of more than 130,000 under business-as-usual cases.[7] Supporting the evolution and growth of this workforce with educational science, technology, engineering, and math (STEM) outreach, training opportunities, and diversity initiatives will be important to ensuring that tens of thousands of good-paying, clean energy jobs continue.

Marine energy, the newest suite of clean energy technologies, is material to both the nation's short-term and long-term goals for decarbonization, sustainability, and economic growth.

Given the current maturity of marine energy technologies—with little more than a decade of significant research compared to 40 to 50 years for other renewable technologies—it is true that it will take longer for the industry to realize significant commercial deployment potential. But there are also hundreds of nearer-term opportunities in high-energy-cost remote and distributed communities across the United States and in U.S. territories where there may be limited energy options. These opportunities are real and impactful, and the focus on community-centric needs in the iterative technology development and demonstration cycle is increasingly important.

Marine energy technology development also directly supports and engages blue economy priorities, including building sustainable aquaculture systems and dramatically expanding data collection from our oceans, that will be important for the nation. Oceans themselves can serve as assets for resilience against climate change, and options for marine-powered data collection or renewable fuels production could enable new ways to utilize the oceans as environmentally appropriate sinks for carbon or to decarbonize the maritime transportation sector. Opportunities to apply marine energy technologies include powering desalination systems and ocean observation and providing onsite power to aquaculture production. For example, as water stress likely increases due to climate change, different options for desalination will become increasingly important. Coastal wave-powered desalination systems are already being pursued in some parts of the world. There are near-to-medium-term opportunities for thousands of marine energy systems to be deployed in support of these opportunities.

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4 Duka, M., Shintani, T., and Yokoyama, K, 2021. "Mediating the Effects of Climate on the Temperature and Thermal Structure of a Monomictic Reservoir through Use of Hydraulic Facilities." https://www.mdpi.com/2073-4441/13/8/1128.

5 Milt, A.W., Diebel, M.W., Doran, P.J., Ferris, M.C., Herbert, M., Khoury, M.L., Moody, A.T., Neeson, T.M., Ross, J., Treska, T., O'Hanley, J.R., Walter, L., Wangen, S.R., Yacobson, E. and McIntyre, P.B, 2018. "Minimizing opportunity costs to aquatic connectivity restoration while controlling an invasive species." https://conbio.onlinelibrary.wiley.com/doi/10.1111/cobi.13105.

6 California Legislative Analyst's Office, 2017. Managing Floods in California.

7 U.S. Department of Energy, 2016, "Hydropower Vision Report." https://www.energy.gov/sites/default/files/2018/02/f49/Hydropower-Vision-021518.pdf.

Even though marine energy is not yet a sizable industry with significant numbers of jobs, investments in STEM and foundational research capacity at universities and other research organizations can support broader innovations and growth across important blue economy sectors and lay the groundwork for a robust set of future U.S. industries.

There is also significant deployment potential out to 2050 and beyond, and many reasons why continued investment in marine renewables can be important for long-term U.S. goals. U.S. economy-wide decarbonization targets are ambitious, and even technologies that do not have commercial potential on the scale of other renewables in the next one to two decades can play impactful roles in the long term. Given the trajectory of continuing cost reductions and the historical progress of innovation for other renewable technologies, up to 50 GW of marine energy capacity could be added in the United States by 2050. Modeling efforts also show that to achieve long-term 2050 clean energy goals while also meeting America's growing energy needs, the pace of renewables deployment will need to continue accelerating past 2040, and relatively newer technologies—like marine energy that can utilize other resources—may be well positioned to support ambitious long-term targets. Wind and solar technologies took decades of sustained research to reach their current levels of cost and maturity. For marine energy technologies to be in similar positions a few decades from now, sustained long-term efforts are needed.

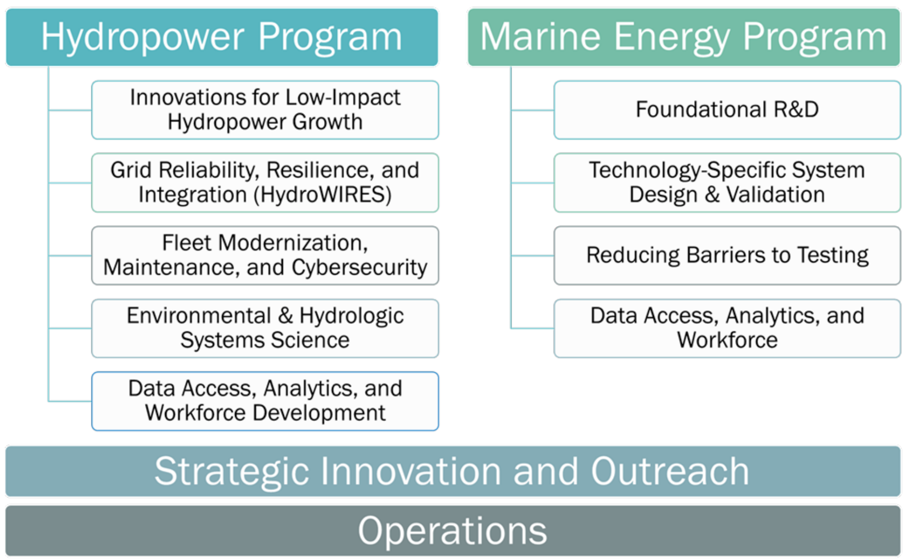
Marine energy technologies hold the potential for significant deployment along densely populated coasts and utilize different materials, manufacturing, and supply chains than other renewables. With huge amounts of wind, solar, and new land-based transmission predicted to be needed, marine energy technologies may be desirable and complementary options if circumstances demand it, especially if there are unforeseen difficulties deploying other renewables to the degree and scales needed. Most marine energy resources are also highly predictable, and in many places, their potential generation profiles are complementary to other renewables in seasonal profiles.

Even if U.S. decarbonization goals are achieved on time, other parts of the world may still have much more work to do to achieve their targets, and marine energy technologies will continue to be highly competitive and desirable options in some places. Other nations are investing significantly in marine energy technology development. Continuing to develop expertise and competitive advantage in the sector will benefit the U.S. economy.

Water Power Technologies Office Overview

Aligned with the opportunities discussed directly above, WPTO has developed its MYPP for the next decade to broadly address the identified challenges and rapidly innovate new solutions. WPTO supports DOE and EERE objectives of combating the climate crisis, creating new clean energy jobs, and promoting energy and environmental justice. WPTO consists of two R&D programs: the Marine Energy Program and the Hydropower Program. The office also has two teams who work across the programs: the Operations team and the Strategic Innovation and Outreach team (Figure 1). The Multi-Year Program Plan focuses specifically on the Marine Energy and Hydropower Program activities and supporting goals, but these crosscutting teams are critical to implementation of WPTO goals and objectives.

Figure 1. WPTO's Organizational Structure



The following sections are summaries of the major activity areas within WPTO's Hydropower and Marine Energy Programs. These summaries also include the key results and performance goals that WPTO is targeting in Fiscal Year (FY) 2021–2025. Accomplishing the 2021–2025 performance goals are critical to achieving longer-term FY 2026–2030 follow-on objectives. These goals are specific to programmatic objectives. Larger, macroeconomic outcomes—like the impact on deployment goals for the United States—are outside the scope of this document but could be included in higher-level DOE or EERE plans. For a discussion of other performance measures and evaluation mechanisms (including Government Performance and Results Act goals), see the Assessing Performance and Evaluating Success section.

Hydropower Program Overview

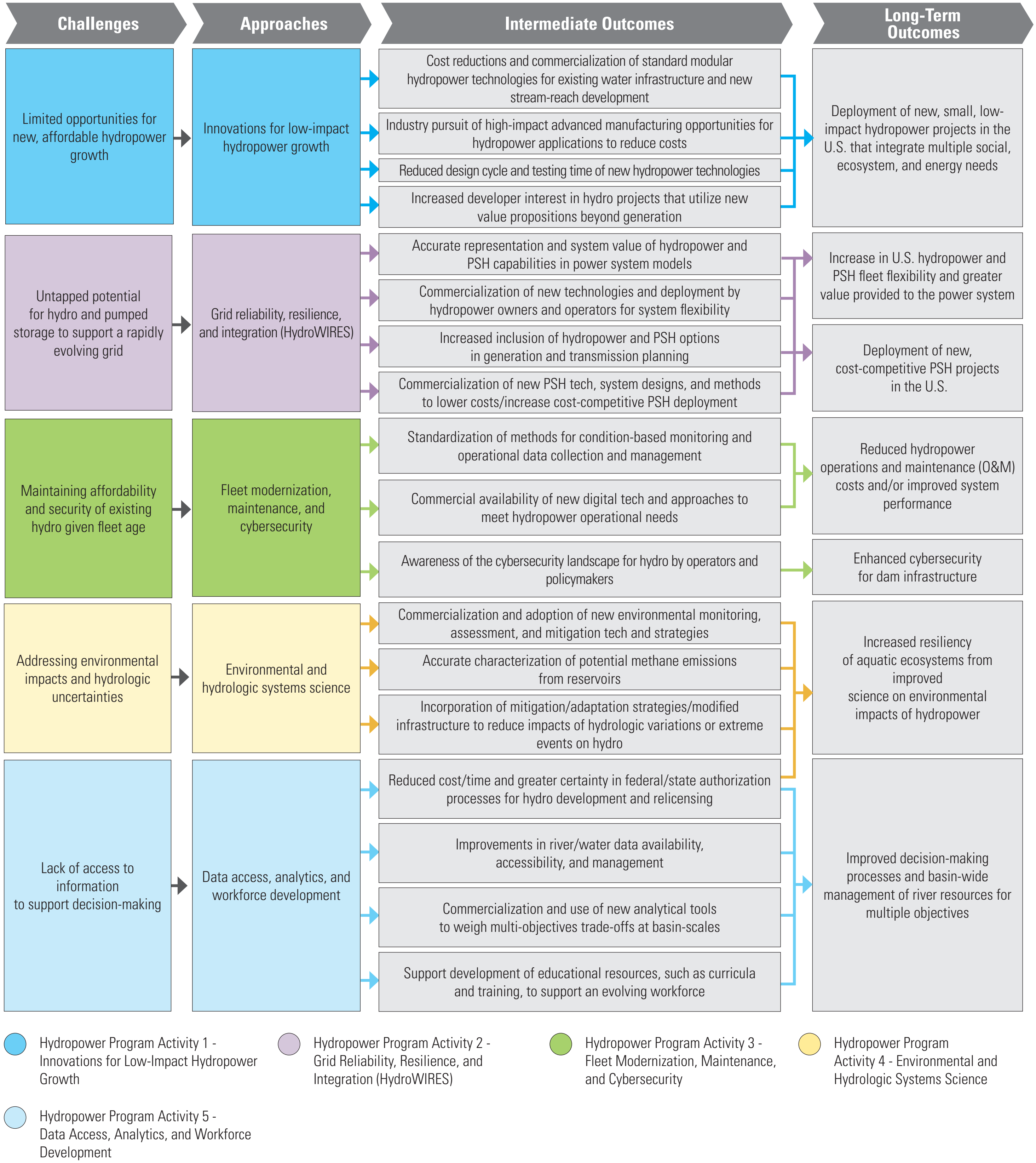
VISION	A U.S. hydropower and pumped storage industry that modernizes and safely maintains existing assets; responsibly develops new low-impact hydropower; promotes environmental sustainability; and supports grid reliability, integration of other energy resources, and energy-water systems resilience.
MISSION	Conduct research, development, demonstration, and commercial activities to advance transformative, cost-effective, reliable, and environmentally sustainable hydropower and pumped storage technologies; better understand and capitalize upon opportunities for these technologies to support the nation's rapidly evolving grid; and improve energy-water infrastructure and security.

The Hydropower Program focuses on the following key opportunity areas for potential impact:

- ***Enabling a 100% clean energy future***: Hydropower, including PSH, provides flexibility, inertia, storage, and grid services to support the increased integration of variable renewables like wind and solar energy.
- ***Expanding new value propositions for sustainable hydropower***: Retrofitting existing dams and adding generation at non-powered dams (NPDs) can increase renewable energy production, while rehabilitating dams can address safety problems, increase climate resilience, and mitigate environmental impacts.
- ***Understanding and adapting to climate change impacts on hydropower***: Advances in climate and hydrologic science, coupled with hydropower decision-making tools, can improve hydropower reservoir management by ensuring the continued reliability and climate resilience of our energy-water infrastructure.
- ***Building our hydropower fleet back better***: Modernization of the existing hydropower fleet can restore reliability and improve performance by adding cutting-edge technologies.

The Hydropower Program activities, goals, objectives, and impacts are summarized in Figure 2.

Figure 2. Hydropower Program High-Level Logic Model



Hydropower Program Activity 1 – Innovations for Low-Impact Hydropower Growth

Technology innovation can enable the growth of additional hydropower capacity and generation as an economically competitive source of renewable energy in four resource categories: (1) development in "new stream-reaches" (sometimes referred to as "greenfield" sites); (2) powering of currently non-powered dams; (3) adding generation technology to existing irrigation canals and other water conduits; and (4) upgrades at existing hydropower plants.[8] Different technology pathways addressed in this activity include the major powertrain and civil works components of a hydropower facility—primarily turbine technologies, hydraulic structures, and geotechnical approaches—with an emphasis on standardized, modular designs and approaches centered on environmental performance. Development and adoption of new technologies and strategies could lead to significant U.S. deployment of additional low-impact hydropower that integrates multiple social, environmental, and energy needs, while realizing value and revenue from a variety of sources. Table 1 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 1. Innovations for Low-Impact Hydropower Growth: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Develop datasets and interactive geospatial tools to identify development potential and site characteristics of new stream-reaches, NPDs, and conduit resources. • Publish R&D roadmap that identifies high-impact opportunities to leverage advanced manufacturing and materials in hydropower applications. • Complete testing and pre-commercial demonstrations of new cost-competitive technologies across each class of hydropower resource, with validated energy and environmental performance characteristics. • Complete development of a full-scale, federally sponsored hydropower test facility (or network of facilities). • Establish a framework for assessing costs and benefits of new hydropower projects, particularly those that could utilize new value propositions.
Follow-On Objectives (2026–2030)
• Project developers use geospatial tools to site and design new hydropower projects that balance social and ecological considerations, such as recreation, water quality, and biodiversity. • Technology developers actively pursue and apply high-impact advanced manufacturing opportunities for hydropower applications. • Deployment of new technology with revolutionary improvements in technology costs and environmental performance due to adoption of standardization and modularity principles, incorporation of advanced manufacturing and materials, and ability to test prototypes at full scales. • Increased developer interest in exploring hydropower projects that take advantage of new value propositions in addition to energy generation values.

[8] Increased developer interest in exploring hydropower projects that take advantage of new value propositions in addition to energy generation values.

Hydropower Program Activity 2 – Grid Reliability, Resilience, and Integration (HydroWIRES)

Rapid changes in the U.S. electricity system, including changes in generation mix as well as markets and policy, have created new needs for storage, flexibility, and other grid services that hydropower and PSH are well-suited to provide. In response to these opportunities, the HydroWIRES (Water Innovation for a Resilient Electricity System) Initiative seeks to understand, enable, and improve hydropower's contributions to grid reliability, grid resilience, and integration. HydroWIRES investigates additional value streams, enhanced flexibility, new operational strategies, and innovative technology solutions that enable new roles for hydropower and PSH. Efforts encompass industry and national lab-led modeling, analysis, tool development, technical assistance, and technology R&D. Table 2 outlines the key results, performance goals, and follow-on objectives for this activity area. Additionally, the HydroWIRES Research Roadmap[9] outlines further areas being pursued by WPTO.

Table 2. HydroWIRES: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Publish regionally focused roadmaps for maximizing hydropower's value for reliability, resilience, and integration. • 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. • Release the first version of a system-level 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. • 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.
Follow-On Objectives (2026–2030)
• Accurate representations in power system models of hydropower and PSH capabilities, such as the flexibility of modern designs and reservoir constraints, are widely utilized for research, planning, and unit scheduling. • Quantifiable improvement of hydropower plant operations, including coordination or co-location with other resources, to support greater needs for system flexibility. • Commercialization of new technologies for hydropower asset flexibility and deployment by hydropower owners and operators. • New PSH projects that utilize advanced technologies, system designs, and methods to lower costs/increase cost competitive PSH deployment.

[9] U.S Department of Energy, 2022. "HydroWIRES Research Roadmap." https://www.energy.gov/sites/default/files/2022-02/HydroWIRES%20Roadmap%20FINAL%20%28508%20Compliant%29_0.pdf.

Hydropower Program Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity

Within this activity, the Hydropower Program supports analysis, research, and development in three areas: (1) modernization; (2) maintenance; and (3) cybersecurity. Modernization refers to upgrading or adding new hydropower system capabilities. While the modernization portfolio is currently expanding to encompass a broader suite of R&D activities, research to date has been primarily focused on hydropower fleet digitalization. Digital transformation refers to the application of digital capabilities to not only solve traditional challenges for hydropower operations but also enable access to a new range of opportunities for the industry. This has been the initial focus of the modernization work because it represents one of the broadest opportunities for improvement in the hydropower sector, with the potential to reduce operation costs, improve system performance through continuous assessment and predictions, and ensure inter-generational knowledge retention. Maintenance research focuses on understanding and improving the specific procedures surrounding the preservation of aging hydropower systems. Maintenance represents the broadest component of asset management, where routine servicing to the system will maximize the remaining useful life of the asset. However, eventually performance degradation or risk of failure will require that the component be refurbished (activities intended to remove operational damage and increase remaining useful life) or replaced. Cybersecurity research focuses on assessing the complex regulatory and risk landscapes and helping asset owners to determine the possible benefits of different cybersecurity investments. Table 3 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 3. Fleet Modernization, Maintenance, Cybersecurity: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Develop and make publicly available hydropower digital twin capabilities (e.g., numerical models, computational codes, and underlying physics/engineering data) appropriately scaled for a diverse range of hydropower plant characteristics and operational profiles. • Publish valuation assessment guidance to facilitate right-sized investments into hydropower digitalization, maintenance, and cybersecurity. • Complete initial phases of research on fatigue and wear mechanisms for high-impact hydropower components, including both conventional and advanced materials, which can reduce forced outage instances and help design the next generation of hydropower components. • Develop hydropower plant cyber-surrogate capabilities that can be integrated into existing cybersecurity processes and reduce hydropower plant vulnerabilities.
Follow-On Objectives (2026–2030)
• Asset owners and equipment designers widely utilize new, open-access digital twin capabilities in efforts to improve system/administrative scheduling and condition-based predictive maintenance. • Demonstrated use of new valuation methodologies in hydropower plant capital planning processes as well as the use of these capabilities to identify cost reduction and capability improvement opportunities. • Use of better articulated wear/fatigue mechanisms by asset managers in maintenance scheduling as well as the integration of these insights into plant dispatch strategies. • Integration of cyber-surrogate capabilities into hydropower cybersecurity processes to facilitate the rapid identification cybersecurity intrusions and improve overall system security.

Hydropower Program Activity 4 – Environmental and Hydrologic Systems Science

While hydropower has tremendous value to the power system as a flexible, renewable resource, its long-term value is dependent on maintaining a high level of environmental performance across the fleet. The Hydropower Program develops new technologies, tools, and data to better understand and improve the environmental performance of hydropower facilities. WPTO's work focuses particularly on issues related to fish passage, water quality, and water release management. In addition, this activity area aims to provide a better understanding of potential ecological and economic risks associated with long-term hydrologic variations. This activity area focuses on: (1) developing monitoring and mitigation technologies to improve environmental performance; 2) supporting foundational and applied biological, environmental, and hydrologic systems science research to understand environmental impacts; and (3) establishing relevant standardized metrics to understand environmental impacts and improved performance. Table 4 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 4. Environmental and Hydrologic Systems Science: Performance Goals and Objective

Key Results and Performance Goals (2021–2025)
• Complete field validations of novel and improved fish detection and tracking capabilities relevant for hydropower studies, including demonstration of environmental DNA and prototypes of acoustic telemetry tags for sensitive species and a self-powered acoustic fish tag. • Demonstrate innovative tools and technologies that are benchmarked for cost and performance, including innovative fish passage technologies and sensor systems. • Demonstrate real-time data collection, automation, and visualization to inform decision makers' choices to operate hydropower resources for enhanced environmental performance in water and species management. • Release a nationwide analysis and visualization platform that enables utilities and system operators to evaluate potential long-term water-availability and climate change related risks to existing and new hydropower assets at meaningful local or regional scales. • Validate new technologies to more accurately characterize and model methane emissions from reservoirs and other water bodies.
Follow-On Objectives (2026–2030)
• A suite of demonstrated, cutting-edge tools and technologies for hydropower-specific environmental monitoring, mitigation, and decision-making that enable accurate data collection and predictive outputs with reduced cost and time and can be utilized for community developed standardized processes and Federal Energy Regulatory Commission (FERC) relicensing. • Quantifiable improvements in fish passage performance that can be linked to established fish population and restoration goals. • Documented improvements in real-time data collection and accuracy for species of concern and other environmental variables that inform hydropower operations and management. • Better understanding of the risks of long-term hydrologic variations to hydropower generation and flexibility and documented incorporation into licensing or other planning processes. • Accurate and widely agreed-upon characterization of methane emissions from U.S. reservoirs.

Hydropower Program Activity 5 – Data Access, Analytics, and Workforce Development

As a technology-neutral, national research agency with access to some of the most advanced computing, data management, and analytics in the nation, DOE is well-suited to work closely with other agencies and stakeholders to improve the "data landscape" for important hydropower and river-related information. This can help enable the development and commercialization of new crosscutting analytical capabilities to weigh multi-objective tradeoffs and support stakeholder decision-making. Also, as a largely non-regulatory agency, DOE is in a unique position to help provide insights to identify areas with the greatest opportunity for hydropower regulatory process improvements. The Hydropower Program's efforts will focus on extracting lessons learned from the substantial record of development over the last century and will use its convening role to engage other federal agencies, tribes, the hydropower industry, and nongovernmental organizations to share this information and develop ways to enhance stakeholder engagement and benefit regulatory processes. As the nation's energy and water systems become even more complex and intertwined, all of these goals aim to support improved decision-making and basin-wide management of river resources for multiple objectives, including energy, enabled by improved data and analytical tools. Finally, access to STEM-relevant data, educational materials, and opportunities for students and other early career professionals to learn more about opportunities in hydropower are critical to supporting long-term workforce needs across the industry. Table 5 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 5. Data Access, Analytics, and Workforce Development: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Launch and improve the new externally oriented HydroSource online data portal with broad use-case capabilities. • Develop a standard suite of application programming interface (API) capabilities that will provide unprecedented access to power market information for the hydropower community. • Leverage machine learning and new big-data access approaches, in collaboration with FERC and other stakeholders, to increase access to information available in FERC's eLibrary. • Publish a report on the key issues on the time, cost, and uncertainty associated with U.S. hydropower regulatory processes. • Release a new hydropower-focused STEM/education portal and initiate new partnered efforts to provide data and informational support for high-priority hydropower workforce training needs. • Launch DOE's first-ever hydropower collegiate competition and hydropower-focused fellowship program, providing students of diverse backgrounds and disciplines the opportunity to develop key skills for a career in hydropower.
Follow-On Objectives (2026–2030)
• Significantly increased use of the HydroSource portal by a diverse set of stakeholders—beyond the current range of application—along with improved ease-of-use metrics and reviews from users. • Power market data are utilized by developers of new hydropower technologies to specifically target the greatest opportunities and approaches for growth, and are incorporated into future technology development and project planning processes. • FERC and other stakeholders leverage eLibrary insights along with interdisciplinary big data approaches to improve licensing and relicensing study efforts while maintaining regulatory effectiveness. • Key issues identified in the U.S. hydropower regulatory process report are utilized by diverse hydropower stakeholders to agree upon and begin to operationalize regulatory process improvements. • Documented increases in hydropower early-career interest/opportunities and improvements in institutional knowledge-transfer landscape.

Marine Energy Program Overview

VISION	A U.S. marine energy industry that expands and diversifies the nation's energy portfolio by responsibly delivering power from ocean and river resources.
MISSION	Conduct research, development, demonstration, and commercial activities that advances the development of reliable, cost-competitive marine energy technologies and reduces barriers to technology deployment.

The Marine Energy Program focuses on the following key opportunity areas for potential impact:

- ***Mitigating climate change and enabling a 100% clean energy future***: Marine energy development and deployment can reduce ocean acidification,[10] ocean warming,[11] and sea level rise[12, 13] through the reduction of greenhouse gas emissions, while contributing to grid decarbonization.
- ***Powering underserved communities and enhancing coastal resilience***: Marine energy can power electric microgrids in coastal, remote, and islanded communities, enhancing energy and coastal resilience and sustaining marine ecosystems.
- ***Accelerating technology development timescales through deployment***: Marine energy can meet the needs of many blue economy markets by producing fresh water through desalination or servicing the power demands for aquaculture and ocean sensing, and deploying marine energy for coastal and ocean-based applications can accelerate marine energy technology development for the grid.

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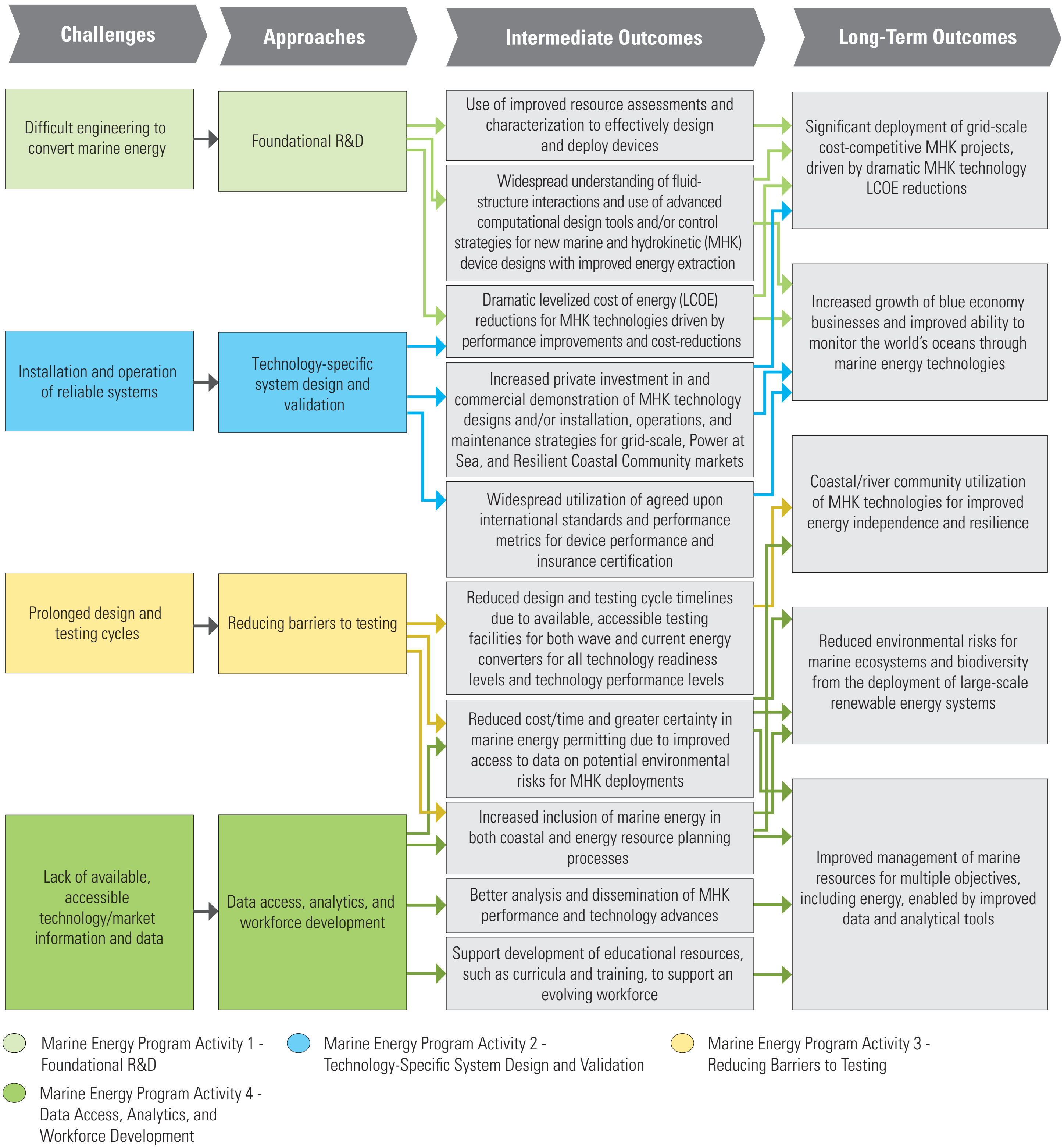
[10] Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. 2009. "Ocean Acidification: The Other CO_2 Problem" https://digitalcommons.law.uw.edu/cgi/viewcontent.cgi?article=1055&context=wjelp.

[11] Cheung, W. W. L., Watson, R., and Pauly, D. 2013. "Signature of ocean warming in global fisheries catch." https://www.researchgate.net/publication/236911499_Signature_of_ocean_warming_in_global_fisheries_catch.

[12] Gattuso, JP., Magnan, AK., Bopp, L., Cheung, WWL., Duarte, CM., Hinkel, J., Mcleod, E., Micheli, F., Oschlies, A., Williamson, P., Billé, R., Chalastani, VI., Gates, RD., Irisson, JO., Middelburg, JJ., Pörtner, HO. and Rau, GH., 2018. "Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems" https://www.frontiersin.org/articles/10.3389/fmars.2018.00337/full#B48.

[13] Yang, Z., Wang, T., Voisin, N., and Copping, A. 2015. "Estuarine response to river flow and sea-level rise under future climate change and human development." https://www.osti.gov/biblio/1188905-estuarine-response-river-flow-sea-level-rise-under-future-climate-change-human-development.

Figure 3. Marine Energy Program High-Level Logic Model



Marine Energy Program Activity 1 – Foundational R&D

In order to reach cost-competitiveness with other energy resources, marine energy technologies need to see dramatic cost reductions over the next 10-20 years. The Marine Energy Program's Foundational R&D supports research to drive these cost reductions, through improving device performance and reducing costs of existing device designs as well as by developing new capabilities that can allow for entirely new designs and approaches to harnessing the energy in water bodies. These early-stage R&D efforts are typically applicable to a wide range of device archetypes and, in some cases, cut across multiple technology types (e.g., wave, tidal, ocean current). Table 6 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 6. Foundational R&D: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Evaluate applicability and performance of composite and other novel materials for marine energy converter systems and subsystems, such as wave energy converter hulls and tidal energy converter blades. • Develop power take-off (PTO)/control system co-design methodologies and partner with technology developers to pilot the use in marine energy converter device design processes. • Validate foundational modeling tools with data from ongoing-water testing projects. • Disseminate high fidelity data sets and models through upgrades of the Marine Energy Atlas and DOE interface to cloud computing services and functional web-based application tools. • Complete resource measurements and assessments in support of marine energy projects to enhance the resilience of specific remote communities. • Test new, important component technologies that support significantly improved installation, operations, & maintenance (IO&M), such as wet-mate connectors and distributed energy conversion technologies. • Advance power electronics technologies that support integration of marine energy devices into power at sea and coastal community microgrid system applications.
Follow-On Objectives (2026–2030)
• Integrated, in-water systems testing completed for new, high-priority materials, power electronics, and other components. • First generation in-water tests completed of device designs documented to have used PTO/control system co-design methodologies and tools. • Early technology readiness levels (TRL) system testing of distributed-energy-conversion technology archetypes. • Widespread utilization (along with positive ease-of-use metrics and value reviews from users) of validated foundational modeling tools.

Marine Energy Program Activity 2 – Technology-Specific System Design and Validation

Technology validation is critical to advancing the commercialization of marine energy technologies. This activity area specifically advances systems beyond foundational R&D and focuses specifically on advancing the prototypes necessary to advance marine energy systems across wave, tidal, current, among other energy captures. The R&D in the Technology-Specific System Design and Validation activity area focuses on (1) supporting the design, manufacture and validation of industry-designed prototypes at multiple relevant scales; (2) improving methods for safe and cost-efficient installation, grid integration, operations, monitoring, maintenance, and decommissioning; (3) supporting the development and adoption of international standards for device performance and insurance certification; (4) supporting the early incorporation of manufacturing considerations into device design processes; and (5) leveraging expertise, technology, data, methods, and lessons from the international marine energy community and other offshore scientific and industrial sectors. Table 7 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 7. Technology-Specific System Design and Validation: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Complete initial field-testing for modular current energy converter systems that capture hydrokinetic river energy in low-flow environments (less than 2 m/sec) and can incorporate and advance IO&M techniques, which require only limited use of port and deployment vessel infrastructure. • Complete first year-long field tests of wave energy converter device designs in fully energetic wave environments (likely at the PacWave facility). • Complete at-sea, pre-commercial demonstrations of newly developed marine energy-powered ocean observing systems and desalination systems. • Concept refinement, design, and small-scale prototype testing of new wave energy system concepts with high techno-economic potential. • Establish U.S. capabilities for third-party certification of compliance to International Electrotechnical Commission (IEC) technical specifications to include power performance assessment, assessment of mooring systems, electrical power quality requirements, and measurement of mechanical loads at PacWave wave energy test facility, and power performance assessment of current energy converters tested with the Mobile Test Vessel.
Follow-On Objectives (2026–2030)
• New, commercially available marine energy-powered ocean observation systems are deployed for a variety of uses. • Wave powered desalination systems are deployed for the first uses in disaster recovery or international development scenarios. • Documented improvements in energy-water system resilience and security for a number of targeted remote communities, enabled by marine energy systems. • International standards developed for device performance and insurance certification for grid-scale and blue economy market applications. Standards use established as best practice for all device tests and deployments. • First in-water, integrated system tests for newly developed wave energy device concepts. • Design and testing of megawatt (MW) scale current energy converter devices/arrays that incorporates installation, operation, and maintenance lessons.

Marine Energy Program Activity 3 – Reducing Barriers to Testing

Testing marine energy technologies is inherently more complex, expensive, and time consuming than for land-based energy generation technologies. The already slow pace of design and in-water testing cycles is further exacerbated by the limited availability of testing infrastructure at various scales, complex and time-consuming permitting processes, and expensive environmental monitoring (again, driven by being in-water). These challenges severely limit the ability of technology developers to quickly assess the performance of devices and components, innovate solutions where necessary, and iteratively test the next generations of devices. Because of the complex physics of the ocean wave and current environments, marine energy prototypes must be tested in real-world environments to fully characterize their performance and reliability. These challenges associated with testing, deploying, and optimizing technologies in a timely and cost-effective manner must be overcome to accelerate the pace of marine energy technology development. The Reducing Barriers to Testing activity area supports national assessments of testing infrastructure and needs, the development of testing facilities (including open-water, grid-connected and non-grid connected facilities) and National Marine Renewable Energy Centers (NMRECs), instrumentation hardware and software dedicated to high resolution data acquisition, as well as environmental data collection. Table 8 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 8. Reducing Barriers to Testing: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Complete a minimum of 100 technical support actions under the Testing Expertise and Access for Marine Energy Research (TEAMER) initiative in collaboration with U.S. universities and national laboratories. • Develop a U.S testing network of at minimum 30 facilities, including a range of capabilities across traditional marine energy research facilities as well as new incumbent facilities with interdisciplinary expertise including non-grid applications. • Identify testing infrastructure gaps, including needs for non-grid applications, at universities and the national laboratories and, as appropriate, address those needs through infrastructure upgrades and development of new capabilities. • Commission, initiate testing, and gain accreditation for the PacWave grid-connected, open-ocean, wave test facility. • Demonstrate the improved technical performance of seven environmental monitoring technologies in relevant marine energy environments while opportunistically collecting data on acoustic outputs, electromagnetic field signatures, benthic habitats, and marine organism interactions with marine energy devices.
Follow-On Objectives (2026–2030)
• Significantly reduced timelines of design iterations for developers and researchers working in the marine energy industry, ultimately accelerating the iterative R&D process. • Validate cost and performance of devices through industry standards, providing confidence to regulatory, investor, and insurance communities. • Adoption of best practices for environmental monitoring technologies resulting in more consistent data collection across projects and greater confidence in the conclusions about the level of risk of specific environmental concerns.

Marine Energy Program Activity 4 – Data Access, Analytics, and Workforce Development

As a public research agency and the primary funder of U.S. marine energy R&D, DOE is uniquely capable of aggregating and disseminating objective and accurate information about marine energy. The Marine Energy Program ensures that data and analysis produced are easily accessible and useful to multiple audiences, such as technology developers, researchers, regulators, educators and students. Improved access to and use of data, tools, and STEM resources can lead to: (1) improved awareness of marine energy technology advances and lessons learned; (2) reduced cost, time, and uncertainty around the marine energy permitting processes; and (3) increased opportunities for students and early career professionals to develop skills needed to enter the marine energy workforce. In the long term, these outcomes can support innovation, increase the development and testing of devices at scale, provide a greater understanding of opportunities for marine energy across the blue economy, enhance energy resilience of coastal and river communities, improve marine resource management, and prepare a skilled workforce to advance marine energy into the future. Table 9 outlines the key results, performance goals, and follow-on objectives for this activity area.

Table 9. Data Access, Analytics, and Workforce Development: Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Publish an assessment of marine energy industry and researcher data needs. • Collect, analyze, and publish data from the existing in-water testing projects to generate new foundational understanding of marine energy devices and identify promising areas for additional research. • Complete integration of publicly available, WPTO-funded marine energy databases with interconnected search functionality. • Launch a new marine energy permitting toolkit to improve regulators' access to and understanding of information about marine energy resources, devices, and potential environmental effects. • Release a new marine energy STEM portal consisting of educator and student resources and curricula. • Improve targeted outreach with the intention of diversifying the pool of students participating in WPTO workforce development programs such as the graduate student research fellowship and Marine Energy Collegiate Competition.
Follow-On Objectives (2026–2030)
• Increased usage of WPTO-developed data, along with supported marine energy databases and toolkits (including the Marine Energy Environmental Toolkit, Marine Energy Permitting Handbook, and State of the Science Report) by a diverse set of stakeholders (along with positive value and ease-of-use metrics collected from users). • Dramatic improvement in regulators' access to useful marine energy data, helping to reduce uncertainty, improve their ability to assess risk, and achieve efficiency gains when permitting projects. • Measurable and significant increases in use of marine energy STEM portal by educators and individuals. • Measured improvement in the diversity of students and student teams participating in WPTO's fellowship programs and Marine Energy Collegiate Competition, including minority students as well as students from minority-serving institutions, such as historically Black colleges and universities, Hispanic-serving institutions, and tribal colleges.

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LIST OF ACRONYMS

AITO	Artificial Intelligence and Technology Office
AMEC	Atlantic Marine Energy Center
AMO	Advanced Manufacturing Office
AOP	annual operating plan
API	application programming interface
AUV	autonomous underwater vehicle
BETO	Bioenergy Technologies Office
BOEM	Bureau of Ocean Energy Management
CEATI	Centre for Energy Advancement through Technological Innovation
CEC	current energy converters
CESER	Office of Cybersecurity, Energy Security, and Emergency Response
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
ECM	extreme conditions modeling
EDA	U.S. Economic Development Administration
EERE	Office of Energy Efficiency and Renewable Energy
EEZ	Exclusive Economic Zone
EISA	Energy Independence and Security Act of 2007
EPAct	Energy Policy Act of 2005
ESGC	Energy Storage Grand Challenge
ETI	Energy Transitions Initiative
FECM	Office of Fossil Energy and Carbon Management
FERC	Federal Energy Regulatory Commission
FIHWG	Federal Inland Hydropower Working Group
FOA	funding opportunity announcement
FY	fiscal year
GPRA	Government Performance and Results Act
GW	gigawatts
HFTO	Hydrogen and Fuel Cell Technologies Office
HydroWIRES	Hydropower and Water Innovation for a Resilient Electricity System
IEA	International Energy Agency
IEC	International Electrotechnical Commission

IEC-TC	International Electrotechnical Commission Technical Committee
IO&M	installation, operations, and maintenance
kWh	kilowatt-hour
LCOE	levelized cost of energy
MARAD	U.S. Maritime Administration
MHK	marine and hydrokinetics
MHKDR	Marine Hydrokinetic Data Repository
MHKit	Marine and Hydrokinetic Toolkit
MOU	memorandum of understanding
MRE	marine renewable energy
MTV	mobile test vessel
MW	megawatts
NAERM	North American Energy Resilience Model
NARIS	North American Renewable Integration Study
NGO	nongovernmental organization
NMREC	National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NPD	non-powered dam
NSTC	National Science and Technology Council
O&M	operations and maintenance
OE	Office of Electricity
OES	Technology Collaboration Programme on Ocean Energy Systems
OTEC	ocean thermal energy conversion
PBE	Powering the Blue Economy
PMAs	Power Marketing Administrations
PRIMRE	Portal and Repository for Information on Marine Renewable Energy
PSH	pumped storage hydropower
PTO	power take-off
PWR	power-to-weight ratio
R&D	research and development
RCC	resilient coastal communities
RDD&CA	research, development, demonstration, and commercial application
RFI	request for information

S&T	science and technology
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer
SETO	Solar Energy Technologies Office
SMH	standard modular hydropower
SOST	Subcommittee on Ocean Science and Technology
STEM	science, technology, engineering, and mathematics
TCP	Technology Collaboration Programme
TEAMER	Testing Expertise and Access for Marine Energy Research
TRL	technology readiness levels
TS	technical specifications
TWh/yr	terawatt-hours per year
UARC	University-Affiliated Research Center
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WAPA	Western Area Power Administration
WDRT	WEC Design Response Toolbox
WEC	wave energy converter
WEC-Sim	Wave Energy Converter Simulation
WETO	Wind Energy Technologies Office
WETS	U.S. Navy's Wave Energy Test Site
WPTO	Water Power Technologies Office

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1 INTRODUCTION

Report Purpose

The Water Power Technologies Office (WPTO) is pleased to deliver this first Multi-Year Program Plan (MYPP) to interested stakeholders and the general public. The purpose of this MYPP is to communicate WPTO's overarching goals and potential future initiatives, strategies, programs, and activities and demonstrate alignment to administration, U.S. Department of Energy (DOE), and Office of Energy Efficiency and Renewable Energy (EERE) priorities. These efforts will help guide WPTO's activities for future years and ensure that priorities and opportunities are transparently communicated. This plan is intended to provide a framework to inform budget formulation, funding opportunity announcement (FOA) plans, lab calls, and lab annual operating plans (AOPs).

However, this report does not contain detailed budget information or specific annual/yearly plans for projects. It assumes relatively consistent funding based on appropriations from recent fiscal years. It also assumes that it may not be feasible to support efforts aligned with all activities at all times because of a range of factors, including budget limitations, competing priorities, policy decisions, or the relative priority for work in a particular time period.

Additionally, the relative level of effort required to support each activity is likely to vary. Activities and projects aligned with the various programmatic approaches are intended to be implemented in a logical, phased manner that focuses resources on high-priority, near-term challenges, while also supporting foundational work necessary to address longer-term challenges moving forward. Details on how each program plans to implement work via specific projects or funding opportunities are limited to internal DOE operational plans and not described in this document.

Report Development Process

The development process for the MYPP and technical appendices were informed by extensive stakeholder engagement over multiple years, including public workshops, requests for information (RFI) on program-level strategies[14, 15] and WPTO's 2019 Peer Review.[16] DOE's national laboratories are also integral to WPTO's program planning process, and feedback was solicited from the six national laboratories that WPTO currently works with. EERE's MYPP Guidance and Templates[17] were also utilized in formulating this document.

[14] U.S. Department of Energy, 2016. "RFI on a Draft Marine and Hydrokinetics (MHK) Program Strategy." https://www.energy.gov/eere/water/articles/wpto-releases-updated-draft-mhk-strategy.

[15] U.S. Department of Energy, 2020. "RFI: Hydropower Program R&D Strategy and HydroWIRES Research Roadmap." https://www.energy.gov/eere/water/articles/wpto-issues-rfi-hydropower-program-rd-strategy-and-hydrowires-research-roadmap/.

[16] WPTO Peer Review website: https://www.energy.gov/eere/water/2019-water-power-program-peer-review-report-and-presentations.

[17] Publicly available multi-year program plan guidance can be found at: https://www.energy.gov/sites/prod/files/2016/08/f33/EERE%20800%20-%20MYPP%20Guidance%20and%20Template.pdf.

2 WATER POWER TECHNOLOGIES OFFICE OVERVIEW

Statutory Authorities

The following is a brief summary of the most recent relevant congressional authorizations for WPTO activities under the Hydropower and Marine Energy Programs.

Energy Act of 2020, Division Z of the Consolidated Appropriations Act, 2021 (Public Law 116-260 - December 27, 2020)
Section 3001 (Water power research and development) reauthorized DOE's marine energy and hydropower research, development, demonstration, and commercial application (RDD&CA) activities, including the National Marine Renewable Energy Centers (NMRECs) and research on reducing potential environmental impact and pumped storage hydropower technologies. It also amended relevant authorizing language from Energy Independence and Security Act of 2007 (Public Law 110–140—December 19, 2007). The Energy Policy Act of 2005 (Public Law 109–58—August 8, 2005), also contains prior authorization language, though the definitions and direction set forth in the Energy Act of 2020 are now seen as the most relevant.

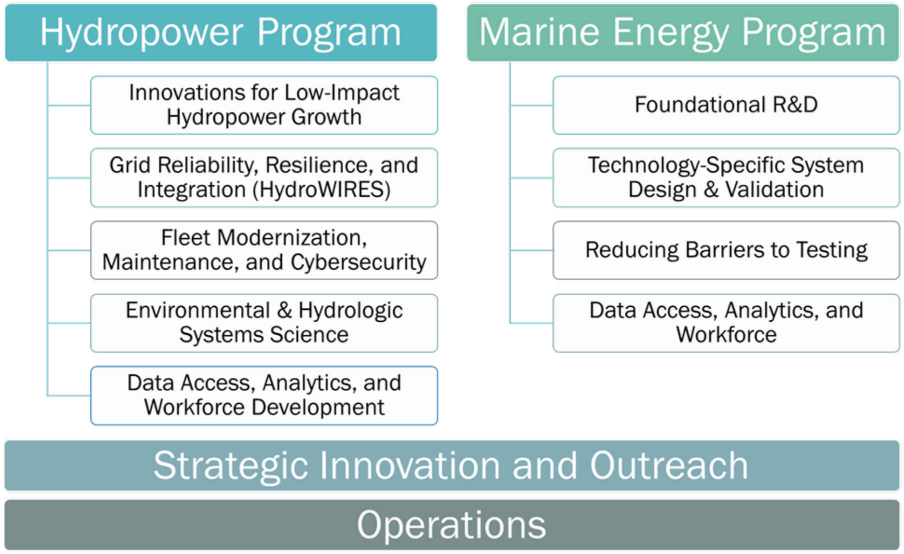
Office Mission, Values, and Structure

The mission of WPTO is to enable research, development, and testing of new technologies to advance marine energy, and next-generation hydropower and pumped storage systems, for a flexible, reliable grid. To reduce marine energy costs and fully leverage hydropower's contribution to the grid, WPTO invests in early-stage research and technology design; validates performance and grid-reliability for new technologies; develops and enables access to necessary testing infrastructure; and disseminates objective information and data for technology developers and decision makers. WPTO works with national laboratories, industry, universities, and other federal agencies to conduct R&D activities through competitively selected, directly funded, and cost-shared projects. In pursuing these objectives, WPTO always endeavors to:

- Catalyze innovation in technology and science.
- Steward natural resources and support the public good.
- Expand access to affordable, reliable, and secure energy.
- Invest taxpayer funds wisely and to drive the greatest impact.
- Collaborate and actively seek input from stakeholders and partners.
- Advance diversity, equity, and inclusion goals wherever possible for our teams and our projects.
- Demonstrate transparency and share results widely.

WPTO works to support DOE and EERE objectives of combating the climate crisis, creating millions of new clean energy jobs, and promoting energy and environmental justice. WPTO consists of two R&D programs: the Marine Energy Program and the Hydropower Program. The office also has two teams who work across the programs: the Operations team and the Strategic Innovation and Outreach team (Figure 4).

Figure 4. WPTO's Organizational Structure



WPTO considers external engagement a top priority and strives to engage a diverse array of stakeholders, such as researchers, technology developers, regulators, and the general public. Active collaboration and communication with key stakeholders enable WPTO to achieve its mission more effectively by identifying critical challenges in water power research, outlining opportunities for accelerating industry development, and informing the strategy and direction of the office's portfolio. WPTO's Engagement and Outreach Strategy represents values that are essential to WPTO's success and inherent to its role as a publicly-funded entity, such as appropriately and transparently incorporating public and expert feedback into our R&D and maximizing the impact of DOE's investments for the public good.

WPTO's Engagement and Outreach Strategy includes four key goals:

- **Transparency**: Demonstrate good stewardship of taxpayer funds by persistently and transparently communicating how WPTO funds are utilized and evaluating project impacts.
- **Feedback**: Gather feedback from stakeholders to inform and improve WPTO projects and strategy.
- **Dissemination**: Maximize the impact of WPTO-supported research by effectively disseminating results of projects and tracking usage of various products.
- **Objective and accurate information**: Provide access to accurate and objective information and data that can help to accelerate industry development and inform decision makers.

Program Logic Models

WPTO developed program-level logic models to:

- Generate a clear and shared understanding of and focus on program goals.
- Support program planning, implementation, and management.
- Create a solid foundation for future program evaluations.

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. This progression of linkages summarized in Figure 5 and Figure 6 supports the framework for WPTO's strategy and this MYPP.

Figure 5. Hydropower Program High-Level Logic Model

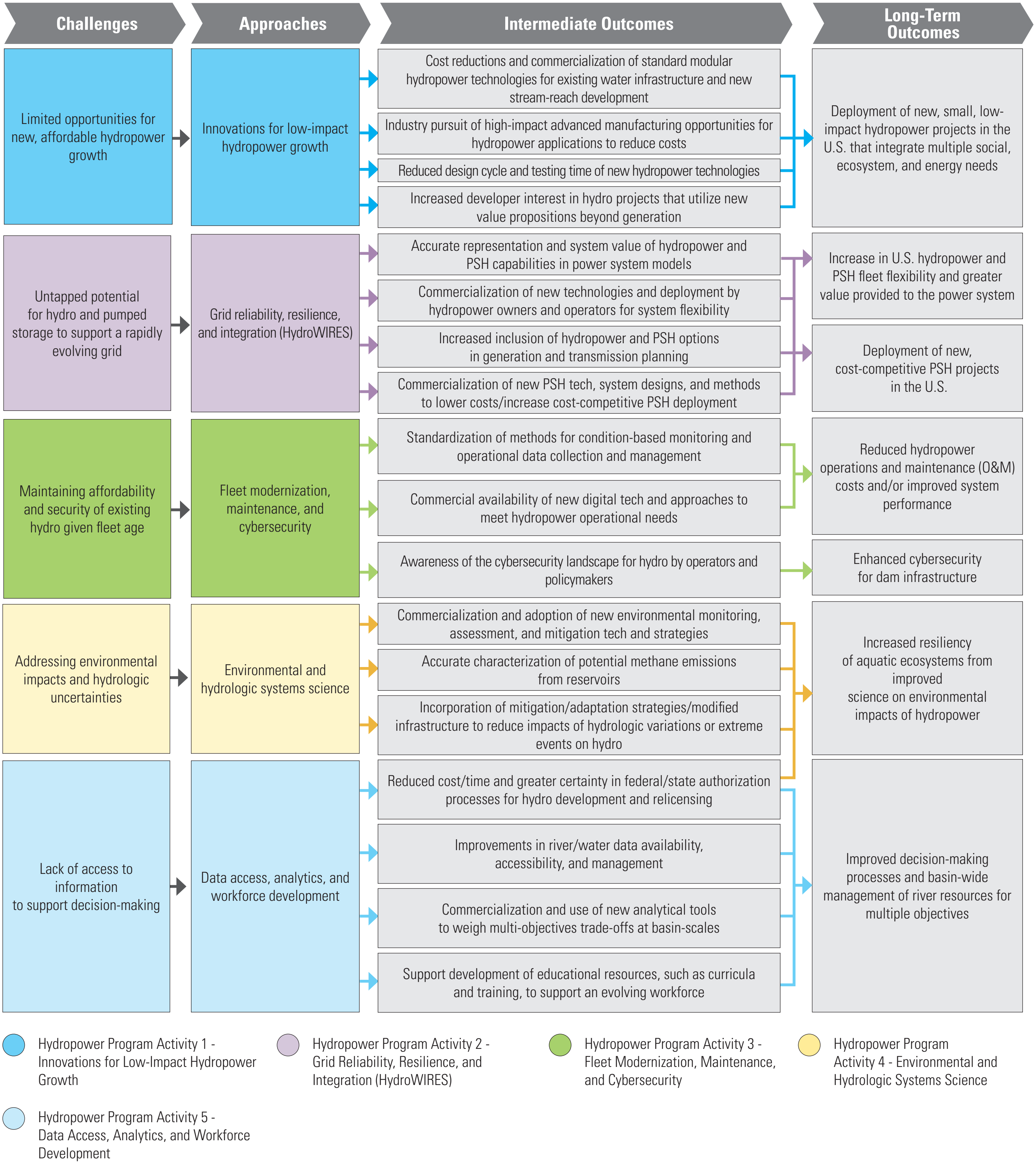
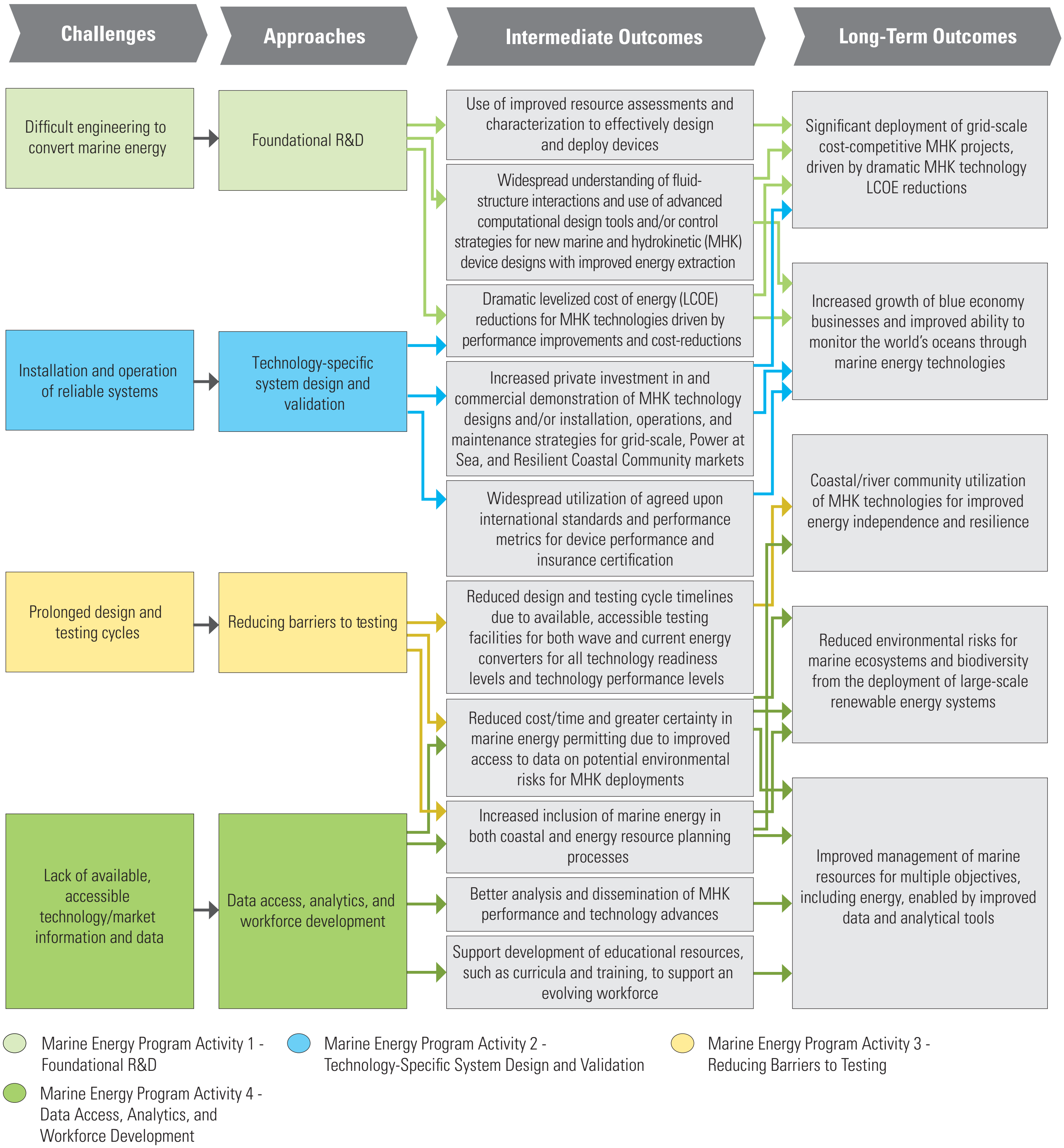


Figure 6. Marine Energy Program High-Level Logic Model



Budget

Water power R&D has taken place at DOE consistently since Fiscal Year (FY) 2008 after the Energy Independence and Security Act of 2007 directed DOE to establish the "Water Power Program." Prior to FY 2016, water power research was conducted in the former Wind and Water Power Technologies Office. In FY 2016, in response to congressional direction, WPTO was established as a standalone office dedicated to marine energy and hydropower R&D. The time period for the 2019 Peer Review included the first three years of WPTO as an independent office within EERE.

Funding for DOE's water power R&D has increased since FY 2008, as shown in Figure 7. Congressional appropriations have directed portfolio allocations with roughly two-thirds of the budget historically focused on marine energy R&D and one-third on hydropower. Figure 8 shows historical budgets for EERE's Renewable Power Offices since FY 2008 (with Water Power Program budgets indicated separately from Wind Power Program budgets during the period when the offices were combined).

Figure 7. Water Power Technologies Office Budget from FY 2008 to FY 2021

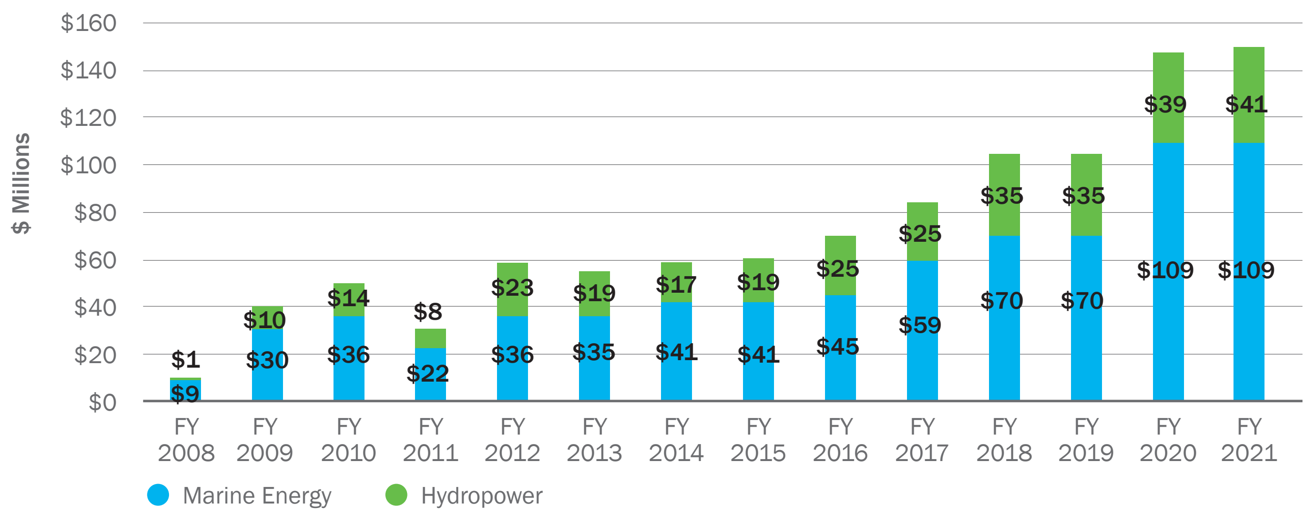
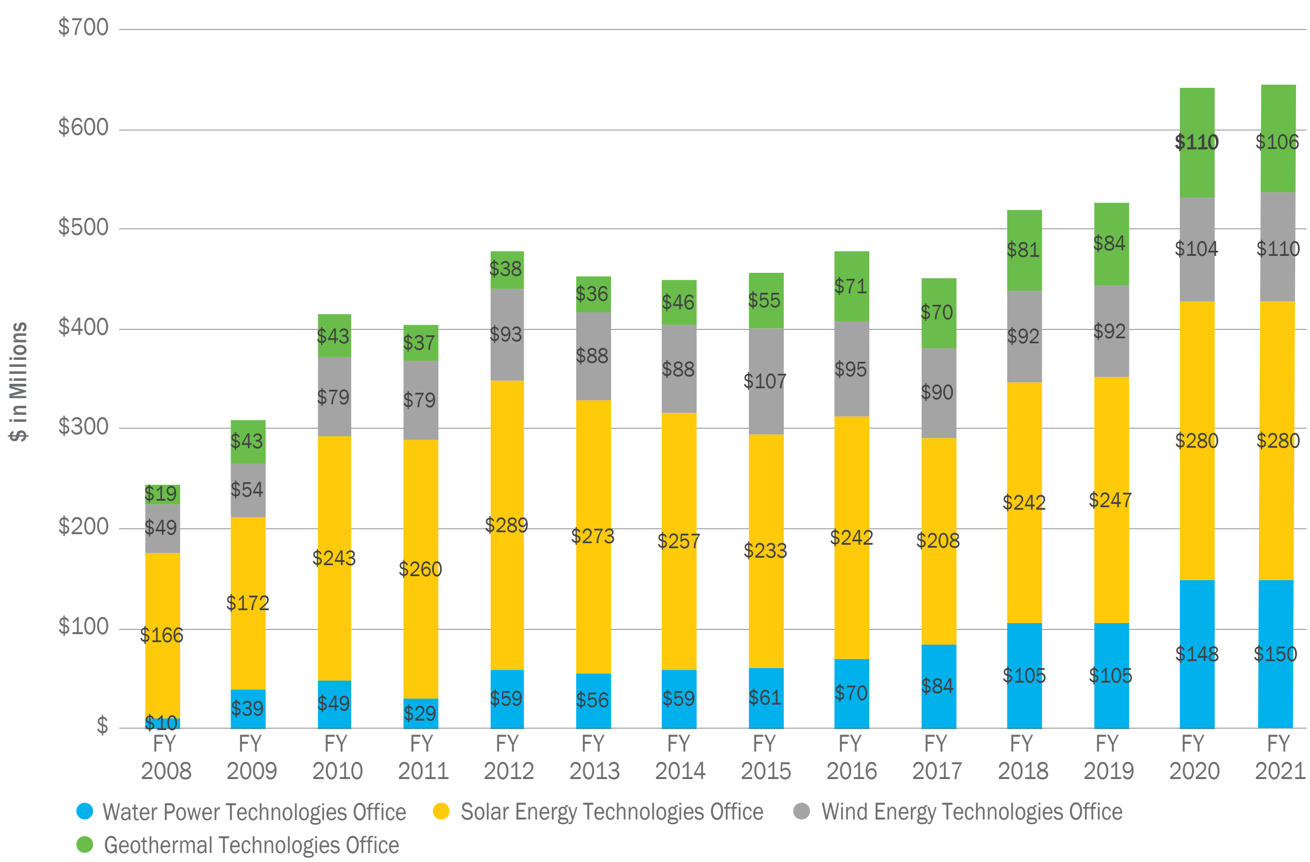


Figure 8. Office of Renewable Power Budget from FY 2008 to FY 2021



Funding Mechanisms

WPTO leverages a variety of funding mechanisms and increasingly focuses on developing and utilizing innovative approaches to support R&D in different ways. The following describes the main mechanisms WPTO leverages to fund R&D.

- **Financial Assistance**: These are regularly occurring, public, competitive solicitations that aim to identify and fund innovative ideas and solutions to WPTO-identified challenges.
  - **Funding Opportunity Announcements (FOAs)**: WPTO provides notice of available funding for R&D projects that address areas of interest identified by the office. Applications submitted through FOAs are evaluated by independent reviewers based on publicly shared criteria. Selected applications result in cooperative agreements through which DOE provides multi-year funding with a cost-share commitment from the awardee (though some applicants can be exempted from the EERE cost-share requirements, like academic institutions). Cooperative agreements are similar to grants but provide for more substantive involvement between the federal awarding agency and the awardee.
  - **The Small Business Innovations Research (SBIR) and Small Business Technology Transfer (STTR)** Programs are competitive programs limited to small businesses to support prototyping and commercialization activities. Both programs offer zero cost-share grants through a three-phased approach focused on products and services with commercial potential.
- **Prizes and Competitions**: Since 2010, the United States government has run nearly 1,000 prizes and challenges in more than 100 federal agencies, and with solvers spanning the gamut between students and hobbyists to small business owners and academic researchers. Prizes are organized with defined goals and within a defined timeframe. Compared to funding made available through traditional DOE financial assistance mechanisms, prizes usually offer smaller amounts of funding within a faster timeline. Prizes and challenges can be powerful tools to disrupt traditional thinking in a sector, and introduce, expand, and evolve what is possible. Prizes and challenges enable federal agencies to:
  - Pay only for success and establish an ambitious goal without having to predict which team or approach is most likely to succeed.
  - Reach beyond the "usual stakeholders" to increase the number of perspectives working to develop solutions for a specific problem.
  - Foster interdisciplinary collaboration and perspectives, reflective of the modern research environment.
  - Inspire the next generation of scientists, engineers, and entrepreneurs to work on difficult and important problems.
  - For more information on federal government prizes, challenges, and competitions, go to Challenge.gov, a one-stop shop for the American people to learn about open innovation challenges.
- **National Lab-Led R&D**: These research agreements take the form of contracts (also known as AOPs) with DOE national laboratories that define the scope, schedule, milestones, and cost for work. WPTO funds national lab partners to conduct research and analysis, as well as to develop tools and resources that broadly benefit of the water power field. Ongoing, multi-year efforts funded at DOE labs are also subject to external merit review requirements, similar to financial assistance awards.
- **National Lab Support to Others**: There are number of different mechanisms that leverage the expertise and resources of the national laboratories to support work being conducted by industry or academia.

   - "FOA support" occurs when labs receive funds to directly support a WPTO FOA awardee. Labs are currently ineligible to apply for most WPTO FOAs, but they may be requested by a FOA recipient to partner on an awarded project. In these cases, WPTO provides funding to the lab directly.
   - The Small Business Vouchers program has previously provided funding to the national laboratories to support small businesses in helping test, develop, and validate their innovations by tapping into national laboratory intellectual and technical assets.
   - The Technology Commercialization Fund helps industry to commercialize or license lab-developed technologies. This is a congressionally mandated program which comprises 0.9% of annual DOE program budgets and requires cost share.
   - Notices of opportunity for technical assistance are public, competitive processes for targeted and specific types of technical assistance provided by the national laboratories. See information on recently selected recipients from December 2019 here.
- **The EPAct 2005 Section 242 Hydro Incentive Program**: The Hydro Incentive Program provides funding for projects adding hydroelectric power generating capabilities to existing dams throughout the United States. This is a congressionally mandated program appropriated to the Hydropower Program.
- **Other mechanisms** include a variety of contractual mechanisms to conduct work, including directed funding and contracting agreements. Interagency agreements involve the transfer of funds between agencies for interagency work.
- All **other** funded work that does not fall within one of the categories above normally involves program-led analyses, stakeholder engagement and feedback activities, program and project reviews, and dissemination efforts.

Assessing Performance and Evaluating Success

WPTO assesses its progress, decisions, goals, and approaches by continuously monitoring and evaluating performance at both project and program levels.

Project Evaluations

WPTO also ensures that all projects and funded activities are managed utilizing the best practices and guidance from EERE. Active project management and other standardized processes used to monitor and manage project performance include the following:

- Quarterly project progress reports are submitted by all funded organizations, outlining financial and technical status, identifying problem areas, and highlighting achievements. The office performs a quarterly assessment of progress against the planned scope and schedule as well as financial performance against cost projections. The assessment is documented in a quarterly management report.
- Face-to-face or virtual meetings are held between DOE technical project officers and contractors with the project principal investigator or project team at least two times per year.
- Go/no-go reviews, conducted by a combination of WPTO staff and external, independent reviewers, are utilized for larger, longer-term, and higher dollar-value projects. These reviews provide recommendations to inform go/no-go decisions for projects. Go/no-go reviews are generally aligned with defined budget periods defined in the contractual assistance agreement or AOP for each project. Milestones and associated completion criteria are set at the beginning of a budget period for project. Projects are required to present not only progress to date, but also plans for the remainder of the project. At a pre-determined point in the project, progress is evaluated against previously-established review criteria resulting in one of three possible outcomes: (1) review criteria are met resulting in a "go" decision to continue with the project as originally scoped, (2) review criteria are not met resulting in project termination ("no-go"), or (3) review criteria are partially met, resulting in required changes to the project; for example, by changing the scope of the effort or by extending the timeline to completion.

Program and Office Evaluations

The Office of Management and Budget monitors performance of WPTO programs against established technical annual and long-term performance targets, as specified in the Government Performance and Results Act (GPRA). Each EERE office is responsible for establishing and monitoring quarterly milestones aligned to these targets, as well as reporting on annual performance targets established in congressional budget requests.

WPTO and other Renewable Power Offices in EERE utilize modeled levelized cost of energy (LCOE), in addition to other metrics, to set targets and evaluate R&D progress. Modeled LCOE will continue to be used as a standardized way of measuring progress, as it is useful for comparing costs to other energy technologies and evaluating the degree to which assumptions are comparable. However, there are many documented shortcomings in a sole focus on LCOE as a measure of energy technology performance and value. In a rapidly changing and evolving U.S. grid, there is an increasing focus on flexibility, energy storage, and other ancillary services. WPTO is closely integrated in crosscutting DOE initiatives like the Grid Modernization Initiative and Energy Storage Grand Challenge (ESGC), which are working to develop methods to better assess technology capability and performance utilizing new and different metrics.

Another important mechanism to evaluate progress are regular public peer reviews to evaluate individual R&D projects as well as performance and strategy of the entire Office. These rigorous, independent reviews take place every two to three years in alignment with EERE Guidance and Best Practices to ensure and enhance the management, relevance, effectiveness, and productivity of projects, and to evaluate overall office strategy. Industry, national laboratories, academic institutions, and nongovernmental organizations that have received support are all required to participate in the review process. Panels of independent reviewers are tasked with reporting their findings to DOE, which are then made public.[18] The feedback obtained from each peer review is utilized to inform future funding and programmatic decisions.

For more information on accomplishments and reviews of recent work, please also see the most recent WPTO Accomplishments Report and the 2019 Peer Review Report.

[18] WPTO Peer Review website: https://www.energy.gov/eere/water/water-power-program-peer-reviews.

3 HYDROPOWER PROGRAM OVERVIEW

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

Hydropower and Pumped Storage: Benefits and Potential Impacts

Enabling a 100% Clean Energy Future

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

Hydropower Flexibility

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

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

Pumped Storage: Cost-Effective, Long Duration Storage Asset

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

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

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

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

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

Expanding the Value of Sustainable Hydropower

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

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

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

Understanding and Adapting to Climate Change Impacts on Hydropower

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

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

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

Building Our Fleet Back Better

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

Modernization through Asset Management

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

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

Modernization through Environmental Mitigation and Relicensing

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

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

Hydropower Program Vision and Mission

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

VISION

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

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

Table 10. Hydropower Program Overview

<table>
<tr><th colspan="3">HYDROPOWER PROGRAM MISSION</th></tr>
<tr><td colspan="3">Conduct research, development, demonstration, and commercial activities to advance transformative, cost-effective, reliable, and environmentally sustainable hydropower and pumped storage technologies; better understand and capitalize upon opportunities for these technologies to support the nation's rapidly evolving grid; and improve energy-water infrastructure and security.</td></tr>
<tr><th>INNOVATIONS FOR LOW-IMPACT HYDROPOWER GROWTH</th><th>GRID RELIABILITY, RESILIENCE, AND INTEGRATION (HYDROWIRES)</th><th>FLEET MODERNIZATION, MAINTENANCE, AND CYBERSECURITY</th></tr>
<tr><td>Develop, test, and validate cost-effective, sustainable technologies for non-conventional hydropower applications in new-stream reaches, NPDs, and conduits.</td><td>Understand, enable, and improve hydropower and PSH's contributions to reliability, resilience, and integration in a rapidly evolving electricity system.</td><td>Develop digitalization, maintenance, and cybersecurity tools and capabilities to enable data-driven decision making, improve system reliability and reduce costs; and enhance infrastructure security.</td></tr>
<tr><th colspan="3">ENVIRONMENTAL AND HYDROLOGIC SYSTEMS SCIENCE</th></tr>
<tr><td colspan="3">Research and develop new technologies to better characterize river systems and evaluate potential impacts; avoid, minimize, or mitigate environmental impacts; and improve understanding of various hydrologic risks and uncertainty.</td></tr>
<tr><th colspan="3">DATA ACCESS, ANALYTICS, AND WORKFORCE DEVELOPMENT</th></tr>
<tr><td colspan="3">Improve access to relevant hydropower, river, and water information—including hydropower educational and training materials—and develop analytical tools to explore opportunities and weigh potential trade-offs across multiple objectives at basin-scales.</td></tr>
</table>

Challenges and Hydropower Program Approaches

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

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

Table 11. Challenges and Hydropower Program Approaches to Overcome Them

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

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

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

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

Limited Opportunities for New, Affordable Hydropower Growth Given Existing Technologies

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

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

Untapped Potential for Hydropower to Support a Rapidly Evolving Grid

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

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

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

Addressing Environmental Impacts and Climate Change

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

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

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

Lack of Access to Information Necessary to Support Decision-Making

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

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

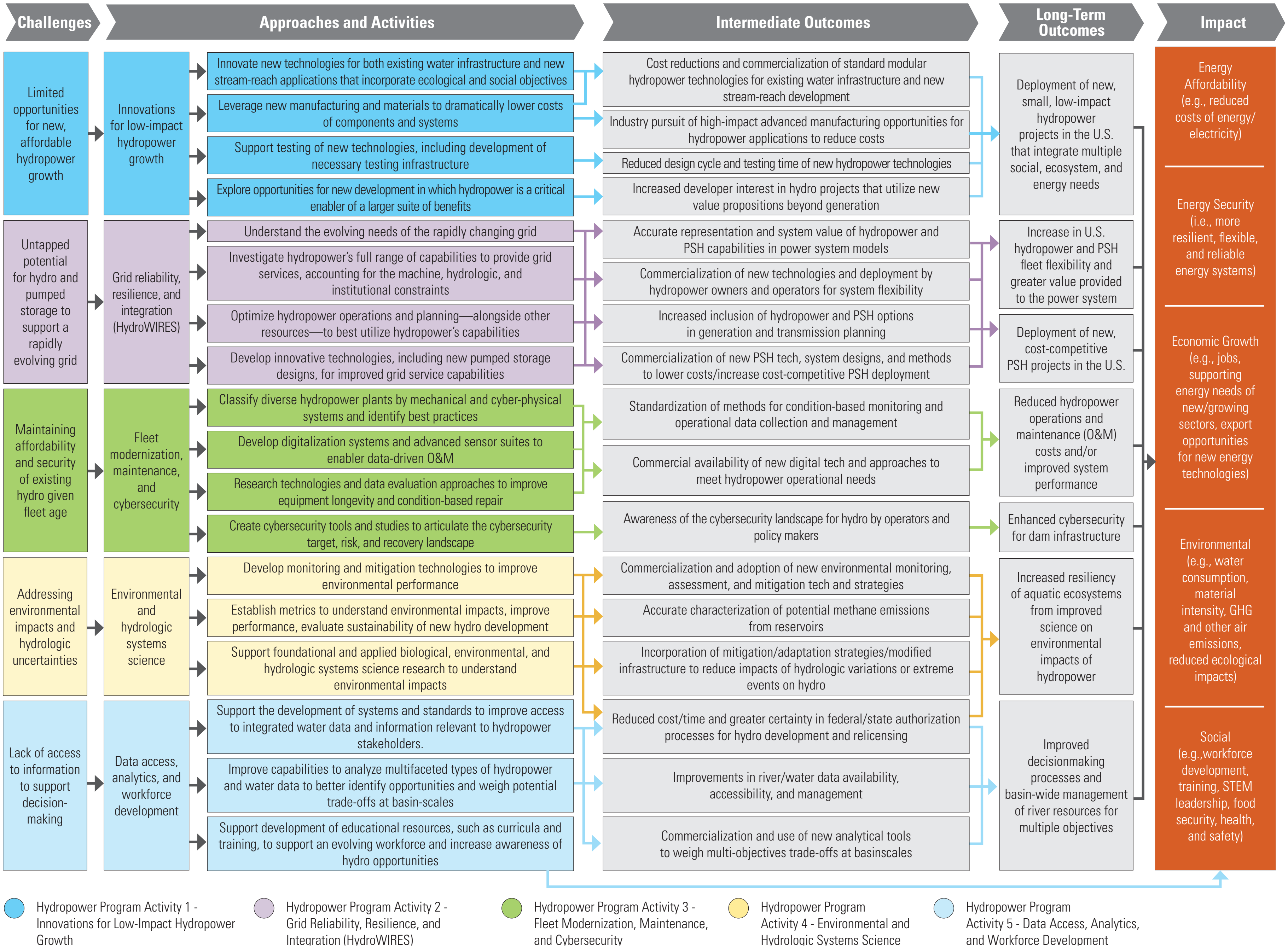
Hydropower Program Goals and Objectives

Hydropower Program Logic Model

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

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

Figure 9. Hydropower Program Logic Model



Assessing Performance

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

4 MARINE ENERGY PROGRAM OVERVIEW

Marine energy resources, such as wave, tidal and ocean currents, are abundant, geographically diverse, energy dense, predictable, and complementary to other renewable energy sources. Significant in-water testing and demonstrations have occurred in recent years, both domestically and internationally, to prove performance and reliability for systems that provide utility grid-scale electricity. Marine energy can also serve the needs of many blue economy markets, including producing fresh water through desalination, servicing the power demands for aquaculture and ocean sensing, and supporting coastal resilience through microgrid functionality. Marine energy therefore has the potential to contribute to a carbon pollution-free power sector in an environmentally just and sustainable way.

Basics of Marine Energy

WPTO's Marine Energy Program (formerly the Marine & Hydrokinetics Program) supports research, development, demonstration, and the commercial application of marine renewable energy technologies that expand and diversify the nation's clean energy portfolio by delivering power from ocean and river resources. These firm renewable resources, and the technologies that tap into them, are an integral part of the solution to achieve 100% electricity generation from zero carbon sources by 2035, generating economic opportunity and growth through the deployment of new energy technologies, and supplying clean, reliable power to underserved coastal communities.

As defined in the Energy Act of 2020 (Title 3, Subtitle A, Sec. 3001, the term "marine energy" means energy from:

- Waves, tides, and currents in oceans, estuaries, and tidal areas.
- Free flowing water in rivers, lakes, streams, and man-made channels.
- Differentials in salinity and pressure gradients.
- Differentials in water temperature, including ocean thermal energy conversion.

Utility-scale marine energy technologies are at an early stage of development compared to other renewable energy technologies due to the fundamental challenges of generating power from dynamic, low-velocity, and high-density waves and currents, while surviving in corrosive marine environments. These challenges are intensified by high costs and lengthy permitting processes associated with in-water testing. Addressing these challenges is a key part of WPTO's portfolio.

Marine Energy Resource Potential

Marine energy resources—such as wave, tidal, and ocean currents—are abundant, geographically diverse, energy dense, predictable, and complementary to other renewable energy sources. More than 50% of the U.S. population lives within 50 miles of coastlines, where there is vast potential to provide clean, renewable electricity to communities and cities using ocean waves, tides, and currents. To understand the full potential for future electricity production that can be harnessed through our nation's water resources, WPTO has conducted resource assessments to assess the potential of marine energy resources.[23]

Marine Energy Technologies and Resources Assessment

Wave energy is the most abundant and geographically diverse marine energy resource in the United States. However, it is also the most complex and expensive resource from which to extract marine energy. The materials and manufacturing costs for devices harnessing energy from waves, along with performance and

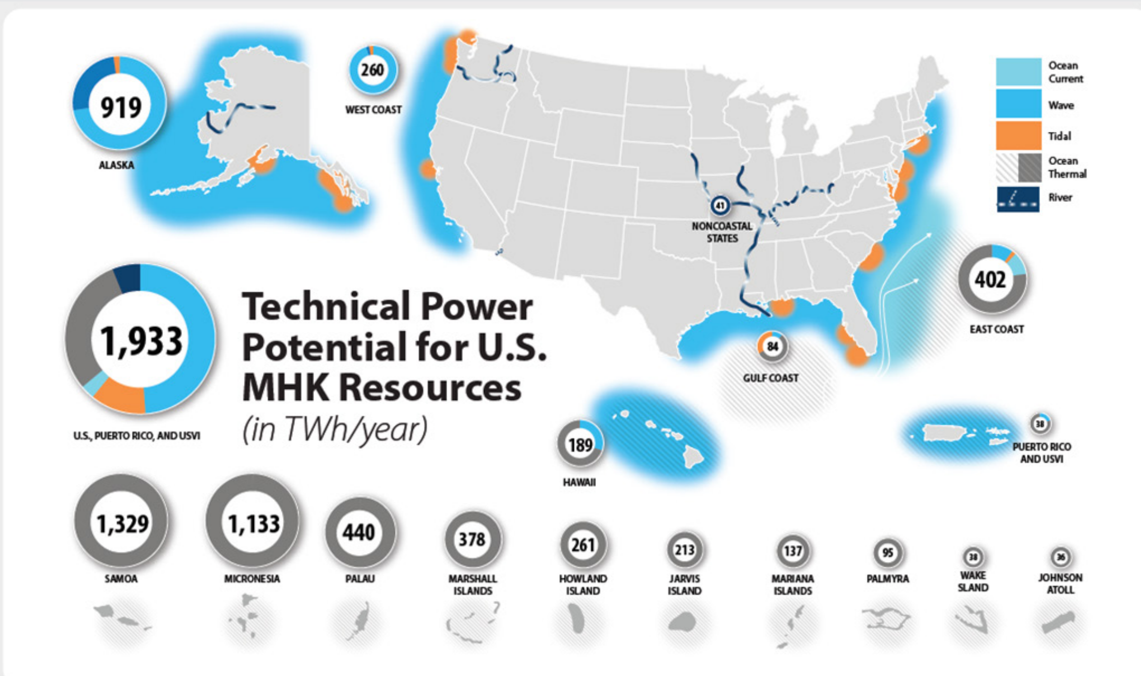
[23] U.S. Department of Energy, "Marine Energy Resource Assessment and Characterization" https://www.energy.gov/eere/water/marine-energy-resource-assessment-and-characterization.

Marine Energy Resource Potential *continued*

reliability improvements yet to be realized for wave energy converters (WEC), result in modeled levelized cost of energy values over $0.50/kWh. This complexity has resulted in a wide range of wave energy converter. archetypes in the industry.[24] While this diversity can enable systems to be optimized for specific markets and locations, it comes at the price of supply chain availability and cost and also complicates workforce training. Tidal and river current energy converter technologies have fewer archetypes[25] and a lower cost compared to wave energy. However, ocean current technologies have a longer-term development timeframe, since the ocean current resource in the United States, specifically in the gulf stream, is more geographically isolated then tidal or river currents, and have challenges with siting optimization. Ocean thermal energy conversion[26] (OTEC) is a technology that extracts energy from temperature differentials in the ocean, and is a significant resource globally, though it is limited to specific U.S. geographic regions such as southern Florida, Hawaii, Puerto Rico, and the Virgin Islands for utility-scale applications.

The technical potential[27] for electric generation from ocean wave, ocean current, tidal current, river current, and ocean thermal resources in the United States in terawatt-hours per year (TWh/yr) are summarized in Figure 10.

Figure 10. Technical Power Potential for U.S. Marine and Hydrokinetic Resources



US States & Territories	MW	TWh/yr	Avg. Homes That Could Be Powered*	Resource as a Percent of U.S. States' Total Electricity Generation (%) ***
Wave (to 10 nm)	112,557	986	92,590,854	
Tidal	25,381	222.34	20,878,727	5.4
Ocean Current	5,594	49	4,601,371	1.2
Ocean Thermal	65,753	576	54,089,586	14.0
River	11,342	99.36	9,330,454	2.4
Total	**220,628**	**1,933**	**181,490,991**	**46.8**

East Coast	MW	TWh/yr	Avg. Homes That Could Be Powered*	Resource as a Percent of Regional Electricity Generation (%) **	Resource as a Percent of U.S. States' Total Electricity Generation (%) ***
Wave (to 10 nm)	0	0	0	0	0.0
Tidal	1,153	10.10	948,431	1	0.2
Ocean Current	5,594	49	4,601,371	5	1.2
Ocean Thermal	39,041	342	32,115,692	37	8.3
River	77	0.67	63,091	0	0.0
Total	**45,864**	**402**	**37,728,585**	**43**	**9.7**

[24] Different wave energy converters (WEC) technologies: https://openei.org/wiki/PRIMRE/MRE_Basics/Wave_Energy.

[25] Different tidal and river current energy current converter technologies: https://openei.org/wiki/PRIMRE/Glossary/Current_Energy.

[26] Further information on Ocean Thermal Energy Conversion (OTEC): https://openei.org/wiki/PRIMRE/MRE_Basics/Ocean_Thermal_Energy_Conversion.

[27] Technical resource potential refers to the portion of a theoretical resource (annual average amount of energy that is contained within the resource) that can be captured by using a specific technology.

Marine Energy Resource Potential *continued*

The most recent marine energy resource assessment[28] calculates the total technical marine energy resource for the continental United States, extending to the Exclusive Economic Zone (EEZ),[29] to be 2,528 TWh/yr, equivalent to the power needs of more than 87 million homes[30] —or 22.5% of the total electricity generation by U.S. states in 2019.[31] When Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands are included, the total technical marine renewable energy (MRE) resource increases to 2,777 TWh/yr, equivalent to the power needs of more than 260 million homes, or 67.3% of the total electricity generation by U.S. states in 2019. This increase is largely attributable to the substantial wave and tidal resources in Alaska. Finally, when the immense OTEC resources found within the EEZ of the U.S Pacific territories are included, amounting to 4,060 TWh/yr of the 4,636 TWh/yr available from OTEC in all U.S. states and territories, the total technical MRE resource is 6,837 TWh/yr—equivalent to the power needs of more than 642 million homes, or 166% of the total electricity generation by U.S. states in 2019. If a significant fraction of this potential is realized, marine energy can contribute to a 100% clean energy grid, particularly given the proximity of marine resources to electricity load centers, and the predictability and forecast-ability of electricity generation that complements other daily, seasonal, and annual variable-generation sources.

Marine Energy and Powering the Blue Economy

Even though deploying marine energy to power the electric utility grid remains challenging, there are near-term opportunities for smaller scale marine energy systems to enhance the resilience of coastal communities, including through offsetting a significant amount of fossil fuels,[32] and to power systems in the ocean where other energy sources are challenging to access. Marine energy technologies are persistent, predictable, and renewable sources of energy in the ocean that can serve both deep offshore and nearshore energy solutions. Many remote coastal and islanded communities have significant co-located marine energy resources: Alaskan communities are near rivers and wave energy resources; Hawaiian Islands have wave energy and OTEC resources, and communities on the East Coast and Puerto Rico are located near many kinds of marine energy resources.

To this end, WPTO's Powering the Blue Economy (PBE) initiative addresses the energy needs of the rapidly growing "blue economy"[33] and ocean-based activities with marine renewable energy. Oceans can serve fundamental human needs and drive economic growth; reliable ocean-based energy can enable sustainable aquaculture, observations that expand the understanding of the ocean and track the changing climate, power desalination systems, and more. Additionally, the blue economy is anticipated to double in size to $3 trillion by 2030, but its growth is constrained by a lack of energy due to sources that require frequent refueling or battery changes and are often unfit for purpose, limited in capacity, expensive, and emit greenhouse gases. Deploying marine energy systems in the blue economy requires new approaches in energy development through working with remote communities as partners in assessing energy needs, multidisciplinary collaborations, co-development of energy solutions embedded within or tied to blue economy platforms, and innovation across multiple technology domains.

[28] Resource assessments for wave, tidal currents, ocean currents, OTEC, and river currents have not been completed for all U.S. states and territories; therefore, the technical resources shown underestimate the full MRE resources contained within all U.S. land and EEZ extents.

[29] The EEZ is defined as is a concept adopted at the Third United Nations Conference on the Law of the Sea (1982), whereby a coastal State assumes jurisdiction over the exploration and exploitation of marine resources in its adjacent section of the continental shelf, taken to be a band extending 200 miles from the shore.

[30] In 2019, the average annual electricity consumption for a U.S. residential utility customer was 10,649 kWh, an average of about 877 kWh per month. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3.

[31] U.S. Energy Information Administration. "Net Generation by State by Type of Producer by Energy Source." https://www.eia.gov/electricity/data/state/.

[32] U.S. Department of Energy, 2019. "Energy Department Funding Helps Transform Alaskan River Renewable Energy Resource." https://www.energy.gov/eere/water/articles/energy-department-funding-helps-transform-alaskan-river-renewable-energy-source.

[33] The World Bank defines the blue economy as the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystem.

Marine Energy Resource Potential *continued*

WPTO released a report in April 2019 titled *Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets*,[34] demonstrating that marine energy can decarbonize and enable innovation and growth in the blue economy through direct engagements between relevant end-user communities and public and private sector organizations. The report identifies potential opportunities and challenges for marine energy in eight different ocean applications and markets, including some far out at sea—like ocean observation and seawater and mineral mining—and some nearshore, like desalination and coastal resilience. A recent report by The Economist Intelligence Unit,[35] commissioned by the Pacific Northwest National Laboratory, states that "marine energy presents opportunities for renewable, in-situ or local power generation" for maritime transport and tourism, ship building, and fishing and aquaculture, ocean observation and navigation. Further, the International Energy Agency's (IEA) Technology Collaboration Programme on Ocean Energy Systems (OES) recently released a report describing "Blue Economy and its Promising Markets for Ocean Energy."[36] These reports confirm the potential connections between blue economy markets and marine energy is not only multifaceted and nationwide, but global.

Marine Energy: Benefits and Potential Impacts

Mitigating Climate Change and Enabling a 100% Clean Energy Future

Marine energy has the potential to contribute to an electric grid primarily powered by renewable energy[37, 38] while also addressing the need for climate change mitigation.[39, 40] While the manufacturing process and other elements of marine energy technologies' life cycle may generate carbon emissions, these emissions are comparable to those of other renewable technologies. Moreover, marine energy development and deployment can have a significant impact on reducing ocean acidification,[41] ocean warming,[42] and sea level rise,[43, 44] through the permanent reduction

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34 U.S. Department of Energy, 2019. "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets." https://www.energy.gov/eere/water/downloads/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime.

35 Economist Intelligence Unit, 2020, "Accelerating Energy Innovation for the Blue Economy." https://www.woi.economist.com/energyinnovation/.

36 International Energy Agency, "OES releases 'Blue Economy and its Promising Markets for Ocean Energy." https://www.ocean-energy-systems.org/newsletter/oes-releases-a-blue-economy-and-its-promising-markets-for-ocean-energya-/.

37 Copping, A., LiVecchi, A., Spence, H., Gorton, A., Jenne, S., Preus, R., Gill, G., Robichaud, R., Gore, S., 2018. "Maritime Renewable Energy Markets: Power from the Sea." https://tethys.pnnl.gov/publications/maritime-renewable-energy-markets-power-sea.

38 Thresher, R., and Musial, W, 2015. "Ocean Renewable Energy's Potential Role in Supplying Future Electrical Energy Needs." https://www.osti.gov/biblio/1251349.

39 International Renewable Energy Agency, 2019. "Renewable Energy Statistics 2019." https://www.irena.org/publications/2019/Jul/Renewable-energy-statistics-2019.

40 United Nations General Assembly. 2012. Report on the work of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea at its thirteenth meeting (A/67/120). https://undocs.org/A/67/120.

41 Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A, 2009. "Ocean Acidification: The Other CO_2 Problem." https://digitalcommons.law.uw.edu/cgi/viewcontent.cgi?article=1055&context=wjelp.

42 Cheung, W. W. L., Watson, R., and Pauly, D. 2013. "Signature of ocean warming in global fisheries catch." http://www.ecomarres.com/downloads/warm.pdf.

43 Gattuso, JP., Magnan, AK., Bopp, L., Cheung, WWL., Duarte, CM., Hinkel, J., Mcleod, E., Micheli, F., Oschlies, A., Williamson, P., Billé, R., Chalastani, VI., Gates, RD., Irisson, JO., Middelburg, JJ., Pörtner, HO. and Rau, GH., 2018. "Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems" https://www.frontiersin.org/articles/10.3389/fmars.2018.00337/full#B48.

44 Yang, Z., Wang, T., Voisin, N., and Copping, A. 2015. "Estuarine response to river flow and sea-level rise under future climate change and human development." https://www.osti.gov/biblio/1188905-estuarine-response-river-flow-sea-level-rise-under-future-climate-change-human-development.

of greenhouse gas emissions. Marine renewable energy projects, when sited and scaled in an environmentally responsible manner, can be part of the solution towards decarbonizing the electric grid and overcoming any potential environmental impacts to marine animals and habitats.[45]

Marine renewable energy can also help advance many of the United Nations Sustainable Development Goals. In the near term, marine energy can power ocean observing devices that can enable scientists to collect better and more data than ever before, providing profound insight to the health of the ocean and the effects of climate change, including ocean acidification. In the medium term, marine energy can power offshore aquaculture farms, providing a clean and environmentally sustainable source of protein for billions of food insecure people across the globe, powered by clean, renewable energy. In the long term, marine renewable energy can power the extraction of critical materials that will be integral to the electrification of transportation and other sectors—materials that are currently mined in an economy rife with human rights and sustainability issues.

The oceans and the blue economy face unique challenges due to climate change but can also serve as potential assets for climate change mitigation. The maritime sector and shipping industry are difficult to decarbonize with existing technologies, but ocean-based renewable energy sources can be part of the solution. Ocean-based aquaculture systems can be a source of affordable, plentiful, and nutritious food powered by co-located marine energy resources. Wave-powered desalination can provide clean water in the ocean and to coastal communities, without requiring fossil fuels. Marine energy-powered technologies may even be able to reverse ocean acidification on small scales. Ocean-based energy, powering ocean observing and navigation systems, can aid in measuring the changing climate, monitoring maritime animals, and tracking extreme weather events.

Accomplishing these goals and deploying marine energy on the scale needed to bridge the gap to a 100% clean energy future will require an acceleration of technology maturity and deployment of marine energy development. This can be facilitated using international standards and specifications during design and testing, ultimately leading to system accreditation.

Powering Underserved Communities and Enhancing Coastal Resilience

Marine energy has the potential to enhance resilience and power electric microgrids in coastal, remote, and islanded communities. These technologies can help make communities more resilient in the face of extreme events such as tsunamis, hurricanes, floods, or droughts. Marine energy applications are ideally suited to coastal development through straightforward installation, operation, and maintenance activities, and provide a predictable and uninterrupted energy supply. Marine energy can also power water quality monitoring for harmful algal blooms or pollutants, extreme event observation tools, microgrids for commercial and residential purposes. Finally, marine energy technologies can enhance the coastal resilience of shorelines and be an integrated component of solutions and strategies for long-term coastal change and hazard response.

Marine energy has an important role to play in sustaining marine and ocean ecosystems. The watch circles and operating boundaries around marine energy projects create pseudo-marine reserves that can benefit local ecosystems of fish and other organisms, as stressors associated with human activities like fishing, shipping, waste disposal, shoreline activities, and other disturbances are removed.[46, 47] Furthermore, marine energy's potential environmental impacts are low compared to other energy sources, particularly fossil fuels, with minimal drilling associated noise pollution and low to non-existing risks of oil spills leading to ecosystem damage. These stresses,

[45] Copping, A.et al, 2016. "Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. https://tethys.pnnl.gov/sites/default/files/publications/Annex-IV-2016-State-of-the-Science-Report_MR.pdf.

[46] Inger, R. et al, 2009. "Marine renewable energy: potential benefits to biodiversity? An urgent call for research." https://tethys.pnnl.gov/publications/marine-renewable-energy-potential-benefits-biodiversity-urgent-call-research.

[47] Crain, C.M., Halpern, B.S., Beck, M.W. and Kappel, C.V., 2009. "Understanding and Managing Human Threats to the Coastal Marine Environment." https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2009.04496.x.

their potential risks to the marine environment, and how these risks might be understood, placed in context, managed, and minimized, are described in detail in the OES 2020 State of the Science Report.[48]

Deploying marine energy for coastal and ocean-based applications is also crucial towards accelerating marine energy technology development for the grid. Near-term deployments serving a variety of applications enable marine energy technologies to be quickly demonstrated, while also benefiting coastal communities and the other blue economy markets. With time, these deployments will improve the marinization of marine energy systems to better understand their survival in harsh, highly corrosive, energic environments, and utilize appropriate materials and technologies. In addition, siting marine energy technologies in an environmentally responsible manner through partnerships between coastal communities, the government, private industry, and technical experts can lead to a sustainable and resilient energy technology.

The Future of Marine Energy

Despite the challenges of operating in a harsh, corrosive environment, the marine energy industry has made measurable progress in recent years. Developers in the United States, such as Ocean Power Technologies, Ocean Renewable Power Company, and Verdant Power, have had significant in-water technology demonstrations; developers in Europe, such as Orbital Marine Power, SIMEC Atlantis, and Minesto, are even further along in proving out their technologies. Marine energy is at an inflection point, building off the momentum garnered over the last decade. The industry and DOE's focus, historically, has been on proving performance and reliability for the U.S. grid; as technology performance and operations continue to be vetted, the next opportunity will be focusing on optimization and reducing costs. Technology vetting, cost reduction, and commercial opportunities will also be enabled through applications in entirely new non-grid markets at sea, supporting coastal resilience, and powering ocean sensors and instruments.

Marine energy technologies can ultimately complement an electric grid with high variable renewable energy (like wind and solar) penetration. Community-scale marine energy technologies can be a part of a resilient and sustainable electricity supply. There are emerging RDD&CA pathways to develop entirely new ways to harness the power of the ocean, needs that are currently addressed through fossil fuels. Marine energy is not just about the electric grid, it is about meeting many of our energy needs, including desalination, pumping water and serving as an energy generation asset for secondary markets like green hydrogen, co-locating production with utilization, and decreasing overall energy costs for many needs. The ocean can be a considerable asset in mitigating and reversing climate change, and marine energy can be the key to unlocking this potential.

48 Copping, A.E. and Hemery, L.G., 2020. "OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES)." https://tethys.pnnl.gov/publications/state-of-the-science-2020.

Marine Energy Program Vision and Mission

VISION

A U.S. marine energy industry that expands and diversifies the nation's energy portfolio by responsibly delivering power from ocean and river resources.

To help realize the vision of the Marine Energy Program, WPTO conducts research, development, demonstration, and commercial activities that advances the development of reliable, cost-competitive marine energy technologies and reduces barriers to deployment. The Marine Energy Program comprises four core R&D activity areas and one initiative that represent the program's strategic approach to addressing the challenges faced by U.S. marine energy stakeholders, as summarized in Table 12.

Table 12. Marine Energy Program Overview

<table>
<tr><th colspan="3">MARINE ENERGY PROGRAM MISSION</th></tr>
<tr><td colspan="3">Conduct research, development, demonstration, and commercial activities that advances the development of reliable, cost-competitive marine energy technologies and reduces barriers to technology deployment.</td></tr>
<tr><th>FOUNDATIONAL R&D</th><th>TECHNOLOGY-SPECIFIC SYSTEM DESIGN AND VALIDATION</th><th>REDUCING BARRIERS TO TESTING</th></tr>
<tr><td>Drive early-stage R&D on components, controls, manufacturing, and materials; develop and validate numerical modeling tools; improve resource assessments and characterizations; develop quantitative metrics to evaluate devices' potential.</td><td>Validate performance and reliability of marine energy systems through prototype testing, including in-water testing, for grid-scale, power at sea, and resilient coastal community markets.</td><td>Enable access to open-water, grid-connected, and non-grid connected testing facilities; support environmental monitoring technologies, tools, and data collection to understand potential environmental risks and reduce costs.</td></tr>
<tr><th colspan="3">DATA ACCESS, ANALYTICS, AND WORKFORCE DEVELOPMENT</th></tr>
<tr><td colspan="3">Improve access to and use of data, tools, and science, technology, engineering, and (STEM) resources to increase awareness of marine energy technology advances and lessons learned; reduce cost, time, and uncertainty for marine energy permitting; and develop a skilled marine energy workforce.</td></tr>
</table>

Challenges and Marine Energy Program Approaches

With input from numerous stakeholders, the Marine Energy Program has identified several core challenges that must be addressed to achieve its mission and support the ultimate vision for the U.S. marine energy industry. These challenges illustrate the complexities and difficulties that must be overcome to develop commercial marine energy technologies and highlight why high-risk early-stage R&D is necessary to catalyze the transformative innovations capable of addressing them. However, the below challenges are not all-encompassing of every difficulty identified by the marine energy industry and other stakeholders. The challenges highlighted below are ones the program has a direct and government-appropriate role in helping to address. The wide range of specific challenges and high-level approaches to address them have been organized into four corresponding activity areas that the Marine Energy Program aligns its work and efforts to, which is discussed in the following sections and summarized in Table 13.

In addition to addressing these fundamental technical challenges, WPTO is expanding opportunities to realize the unique value proposition for smaller-scale marine energy systems to (1) power microgrids in remote coastal communities including those currently dependent on fossil fuels; (2) power ocean-based scientific and commercial missions currently limited by incumbent energy sources; and (3) integrate with ocean and coastal-based applications like desalination and aquaculture where marine energy can uniquely improve the resilience and economic sustainability of local communities.

Table 13. Challenges and Marine Energy Program Approaches to Overcome Them

Challenges	Approaches
Difficult Engineering to Convert Marine Energy • Fundamental difficulties for designing systems to efficiently capture usable energy, due to the unique physics of the systems. • Open scientific and engineering questions about how devices interact with these complicated resources or with other devices, and efforts to develop validated methods to measure, model, and predict these interactions are ongoing. • Lack of well-developed manufacturing and supply chains for marine energy applications, resulting in long lead times and high costs for materials and components. • Lack of established, commonly-accepted performance metrics to evaluate the wide range of existing technologies.	**Foundational R&D** • Drive early-stage R&D on components, controls, manufacturing, and materials. • Develop and validate numerical modeling tools and methodologies for improved understanding of important fluid-structure interactions. • Improve marine energy resource assessments and characterizations needed to optimize devices and arrays and understand extreme conditions. • Develop and apply quantitative metrics to identify and evaluate e technologies with high ultimate techno-economic potential.
Installing and Operating Reliable Systems • Difficulties in developing effective and efficient methods for installation, testing, operations, and maintenance (O&M) due to the nature of high-energy and corrosive marine/riverine systems. • Limited infrastructure to deploy marine energy devices and support operations in high-energy, deep-water environments where devices will be deployed, and/or infrastructure not optimized for marine energy applications.	**Technology-Specific System Design and Validation** • Validate performance and reliability of systems through prototype testing, including in-water testing, at multiple scales. • Improve cost-effective methods for installation, operations, and maintenance (IO&M). • Support the development and adoption of international standards for device performance and insurance certification. • Expand opportunities to realize the unique value proposition of marine energy systems for community resilience and ocean-based scientific and commercial power applications. • Evaluate existing and potential future needs for marine energy-specific IO&M infrastructure (e.g., vessels, port facilities, etc.).

Challenges	Approaches
Prolonged Design and Testing Cycles • Limited access to test infrastructure at various scales for rapid iterative design improvements. • Expensive, time-consuming permitting processes with extensive requirements for environmental monitoring driven by high perceptions of risk. • Limited transferability and utilization of accurate information about siting and deployment of marine energy technologies and complicated coordination with existing users of ocean spaces and waterways.	**Reducing Barriers to Testing** • Enable access to world class testing facilities to accelerate technology development. • Work with agencies and other groups to ensure that existing data is well-utilized and identify potential improvements to regulatory processes and requirements. • Support additional scientific research on mitigating environmental risks and reducing costs and complexity of environmental monitoring. • Engage in relevant coastal planning processes to ensure that marine energy development interests are equitably considered.
Limited Availability of Technology/Market Information • Unclear value opportunities for utilizing marine energy technologies due to the limited availability of information and analysis on the potential of marine energy technologies. • Lack of validated, publicly available data on the performance, costs, and reliability of new marine energy systems. • Lack of STEM-relevant and educational information and opportunities to attract students and early-career professionals to marine energy careers.	**Data Access, Analytics, and Workforce Development** • Assess and communicate potential marine energy market opportunities, including those relevant for other maritime markets (e.g., desalination, powering subsea sensors, charging for underwater vehicles). • Aggregate and analyze data on marine energy performance and technology advances and maintain information sharing platforms to enable dissemination. • Leverage expertise, technology, data methods, and lessons from the international marine energy community and other offshore scientific & industrial sectors (e.g., offshore wind, oil, and gas).

Difficult Engineering to Convert Marine Energy

Marine energy device performance is governed by complex fluid-structure interactions between the devices and the marine environment. Fundamental scientific and engineering challenges remain in understanding how to design the most efficient systems to harness high energy-density and dynamic marine resources. Resource characteristics can vary significantly on very short timescales, such as the passing of an ocean wave or turbulence in water currents, and the ranges of energy intensity that devices experience can vary by several orders of magnitude. Devices must be designed to minimize the cost of energy while still operating reliably for the design life of a project, which can be 20 years or more. Therefore, developing marine energy devices is a multifaceted system design and optimization problem that encompasses many engineering disciplines.

Installing and Operating Reliable Systems

Installing, operating, and maintaining marine energy devices in harsh marine environments in a cost-effective and reliable manner presents significant difficulties that are related to, but also independent of, the fundamental scientific and engineering challenges. The corrosive saltwater environment, deep water, and high pressures at depth, dynamic benthic systems where devices will be anchored, sites that are sometimes located far from shore or port infrastructure, and extreme weather events all combine to create difficult conditions in which marine energy systems must be deployed and maintained. Developing and demonstrating solutions to solve these challenges would significantly reduce reliability concerns and enable greater access to project financing. Additionally, existing ships and port infrastructure have been developed specifically for other offshore commercial and industrial uses, and direct utilization of these ships and infrastructure without adaptation for the unique cost and performance requirements of marine energy technologies often results in suboptimal efficiency and high costs.

Prolonged Design and Testing Cycles

Testing marine energy technologies is inherently more complex and time consuming than for land-based energy generation technologies. The already slow pace of design and in-water testing cycles is further exacerbated by the limited availability of testing infrastructure at various scales, complex and time-consuming permitting processes, and expensive environmental monitoring. These challenges severely limit the ability of technology developers to quickly assess the performance of devices and components, innovate solutions where necessary, and deploy the next generation of devices. Because of the complex physics of the ocean wave and current environments, marine energy prototypes must be tested in real-world environments to fully characterize their performance and reliability. These challenges associated with testing, deploying, and optimizing technologies in a timely and cost-effective manner must be overcome to accelerate the pace of marine energy technology development.

Limited Availability of Technology, Market and STEM Information

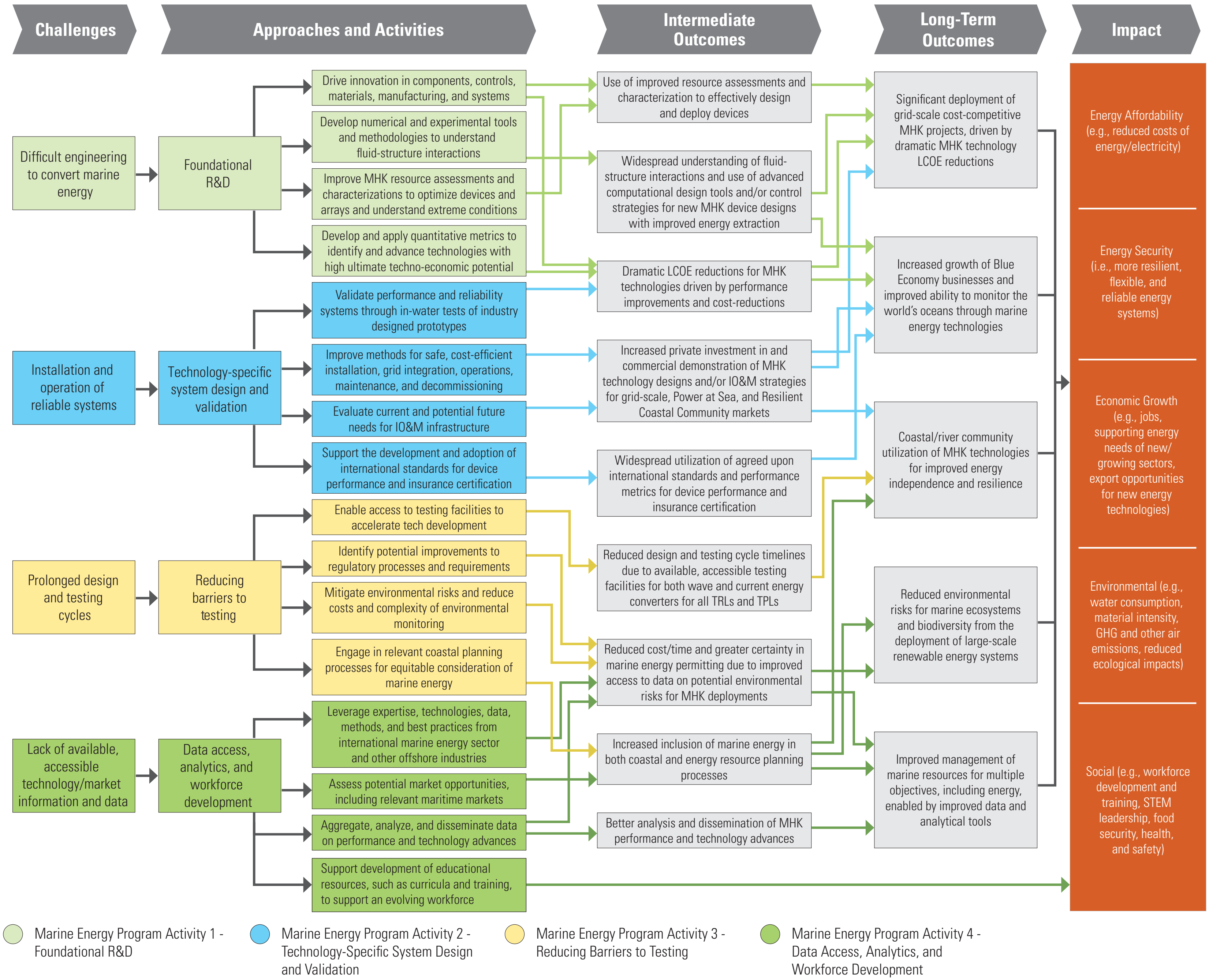
There are a number of challenges associated with the fact that the marine energy industry is in the nascent stages of development. Technologies are largely in the research, development, and demonstration phases, and have not yet been validated as commercially ready. Information and lessons learned from tests and in-water demonstrations that have occurred are often inaccessible or protected. Lack of awareness of different market opportunities and the potential benefits of marine energy technologies, compounded by limited familiarity with the technologies themselves, lead to perceptions of high technical risk. Limited experience in manufacturing devices and designing systems that can be efficiently manufactured at scale add to existing challenges but are capable of being addressed. Finally, access to STEM-relevant data, educational materials, and opportunities for students and other early career professionals to learn more about opportunities in marine energy are critical to supporting long-term workforce needs.

Marine Energy Program Goals and Objectives

Marine Energy Program Logic Model

Figure 9 illustrates the portfolio-wide logic for the Marine Energy Program. The challenges and approaches to addressing those challenges are those identified in the previous section and in Table 13. WPTO's Key Results and Performance Goals for the FY 2021–2025 timeframe are the significant outputs or products that are being targeted within the next five years. Those results and performance goals are critical to achieving the program's 2026-2030 objectives, which are short-term outcomes that are intended to lead directly to one or more of the intermediate outcomes identified in Figure 11. Those intermediate outcomes then hopefully influence the identified long-term outcomes, and the ultimate society or economy-wide impacts.

Figure 11. Marine Energy Program Logic Model



Assessing Performance

The ultimate vision for a successful and dynamic U.S. marine energy industry cannot be realized without intense dedication to technology improvement and ambitious cost-reduction activities. Historically, DOE has targeted roughly 80% reductions in the modeled cost of energy for wave, tidal, and river energy technologies from reference 2015 baselines to the year 2035. These are seen as aggressive, yet feasible, targets.[49] These goals were established several years prior to the publication of this document using the best-available data from literature at the time, along with programmatic and national laboratory expertise. The utilization of modeled levelized costs of energy (LCOE) is useful because it provides a standardized set of assumptions and a means of evaluating the effect of particular device or component R&D improvements over time. One drawback, however, is that the baseline or modeled LCOE values at any particular time may not accurately represent costs for any individual real-world technology because modeled LCOE assumes manufacturing and deployment efficiencies that cannot be realized with prototype devices. LCOE assumptions are also geared toward utility-scale generation technologies and projects and are less directly-applicable for evaluating marine energy devices that are targeted for other types of markets, such as those discussed in the Powering the Blue Economy Initiative Section.

[49] Note: the baseline and goal LCOE values are for generic technology archetypes and not directly attributable to any specific device.

5 HYDROPOWER MULTI-YEAR PROGRAM PLAN

Hydropower MYPP Organization and Structure

The following sections detail plans for each activity and sub-activity area in the Hydropower Program and is organized as follows:

- Activity 1 – Innovations for Low-Impact Hydropower Growth
- Activity 2 – Grid Reliability, Resilience, and Integration (HydroWIRES)
- Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity
- Activity 4 – Environmental and Hydrologic Systems Science
- Activity 5 – Data Access, Analytics, and Workforce Development.

Each activity area section includes the following components:

- *Activity Overview:* This subsection contains a brief overview of the activity area and scope of effort.
- *Key Results and Performance Goals (2021-2025)*: This subsection highlights certain significant outputs or products within the activity area that are expected within the next five years. The key results and performance goals are critical to achieving the program's 2026-2030 objectives. The list of key results and performance goals is not intended to be comprehensive and may not include every output produced within the five-year timeframe.
- *Follow-On Objectives (2025-2030)*: This subsection identifies short-term outcomes that the program aims to achieve by 2030, resulting from the successful completion of the 2021-2025 Key Results and Performance Goals. These follow-on objectives logically lead to the intermediate and long-term outcomes and ultimate impacts defined in the program's logic model.
- *Activity Additional Details*: This subsection provides additional background information, context, and details on the program's activity area, such as links or interdependencies between or among the activities/sub-activities.
    - *Sub-Activity Overview*: This subsection summarizes the various elements that the sub-activity covers and highlights major areas of work to achieve overall activity performance goals and follow-on objectives. A flow diagram illustrates the timing and sequencing of major areas of work.
    - *Sub-Activity FY 2021–2025 Research Priorities*: These are the main efforts the program intends to support within the sub-activity.
    - *Sub-Activity Timing and Sequencing of Research Priorities*: This is a visual representation of the timing, sequencing, and relation of different research priorities to each other.
    - *Additional Details on Sub-Activity*: Additional background information, context, and details on the program's planned efforts within the sub-activity.

Hydropower Program Activity 1 – Innovations for Low-Impact Hydropower Growth

Overview

Technology innovation can enable the growth of additional hydropower capacity and generation as an economically competitive source of renewable energy in four resource categories: (1) development in "new stream-reaches" (sometimes also referred to as "greenfield" sites); (2) powering of currently NPDs; (3) adding generation technology to existing irrigation canals and other water conduits; (4) and upgrades at existing hydropower plants.[50] Different technology pathways addressed in this activity include the major powertrain and civil works components of a hydropower facility—primarily turbine technologies, hydraulic structures, and geotechnical approaches—with an emphasis on standardized, modular designs and approaches centered on environmental performance. Development and adoption of new technologies and strategies could lead to significant U.S. deployment of additional low-impact hydropower that integrates multiple social, environmental, and energy needs, while realizing value and revenue from a variety of sources.[51]

Activity 1 – Innovations for Low-Impact Hydropower Growth consists of the following sub-activities:

1. New Technologies and Advanced Manufacturing*:* Developing new cost-effective technologies that incorporate ecological and social objectives and leverage the latest advances in manufacturing and materials.
2. Testing Infrastructure Access and Development: Increasing access to existing testing capabilities and developing new testing infrastructure to speed development and ultimately enable commercialization of new technologies.
3. New Value Propositions: Identifying specific opportunities where hydropower investments can provide benefits across both energy and other sectors, including water security.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 14.

[50] While total capacity at existing hydropower plants could be expanded through the addition of new generators in existing or new powerhouses, it is expected that hydropower owner/operators will pursue these opportunities without the need for federal R&D investments, and therefore no specific activities or efforts are outlined in this document.

[51] Note: new PSH technologies and designs, and technologies to enhance unit and plant flexibility are addressed in Activity 2 – Grid Reliability, Resilience, Integration, and Storage (HydroWIRES). Sensors research that can better and more reliably assess the condition of hydropower plants will occur under Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity. Technologies targeted towards environmental monitoring and mitigation are addressed in Activity 4 – Environmental and Hydrologic Systems Science.

Table 14. Innovations for Low-Impact Hydropower Growth Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Develop datasets and interactive geospatial tools to identify development potential and site characteristics of new stream-reaches, NPDs, and conduit resources. • Publish R&D roadmap that identifies high-impact opportunities to leverage advanced manufacturing and materials in hydropower applications. • Complete testing and pre-commercial demonstrations of new cost-competitive technologies across each class of hydropower resource, with validated energy and environmental performance characteristics. • Complete development of a full-scale, federally sponsored hydropower test facility (or network of facilities). • Establish a framework for assessing costs and benefits of new hydropower projects, particularly those that could utilize new value propositions.
Follow-On Objectives (2026–2030)
• Project developers use geospatial tools to site and design new hydropower projects that balance social and ecological considerations, such as recreation, water quality, and biodiversity. • Technology developers actively pursue and apply high-impact advanced manufacturing opportunities for hydropower applications. • Deployment of new technology with revolutionary improvements in technology costs and environmental performance due to adoption of standardization and modularity principles, incorporation of advanced manufacturing and materials, and ability to test prototypes at full scales. • Increased developer interest in exploring hydropower projects that take advantage of new value propositions in addition to energy generation values.

Additional Details

The majority of hydropower capacity was installed between 1930 and 1990, first as part of the development of large federal multipurpose water projects, and later for a variety of reasons, including complementing the operation of large baseload coal and nuclear power plants, and cost-effectively balancing electricity load and demand on the transmission grid. Still, there is growth occurring today. Nearly 2.5 GW of new hydropower capacity was added to the grid from 2005 to 2019,[52] but overall, the pace of hydropower development has reduced considerably—especially in comparison to the rapid growth of other renewable energy resources. The results of the 2016 Hydropower Vision analysis imply that future development of hydropower projects is likely to remain limited without three major improvements: transforming the advancements in technologies; creating new project development methods that can achieve cost reductions; and meeting or exceeding sustainability objectives with minimal disruption to natural aquatic life, sediment, water flows, recreation, and other issues.

Though innovation is key to fostering additional hydropower development, new technologies alone may not be sufficient to enable hydropower growth, even with significant cost reductions. Optimal financial performance will depend on a project's ability to provide additional, steady value streams to balance project costs. In recent years, there has been increasing focus on the potential for new value propositions for hydropower projects—other than bulk electricity—that could open the door to non-traditional hydropower development. New value propositions may include co-development opportunities, business cases, and specialized markets in which energy from hydropower is not the principal motivation of the project, but rather a critical enabler of a larger suite of benefits.

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

Sub-Activity 1.1 – New Technologies and Advanced Manufacturing

Overview

This sub-activity consists of developing and advancing technologies for application in three identified resource classes: (1) new stream-reaches, (2) NPDs, and (3) conduits. As illustrated in Figure 12, each resource category follows a similar process—from characterizing the available resource to better target technology investments, to developing and testing technologies that can cost-effectively and sustainably utilize hydropower potential in the respective classes. Though efforts are illustrated linearly, many processes and steps are iterative and cyclical, such as technology development and testing.

FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the Sub-Activity 1.1 – New Technologies and Advanced Manufacturing:

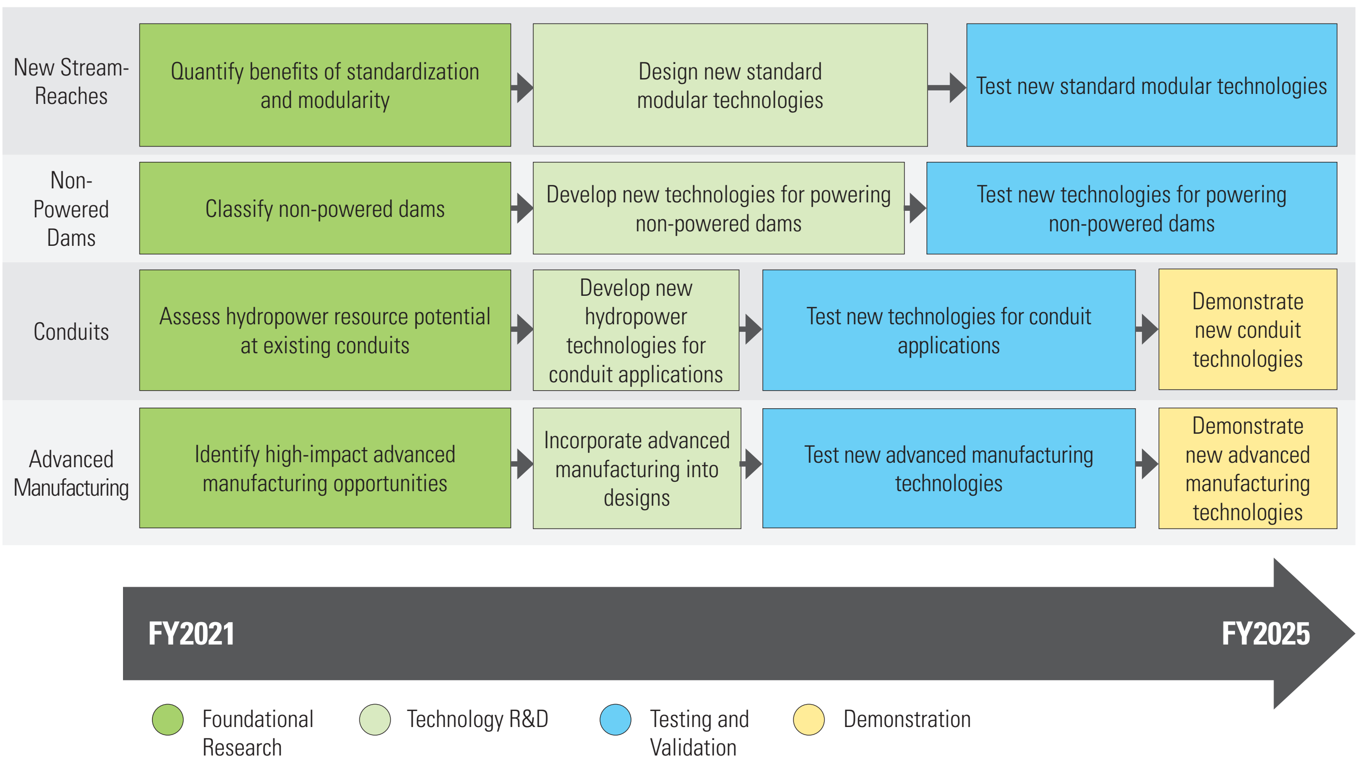
- **New Stream-Reach**
  - **Quantify benefits of standardization and modularity**: Perform techno-economic studies into past investments to quantify the potential benefits of standardization and modularity for new hydropower development, including increased environmental compatibility, lower costs, and shorter construction times.
  - **Design new standard modular technologies**: Use the results of the techno-economic study to revise design guidelines and support development of new standard modular technologies, targeting modules where additional improvements are needed.
  - **Test new standard modular technologies**: Evaluate the performance of new standard modular technologies at a partial and/or full scale.
- **Non-Powered Dams**
  - **Classify NPDs**: Perform a study to classify existing non-powered U.S. dams based on key attributes relevant for hydropower development and integrate those findings into a user-friendly geospatial tool.
  - **Develop new technologies for powering NPDs**: Informed by the classification study, develop design guidelines incorporating lessons learned about standardization and modularity, and support development of new technologies and construction methods to cost-effectively power NPDs.
  - **Test new technologies for powering NPDs**: Evaluate the performance of new technologies and methods for NPDs at a partial and/or full scale.
- **Conduits**
  - **Assess hydropower resource potential at existing conduits**: Perform a geospatial study to identify existing U.S. water conveyance systems and quantify available hydropower resource potential.
  - **Develop new hydropower technologies for conduit applications**: Develop technologies and methods to cost-effectively add hydropower to existing conduits and canals.
  - **Test new technologies for conduit applications**: Evaluate the performance of developed technologies for conduits and canals at a partial and/or full scale.
  - **Demonstrate new conduit technologies**: Conduct a field demonstration to validate new technologies at an existing conduit or canal.

- **Advanced Manufacturing**
  - **Identify high-impact advanced manufacturing opportunities**: Utilize creative funding mechanisms to identify high-impact advanced manufacturing opportunities for hydropower applications.
  - **Incorporate advanced manufacturing into designs**: Incorporate advanced manufacturing and materials with the potential to reduce costs or increase performance into the design of hydropower components.
  - **Test new advanced manufacturing technologies**: Evaluate the performance of new advanced manufacturing technologies and methods at a partial and/or full scale.
  - **Demonstrate new advanced manufacturing technologies**: Conduct a field demonstration to validate new advanced manufacturing technologies and methods in a real-world site.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 12.

Figure 12. Sub-Activity 1.1 – New Technologies and Advanced Manufacturing Research Priorities



Additional Details

New Stream-Reaches

New stream-reach development refers to new hydropower development in stream-reaches that do not currently have hydroelectric facilities or other forms of dams or hydraulic infrastructure. Roughly 75% of identified new stream-reach sites are low-head, or less than 30 feet, and therefore have lower power densities and potentially higher costs, given economies of scale for larger projects. Developing hydropower in new stream-reaches can also result in environmental impacts if not carefully sited, designed, built, and operated to balance ecological considerations, such as species diversity, water quality, recreation, and other physical processes within the ecosystem. These factors make small hydropower development in undeveloped streams—with design engineering, construction, equipment selection, environmental impact mitigation strategies, and total installed costs that are usually driven by very site-specific considerations—a complex and uncertain undertaking.

Since 2016, the Hydropower Program has invested in exploring standardization, modularity, and environmental compatibility to enable low-cost, environmentally sustainable hydropower growth in currently undeveloped streams. This new class of hydropower technology will be standard—meaning its geometry, local hydraulics, aesthetics, cost structure, and other salient design features are site-independent, with limited environmental impacts. It will also be modular, meaning that capacity and function can be scaled to a site through deployment of multiple components that are designed to integrate with minimum cost and maximum value. The SMH concept shifts the design philosophy from custom designing every facility to extract the greatest amount of energy possible and then mitigating impacts, to focus on first sustaining the important hydrologic, hydraulic, geomorphic, physiochemical, and ecologic processes that occur in streams and watersheds. Applying SMH practices can result in new projects that generate renewable energy at low cost while preserving—and in some cases enhancing—stream functionality.

In this sub-activity, the Hydropower Program will conduct an impact analysis on SMH investments to date—which include foundational research at Oak Ridge National Laboratory[54] and two public funding opportunities[55] —to closely examine and document the techno-economic benefits of standardization and modularity in terms of costs, construction time, and environmental impact, among others. The results of this analysis will reveal gaps (e.g., need for better design guidelines, or modules that have not been sufficiently advanced) and help guide the Hydropower Program's future investments in standard modular technologies.

Non-Powered Dams

Only 3% of the nation's roughly 90,000 dams are currently equipped with electricity-generating equipment. Existing NPDs can be retrofitted for hydropower generation without the costs and impacts of additional dam construction. Despite these opportunities, the NPD resources are also characterized by low heads and variable flows, and estimated costs can still be high in many cases where traditional generating equipment and civil configurations are planned. The U.S. NPD fleet is also incredibly diverse in terms of dam condition, purpose (e.g., flood control, water supply), engineered features, capacity, environmental attributes, and socio-economic considerations. For this reason, this sub-activity involves classifying NPDs based on characteristics and key variables relevant to hydropower development, which will result in a web-based tool for exploring NPD development opportunities. Subsequent efforts will focus on developing generalized designs and technologies for NPD hydropower development. Lessons learned regarding the benefits of standardization and modularity explored in the new stream-reach context will be leveraged to reduce costs, timelines, and environmental compatibility of NPDs.

Conduits

Conduit hydropower projects can be developed on existing water-conveyance structures, such as irrigation canals or pressurized pipelines that deliver water to municipalities, industry, or agricultural water users. There are many thousands of miles of existing conduits in the United States that are used to transport and distribute water and wastewater. Although water conveyance structures were not designed for energy generation purposes, excess energy can in many cases be harvested from these systems without the need to construct new dams or diversions. Mainly due to data limitations, the total conduit hydropower potential across states and/or regions is currently unknown.

In this sub-activity, a geospatial assessment will first be performed to identify locations with undeveloped conduit hydropower potential at existing water conveyance systems. This resource assessment will inform technology investments. For instance, hydropower development at conduit projects can be relatively complex and challenging

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[54] Oak Ridge National Laboratory, "Standard Modular Hydropower." https://smh.ornl.gov/.

[55] WPTO Past Water Power Funding Opportunities: https://www.energy.gov/eere/water/past-water-power-funding-opportunities (DE-FOA-0002080 and DE-FOA-0001836).

due to the need to manage multiple water use objectives to avoid any risk of disruption of water delivery while maximizing generation. New fit-for-purpose technologies that have been proven to be reliable could facilitate acceptance, and lead to widespread deployment of hydropower on existing water conveyance systems. Conduit hydropower projects can also take advantage of the expedited permitting process through the Hydropower Regulatory Efficiency Act of 2013 and its amendments in 2018—which provide an accelerated, 60 days or less pathway to acquiring FERC authorization for qualifying small hydropower projects. The sub-activity plans include sponsoring competitive real-world demonstrations of conduit hydropower technologies to serve as exemplary pilots for validating new technologies, while navigating the expedited permitting process.

Advanced Manufacturing

Over the last decade, advanced manufacturing has revolutionized many different parts of the energy sector, boosting U.S. manufacturing and opening pathways to increased American competitiveness. Advanced manufacturing can offer numerous benefits over conventional manufacturing techniques, such as enhanced design flexibility, decreased energy consumption, lower costs, and reduced time to market. While novel applications of advanced manufacturing have ushered in benefits in other energy sectors, the potential benefits for hydropower applications remain largely unexplored. This sub-activity will identify high-impact opportunities to apply advanced manufacturing to address hydropower's challenges, and advance these solutions through targeted investments, including prototyping and testing. These efforts will also be closely coordinated and carried out in partnership with EERE's Advanced Manufacturing Office (AMO).

Leveraging advanced manufacturing is critical for enabling new low-impact growth, but the opportunities identified will also benefit other activities in the Hydropower Program. For example, the use of advanced materials may lead to significant cost reductions for PSH facilities, a key objective of Activity 2 – Grid Reliability, Resilience, and Integration (HydroWIRES). Additive manufacturing presents an opportunity to embed sensors within hydropower components for condition monitoring, thus supporting research under Activity 3 – Fleet Modernization, Maintenance and Cybersecurity to better and more reliably assess the condition of hydropower plants. Research under Activity 4 – Environmental and Hydrologic Systems Science could leverage advanced manufacturing to develop innovative environmental monitoring and mitigation technologies, such as the use of new materials for fish screens and development of miniaturized fish tags and micro-batteries.

Sub-Activity 1.2 – Testing Infrastructure Access and Development

Overview

This sub-activity would perform an initial scoping for a full-scale, grid-connected, federally sponsored hydropower test facility. Full-scale testing for a broad range of hydropower components—including hydraulic, mechanical, electrical, civil/structural, sediment, biological, safety, and instrumentation technologies—could be accomplished at a single facility or may require a network of multiple facilities to provide a greater range of capabilities. The near-term efforts of this sub-activity will focus on (1) performing an assessment of hydropower testing needs, including identification of testing components, scales, and capabilities that will provide value to the hydropower industry; (2) cataloging existing hydropower test facility capabilities; and (3) assessing the suitability of existing federal infrastructure to meet testing needs. These scoping efforts would inform any potential future activities related to the design, development, and operation of a full-scale test facility program.

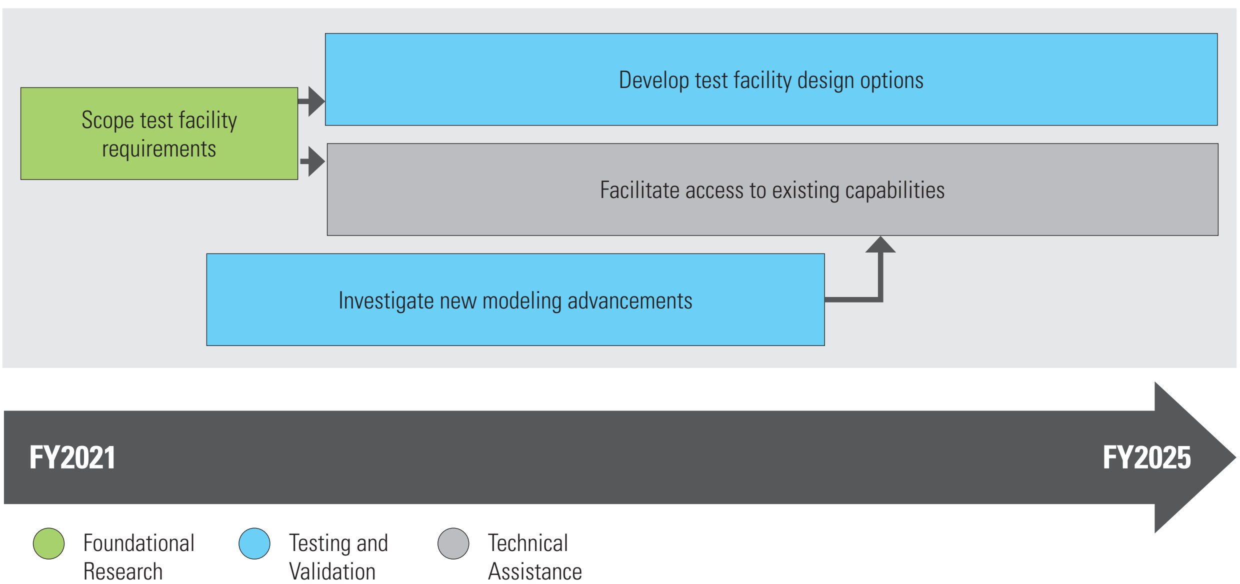
Concurrently, the sub-activity will continue to support smaller-scale testing at existing facilities to help advance new and unproven technologies at earlier stages of design. The sub-activity will also explore the latest advances in high-fidelity modeling that can complement or in some cases replace some physical testing, such as multi-body dynamics simulation and advanced computational fluid dynamics.

FY 2021–2025 Research Priorities
The following are the research priorities that will be emphasized within the Sub-Activity 1.2 – Testing Infrastructure Access and Development:

- **Scope test facility requirements**: Perform an assessment of hydropower testing needs and existing hydropower testing capabilities to inform the requirements and specifications for a full-scale hydropower test facility.
- **Develop test facility design options**: Develop design options for a full-scale test facility (or network of facilities) to meet the testing needs, requirements, and specifications identified in the scoping study.
- **Facilitate access to existing capabilities**: Utilize a technical assistance program to facilitate access to existing test facilities, capabilities, and expertise.
- **Investigate new modeling advancements**: Explore the application of advanced numerical modeling that may reduce the need for physical testing.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 13.

Figure 13. Sub-Activity 1.2 – Testing Infrastructure Access and Development Research Priorities



Additional Details

Hydropower growth is contingent upon validation of the safety, environmental acceptability, reliability, and performance of innovative technologies. New technologies represent risks to first adopters, making it difficult for technology developers to bring nascent and potentially disruptive technologies to market. Given the multi-objective nature of hydropower projects, deployment of technologies prior to validation could present risks to the ecosystem as well as both power and water costumers. Yet existing academic, private, and government-sponsored facilities have limitations of size, hydraulic capacity, and capabilities. In addition, federal permitting requirements limit opportunities for in-river, grid-connected testing of hydropower technologies.

Hydropower technology developers thus face a critical dilemma: new technologies are often not allowed to be deployed without being tested, yet the only way to test them at scale is through deployment. Therefore, there is a need for test facilities where emerging technologies can be tested, validated, and de-risked at full scale to ensure that operational, physical, and environmental requirements are met, and establish credibility with investors and decision makers.

Increased access to testing capabilities and infrastructure will support deployment of new hydropower by enabling validation of technology safety, performance, and reliability of innovative technologies. Testing capabilities and infrastructure developed in this sub-activity will also benefit other activities within the Hydropower Program. Examples of components developed under other activities that could benefit from testing and validation efforts include:

- Hardware and software to increase unit or plant flexibility, such as advanced controls and power electronics (Activity 2 – HydroWIRES).
- Sensors and instrumentation for condition monitoring, such as novel telemetry for cavitation detection (Activity 3- Fleet Modernization, Maintenance, and Cybersecurity).
- Environmental mitigation technology, such as fish passage systems (Activity 4 – Environmental and Hydrologic Systems Science).

Sub-Activity 1.3 – New Value Propositions

Overview

Identifying new value propositions—in concert with efforts to drive down costs and improve environmental performance—can enable hydropower to play an even greater role than it has historically. This sub-activity seeks to provide insight into alternative opportunities, co-benefits, business cases, and specialized markets that hold the potential to increase the value proposition for small and novel hydropower projects. Similar to WPTO's marine energy initiative, PBE, there are unexplored opportunities for new development in which hydropower is not the principal motivation of the project, but a critical enabler of a larger suite of benefits. For example, irrigation districts have been able to modernize their irrigation systems as a result of revenue and energy cost-savings from hydropower project developments. The installation of in-conduit hydropower, coupled with pressurized piping, can reduce evaporative water loss from open conduits, reduce energy use, and provide a predictable revenue stream to support regular operations and maintenance, in addition to further future water-efficiency modernizations.

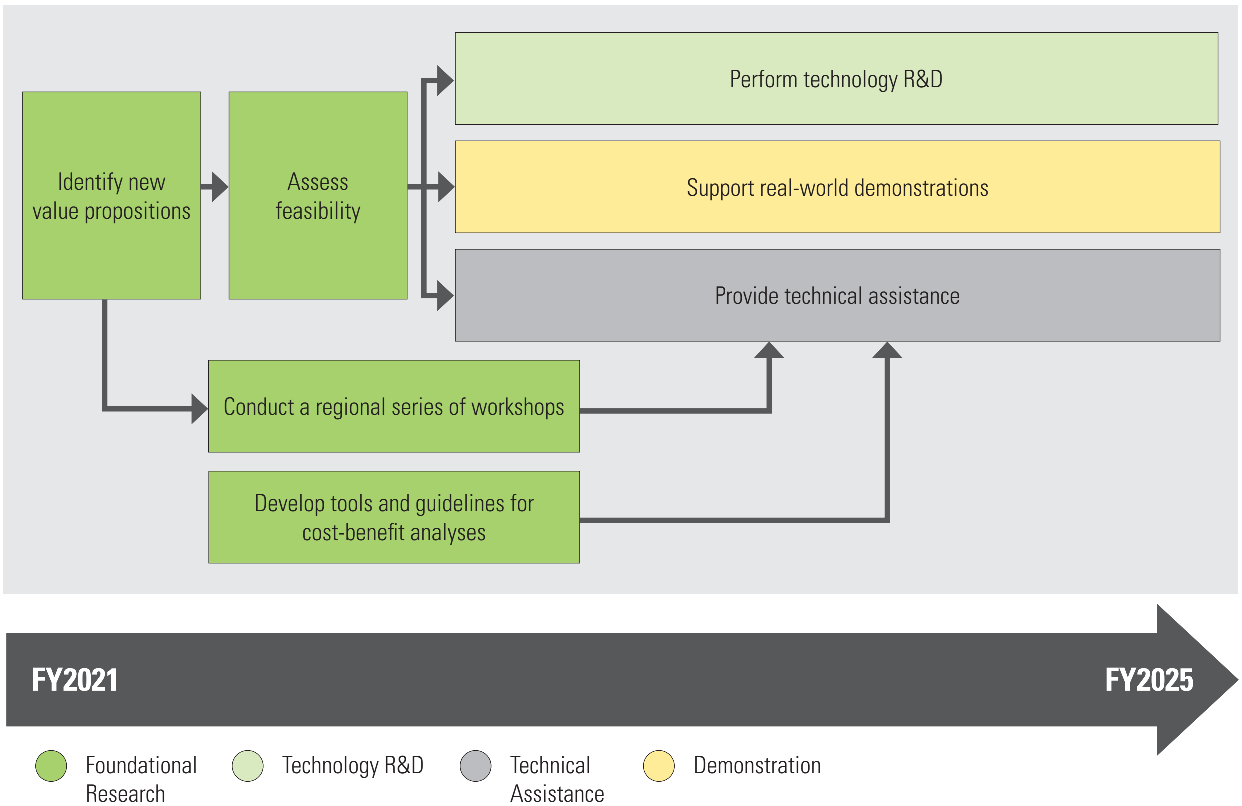
FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the Sub-Activity 1.3 – New Value Propositions:

- **Identify new value propositions**: Investigate new value propositions and alternative opportunities for new, low-impact hydropower development.
- **Assess feasibility**: Evaluate the technical and economic feasibility of identified value propositions and opportunities, and document barriers to their current realization (e.g., need for technology innovation).
- **Conduct a regional series of workshops**: Host a series of regional workshops to solicit feedback on, refine, and educate about identified value propositions and opportunities.
- **Develop tools and guidelines for cost-benefit analyses**: Produce tools and guidelines for stakeholders to evaluate costs and benefits of new, low-impact hydropower projects, including within the context of new value propositions.
- **Perform technology R&D**: When needed, and depending on the individual value proposition or opportunity, develop innovative technologies to enable the realization of a new value proposition.
- **Support real-world demonstrations**: Support real-world demonstration of new value propositions that currently demonstrate sufficient near-term readiness.
- **Provide technical assistance**: Administer a technical assistance program to encourage, enable, and assist relevant stakeholders in pursuing hydropower development in the context of new value propositions.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 14.

Figure 14. Sub-Activity 1.3 – New Value Propositions Research Areas



Additional Details
This sub-activity is intended to not only identify new value propositions and opportunities to provide mutual benefits, but to better understand the technical and economic feasibility of new opportunities. This process may lead to one or multiple pathways. For example, some opportunities may only prove to be feasible if new technologies are developed, which would lead to a technology R&D pathway under Sub-Activity 1.1 – New Technologies and Advanced Manufacturing. Alternatively, other opportunities may be found to be technically and financially feasible given current technologies and conditions, in which case federal investments in full-scale testing and demonstration could enable their more rapid realization and adoption. Lastly, some opportunities may be best enabled through further analysis, best practices and standards development, or other types of technical assistance. A regional series of workshops could help better define these various pathways and connect potential beneficiaries and stakeholders of new value propositions with hydropower stakeholders to catalyze cooperation at larger scales.

New Opportunities for Hydropower to Support Water Infrastructure Resilience

There are known opportunities for new development in which hydropower is not the principal motivation of the project, but a critical enabler of a larger suite of benefits that are currently underexplored by the industry. Such opportunities exhibit a diverse array of stakeholders, users, and benefits with the potential to benefit from non-traditional hydropower applications and innovative partnerships. These include:

1. **Irrigation Modernization**: Irrigation is a cornerstone of many rural and agricultural communities. The retrofitting of irrigation systems with in-conduit hydropower has resulted in community, energy, and water resilience, including a diversified revenue source, increased local energy reliability, increased agricultural productivity, and water savings.
2. **Water Supply and Treatment:** Co-development of hydropower through existing water conduits, delivery or pressure systems seems to have a clear business case, both in terms of added revenues and resilience for treatment facilities and energy generation. There are also ways in which hydropower on water distribution and treatment systems may power behind the meter applications for resilience and reliability within water networks or neighboring infrastructure.
3. **Source Water Recharge**: Exploration of surface and groundwater interactions and mitigation of groundwater depletion provide the potential for hydropower investment. Hydropower slows down water to build up head, and there are innovative designs with an eye specifically towards the recharge of groundwater using surface water that could enable an array of benefits to municipalities, irrigators, and ecosystems.
4. **Environmental Services**: Alternative hydropower development and environmental stakeholders such as nongovernmental organizations (NGOs) and interest groups can establish synergies leading to mutually positive outcomes in the forms of environmental restoration, positive impacts on biological diversity, optimizing environmental flows, or even environmental clean-up.
5. **Deferrable Loads**: A class of loads, characterized by the ability to be quickly ceased and restarted, is compatible with the increased variability posed by hydropower plants with limited storage or without storage entirely. The benefits of cloud computing and environmental restoration, among other activities, can be magnified through the coupling of these deferrable activities with a wide range of hydropower infrastructure types.
6. **Historic Preservation**: New hydropower development often competes with historic preservation. However, this need not be the case, as alternative hydropower applications can be used to aid and enhance historic preservation. New England is already showing interest in this market with its many historic dams and mills.
7. **Recreation**: Many economically important recreational industries rely on predictable water releases and flows (often managed by upstream hydropower and NPD facilities). Examples include rafting, boating, fishing, kayaking, boat racing, swimming, tubing, and the maintenance of riverside parks. Co-development of hydropower at whitewater parks or recreation facilities may be a present niche opportunity for mutual benefits.

Hydropower Program Activity 2 – Grid Reliability, Resilience, and Integration (HydroWIRES)

Overview

Rapid changes in the U.S. electricity system, including changes in generation mix as well as markets and policy, have created new needs for storage, flexibility, and other grid services that hydropower and PSH are well-suited to provide. In response to these opportunities, the HydroWIRES Initiative seeks to understand, enable, and improve hydropower's contributions to grid reliability, grid resilience, and integration. HydroWIRES investigates additional value streams, enhanced flexibility, new operational strategies, and innovative technology solutions that enable new roles for hydropower and PSH. Efforts encompass industry- and national lab-led modeling, analysis, tool development, technical assistance, and technology R&D.

Activity 2 – Grid Reliability, Resilience, and Integration (HydroWIRES) consists of the following sub-activities:

1. Value under Evolving System Conditions: Understanding the needs of the rapidly evolving grid and how they create opportunities for hydropower and PSH.
2. Capabilities and Constraints: Investigating 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.
3. Operations and Planning: Optimizing hydropower operations and planning—alongside other resources—to best utilize hydropower's capabilities to provide grid services.
4. Technology Innovation**:** Investing in innovative technologies that improve hydropower capabilities to provide grid services.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 15.

Table 15. HydroWIRES Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Publish regionally focused roadmaps for maximizing hydropower's value for reliability, resilience, and integration. • 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. • Release the first version of a system-level 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. • 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.
Follow-On Objectives (2026–2030)
• Accurate representations in power system models of hydropower and PSH capabilities, such as the flexibility of modern designs and reservoir constraints, are widely utilized for research, planning, and unit scheduling. • Quantifiable improvement of hydropower plant operations, including coordination or co-location with other resources, to support greater needs for system flexibility. • Commercialization of new technologies for hydropower asset flexibility and deployment by hydropower owners and operators. • New PSH projects that utilize advanced technologies, system designs, and methods to lower costs/increase cost-competitive PSH deployment.

Additional Details

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 generation 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 power system reliability and resilience. Hydropower has historically been operated primarily as a baseload-scheduled or predictable peaking resource, generating energy over relatively long timeframes. However, this operational pattern is changing for some plants, particularly in regions with high variable renewable penetrations. Hydropower and PSH systems' technical characteristics make them well-suited to provide a range of storage, flexibility, and other grid services[56] that can enable integration of variable renewables.[57] The U.S. hydropower fleet of the future may therefore be operated and dispatched not solely for energy benefits but as a key source of flexibility to integrate variable renewables on the grid. Future changes are likely to differ by region and facility, based on the needs of the power system and the existing obligations of individual plants.

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 and opportunities to 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.

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. Work carried out in HydroWIRES thus traces these four opportunities, shown graphically in Figure 15.

56 Black start is example of a grid service, which hydropower is well suited to provide as discussed in this HydroWIRES report.

57 Hydropower's role in future renewable integration is discussed in more detail in a white paper, published by the International Energy Agency with contributions from the HydroWIRES team.

Figure 15. The Four HydroWIRES Research Areas

Industry Challenges	Corresponding Research Areas
As the electricity system is changing, there is limited understanding of which services will be needed, as well as limited ability to accurately value those services.	**1 Value Under Evolving System Conditions** Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower and PSH. **What will the grid need?**
Hydropower and PSH capabilities are bounded by the interaction of machines, water, and institutions, and some of these bounds originate from legacy decisions that did not consider evolving grid needs.	**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 the hydropower fleet do?**
There are gaps in information regarding how to optimize hydropower and PSH operations and planning in coordination with other resources.	**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 best align what it can do with what the grid will need?**
Current hydropower and PSH technology may not be designed for flexible operation.	**4 Technology Innovation** Invest in innovative technologies that improve hydropower capabilities to provide grid services. **What new technology could expand what hydropower can do to meet grid needs?**

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. They provide needed insights into the services and attributes the hydropower fleet can and should be prioritizing. 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 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.

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 current as well as future actions by industry decision-makers.

Sub-Activity 2.1 – Value Under Evolving System Conditions

Overview

Rapid changes in the power system generation mix make it difficult to understand the different ranges of reliability services and associated technical capabilities the grid may require at different points in the future, and how this will differ from system to system. Estimating the future value of different types of capabilities and services is equally, if not more, challenging. The goal of this sub-activity is to 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, and thus be able to estimate the value of different hydropower capabilities within their own system. These goals will be achieved through three technical objectives: producing a grid services taxonomy, quantifying value drivers, and developing valuation methodologies and associated tools. Many of these research efforts have relevance beyond hydropower and will be closely coordinated with relevant offices as part of the ESGC.

FY 2021–2025 Research Priorities

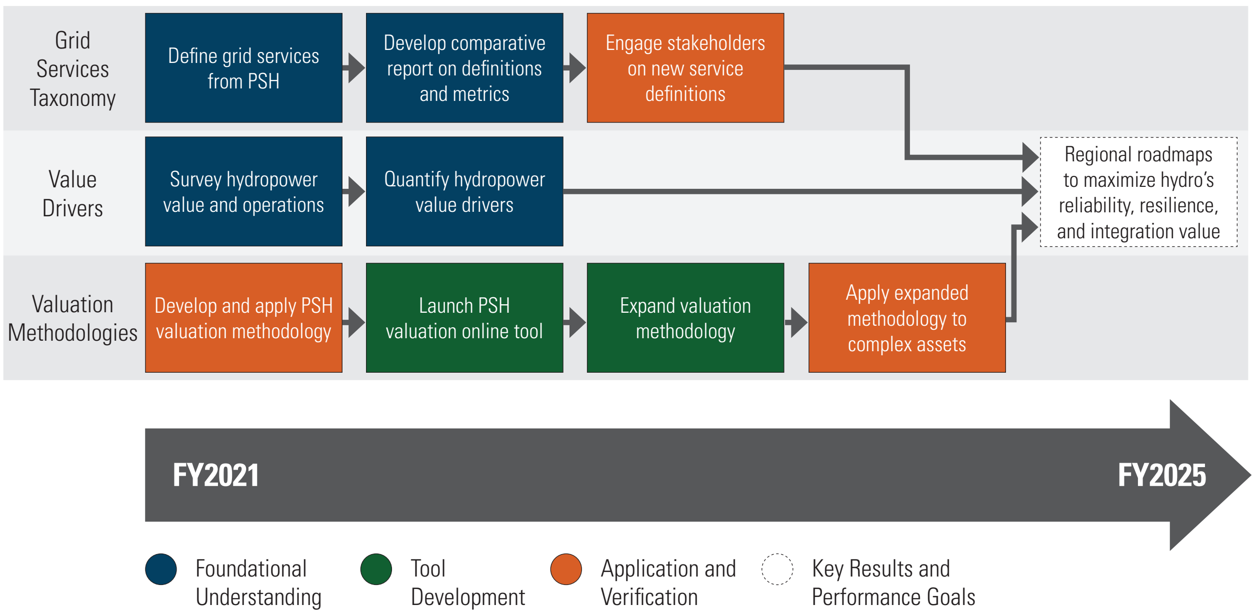
The following are the research priorities that will be emphasized within the HydroWIRES Sub-Activity 2.1 – Value Under Evolving System Conditions:

- **Grid Services Taxonomy**
  - **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**: Engage stakeholders on metrics and definitions of new potential grid services that may be required in future systems.
- **Value Drivers**
  - **Administer a survey on 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.
- **Valuation Methodologies**
  - **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.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 16.

Figure 16. Sub-Activity 2.1 – Value Under Evolving System Conditions Research Priorities



Additional Details
In producing a grid services taxonomy, HydroWIRES seeks to enable unified understanding of grid services and system benefits. While it will be important to create a general framework that can accommodate other technologies and resource classes in coordination with other DOE offices to fully address this problem, the taxonomy will be initially developed for advanced PSH valuation. Future work may include analyzing market design initiatives in different independent system operators/regional transmission organizations and their effects on market product definitions relevant for hydropower.

HydroWIRES also seeks to understand value drivers for hydropower in today's power system and investigate how they might evolve under different future system scenarios. These scenarios could be structured to understand how hydropower might be used in different resource mixes, what new system requirements and/or market products could be needed in the future, and which uncertainties would be the most impactful. Work has already been completed on how hydropower has been valued and compensated historically in various regions of the United States, and this may be extended in the future to include an analysis of prices and market dynamics of energy and ancillary services in countries (such as Austria, Brazil, Norway, Portugal, etc.) that have large amounts of hydro and hydro-based storage to better understand drivers for hydropower value in the United States.

Finally, this sub-activity will develop rigorous, widely applicable methodologies and tools that can be used to better assess the value of hydropower assets. While energy storage valuation capabilities have advanced significantly in recent years, valuing PSH plants presents several interesting technical challenges. For example, generating capacities of the plants are often large enough to significantly influence the supply-demand relationships in markets and change prices and value of the services that PSH plants can provide. Advancing valuation for conventional hydropower resources will be equally important as the use of flexible hydropower operations becomes more prevalent. Work has already been completed on standardizing the valuation process for PSH, and more work may be completed to extend this standardization to conventional hydropower, hybrids, and more. Under this sub-activity, efforts may include an evaluation of emerging power purchase agreement structures that are responsive to changing system needs.

Products from this sub-activity will also directly benefit and be utilized by efforts in Sub-Activity 1.3 – New Value Propositions, to help hydropower developers estimate revenue potential and anticipated power system benefits of new low-impact projects. Valuation of new hydropower projects could also help establish technology development targets (i.e., cost and performance characteristics necessary for favorable financial performance).

Sub-Activity 2.2 – Capabilities and Constraints

Overview

While hydropower plants with moderate-to-significant reservoirs and water storage capacities are some of the most flexible resources on the grid, the inherent technical capabilities of the individual plants are often constrained by a combination of factors such as the design or configuration of generation equipment; current and future water availability (e.g., in a cascading system), or institutional requirements to use water for environmental flows, navigation, and other purposes. HydroWIRES will provide new, 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. This will be achieved through four technical objectives: developing a flexibility framework; quantifying flexibility tradeoffs; improving short-term inflow forecasting; and improving modeling representation.

FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the HydroWIRES Sub-Activity 2.2 – Capabilities and Constraints:

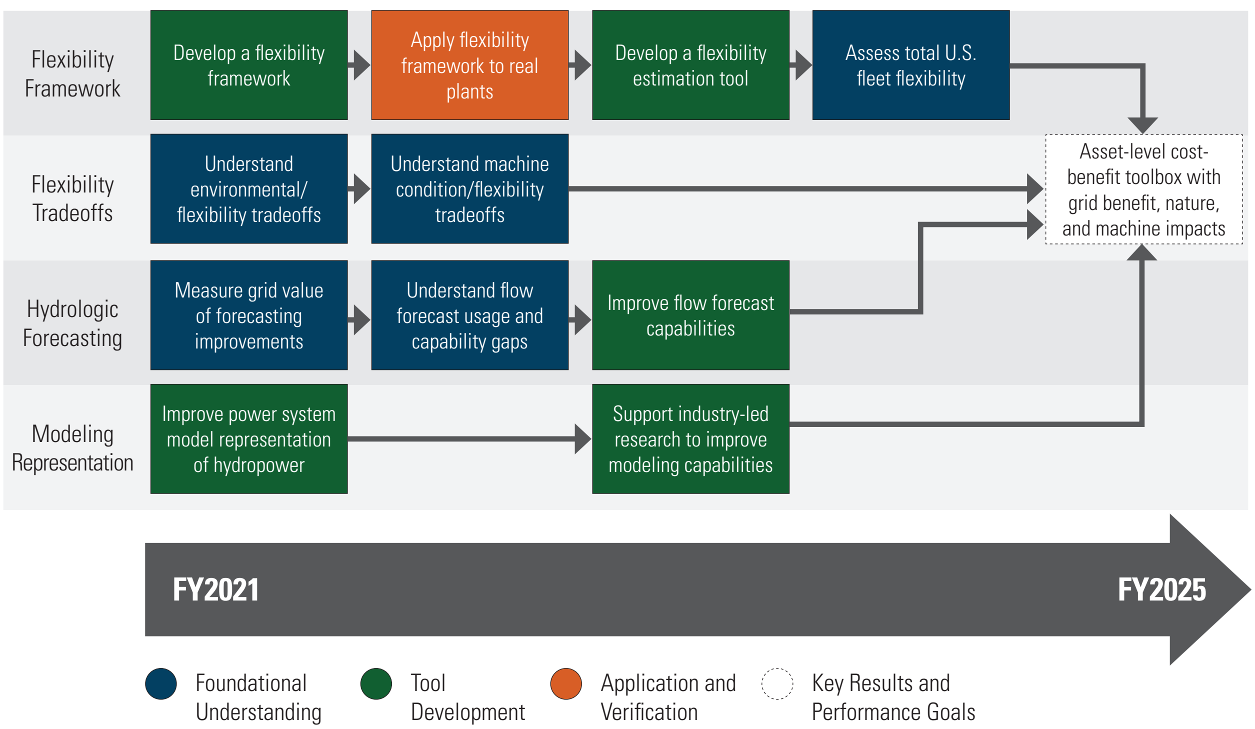
- **Flexibility Framework**
    - **Develop a flexibility framework**: Develop a broadly applicable framework to estimate the amount of flexibility that a hydropower plant can provide.
    - **Apply the flexibility framework to real plants**: Apply the framework to real-world plants in coordination with 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.
- **Flexibility Tradeoffs**
    - **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.

- **Hydrologic Forecasting**
    - **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).
- **Modeling Representation**
    - **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**: Support an industry-led effort to improve targeted power system model capabilities relevant for hydropower and PSH.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 17.

Figure 17. Sub-Activity 2.2 – Capabilities and Constraints Research Priorities.



Additional Details

While many hydropower plants are capable of flexible operation, there is no clear quantification of how much potential flexibility exists in the fleet. 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, the need to provide ecological flows, and water availability. Ongoing work focuses on categorizing and quantifying the types of operational flexibility that the range of hydropower plants can provide, which will be used for a future fleet-wide assessment of total hydropower flexibility available in the United States. A comprehensive, national assessment of the potential flexibility available in the U.S. hydropower fleet could enable improved planning and inform future discussions around renewable integration.

In addition to understanding the potential for flexible operations, equally important are the tradeoffs between operating flexibly versus meeting other objectives related to environmental performance, revenue opportunities, and machine wear and tear. Following the flexibility capability assessment, HydroWIRES will identify areas where there is a need for advanced tools, models, or platforms to help assess and evaluate tradeoffs within the hydropower facility or set of co-managed facilities. Current work seeks to understand the tradeoffs between flexibility and environmental outcomes, and complementary work focuses on the tradeoffs with cost, condition, and availability. In the future, these tools will be integrated into a unified cost-benefit analysis tool for asset-level decision makers.

This sub-activity also seeks to quantify and improve the accuracy and resolution of short-term inflow forecasting tools in conjunction with industry partners to enable more flexible operation. Long-term forecasting at decadal time scales, for example, will be investigated in other areas of the office's portfolio. If hydropower plants are required to operate more flexibly, inflow forecasting, and water management tools will likely require improvements in accuracy and resolution. 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. Currently, the marginal value of improvements to these models is being quantified, and follow-up work will target key areas for model improvements.

The final technical objective of this sub-activity is to improve the representation of hydropower and PSH in power system models to capture their unique capabilities more accurately. There are fundamental differences in hydropower representation between grid models and water management models, creating a need for appropriate coupling. As markets increasingly regionalize and create transfer opportunities for large hydropower, precise models that capture the local operational realities will be critically important. HydroWIRES is currently exploring model improvements to hydropower representation in production cost models and capacity expansion models through multiple, parallel avenues. Future work may include testing these improvements with end-users to validate and scope further improvements.

Sub-Activity 2.3 – Operations and Planning

Overview

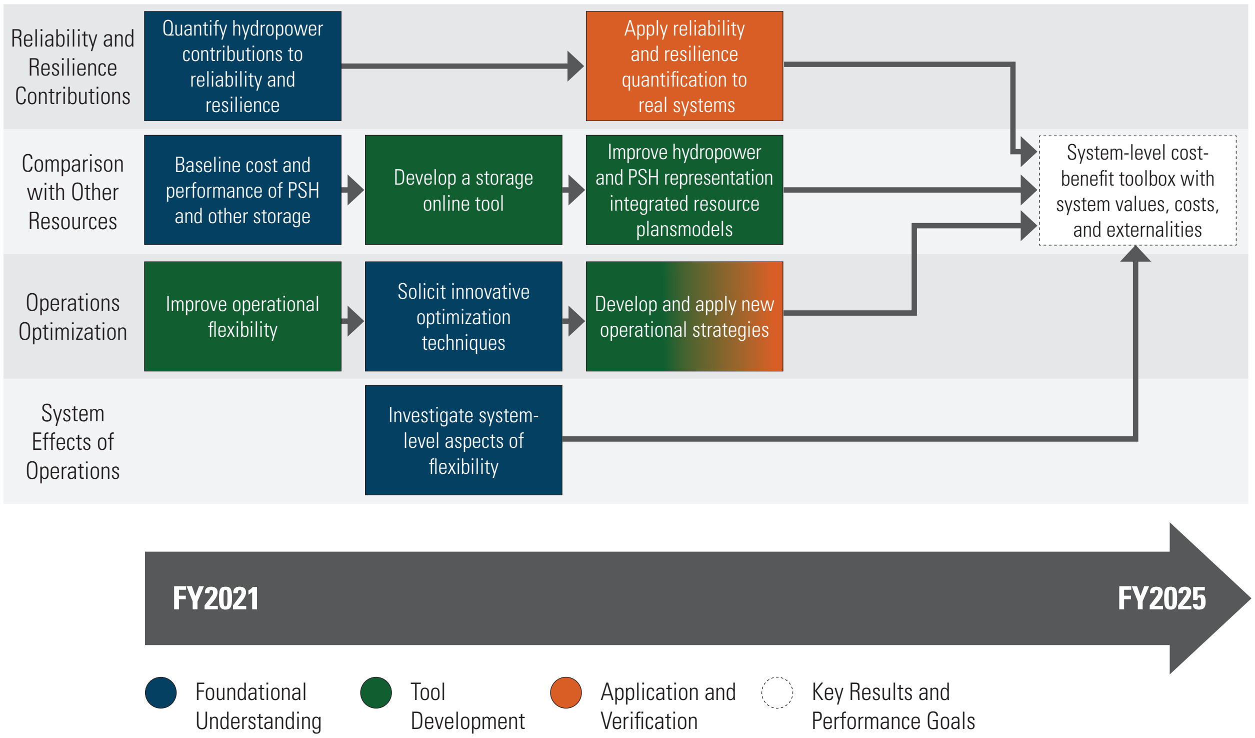
In addition to understanding the value of hydropower's flexibility and the fleet's technical ability to provide them under different circumstances, there is a need to better understand the competitive advantages and disadvantages that hydropower has in providing each of these services compared to other generation technologies for various system conditions. 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. This will be achieved through four technical objectives: (1) quantifying system reliability and resilience contributions; (2) comparing with other resources; (3) optimizing operations; and (4) quantifying system effects on operations.

FY 2021–2025 Research Priorities
The following are the research priorities that will be emphasized within the HydroWIRES Sub-Activity 2.3 – Operations and Planning:

- **Reliability and Resilience Contributions**
    - **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.
- **Comparison with Other Resources**
    - **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 comparisons.
    - **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 integrated resource plans**: Work with planners to apply modeling tools that more accurately capture hydropower and PSH in integrated resource planning processes.
- **Operations Optimization**
    - **Improve operational flexibility**: Support industry-led efforts to increase the operational flexibility of hydropower plants.
    - **Solicit innovative optimization techniques**: Solicit innovative optimization techniques from other fields 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.
- **System Effects of Operations**
    - **Investigate system-level aspects of flexibility**: Investigate the links between increased fleet-scale hydropower flexibility and system-level attributes of ecology, air quality, or water use.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 18.

Figure 18. Sub-Activity 2.3 – Operations and Planning Research Priorities



Additional Details

The first technical objective is to quantify hydropower plant- and fleet-level contributions to system reliability and resilience requirements. While certain metrics are well-established (loss of load probability, expected unserved energy) and new reliability metrics are under development, these measurements represent system capability and condition and do not give insight into how hydropower fleets and individual assets contribute to reliability and resilience. 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. Work is ongoing to develop a framework for quantifying hydropower and pumped storage contributions for reliability and resilience during adverse events. Future work may include technical assistance to end-users of reliability/resilience quantification tools and development of targeted improvements.

Not only is it important to characterize hydropower and PSH's various benefits and costs, but it is also important to put these in context through comparison with other resources to best inform planning decisions. While hydropower and PSH can provide a range of grid-system services, there are almost always other resources available that also can provide the same services. Therefore, there is a need to distinguish hydropower and PSH resources from other comparable technology solutions. Baseline work on identifying cost and performance parameters for PSH alongside other storage technologies has been completed and will feed the development of an online tool to inform utilities and developers. More work may also be directed toward capturing externalities for each technology type in these resource comparison studies in the future. In addition, targeted technical assistance efforts to utilities and regulators can support integrated resource planning processes and ensure the best available modeling tools are utilized to evaluate hydropower and PSH.

This sub-activity also seeks to develop operational strategies and associated tools that enable hydropower to better optimize its operations to provide grid services. At the plant level, the multi-objective nature of reservoirs creates challenges related to competing uses for water, which is further complicated in the case of cascading systems (i.e., rivers with multiple hydropower plants). Furthermore, this situation can lead to competition across different time horizons because an optimal strategy for the next day may be mutually exclusive with an optimal strategy for the next week. This objective seeks to enhance hydropower's potential utilization for grid services through new optimization approaches; develop an evolution of practice within operations modeling, computational improvements, and real real-time sensors; and advance other plant-specific techniques to address constraints or expand capabilities. Some work that analyzes operational strategies to maximize value of PSH plants under future grid scenarios has already been completed, and work on flexible operations of hydropower plants is ongoing. Technical assistance to owners and operators—to better optimize their systems and inform their decision-making regarding market decisions—may occur in the future.

The final technical objective of this sub-activity is to quantify effects of hydropower plant- and fleet-level operations on water availability, environmental, 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 important variables of sustainable energy and water systems. This technical objective is strongly linked with Activity 4 – Environmental and Hydrological Systems Science. For example, scientific studies to determine the impact of flexible operations on particular species, performed in Activity 4, will be incorporated into larger, flexibility cost-benefit and tradeoff tools in this area of work. 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.

Sub-Activity 2.4 – Technology Innovation

Overview

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 projects face significant deployment challenges including high capital costs and long lead-time to commissioning. HydroWIRES will support R&D for innovative technologies that improve hydropower capabilities to provide grid services, and support development of advanced PSH systems critical to drive the utilization of new PSH in the United States. This will be achieved through four technical objectives: identifying technology gaps, enhancing unit flexibility, enhancing plant flexibility, and developing new PSH approaches.

FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the HydroWIRES Sub-Activity 2.4 – Technology Innovation:

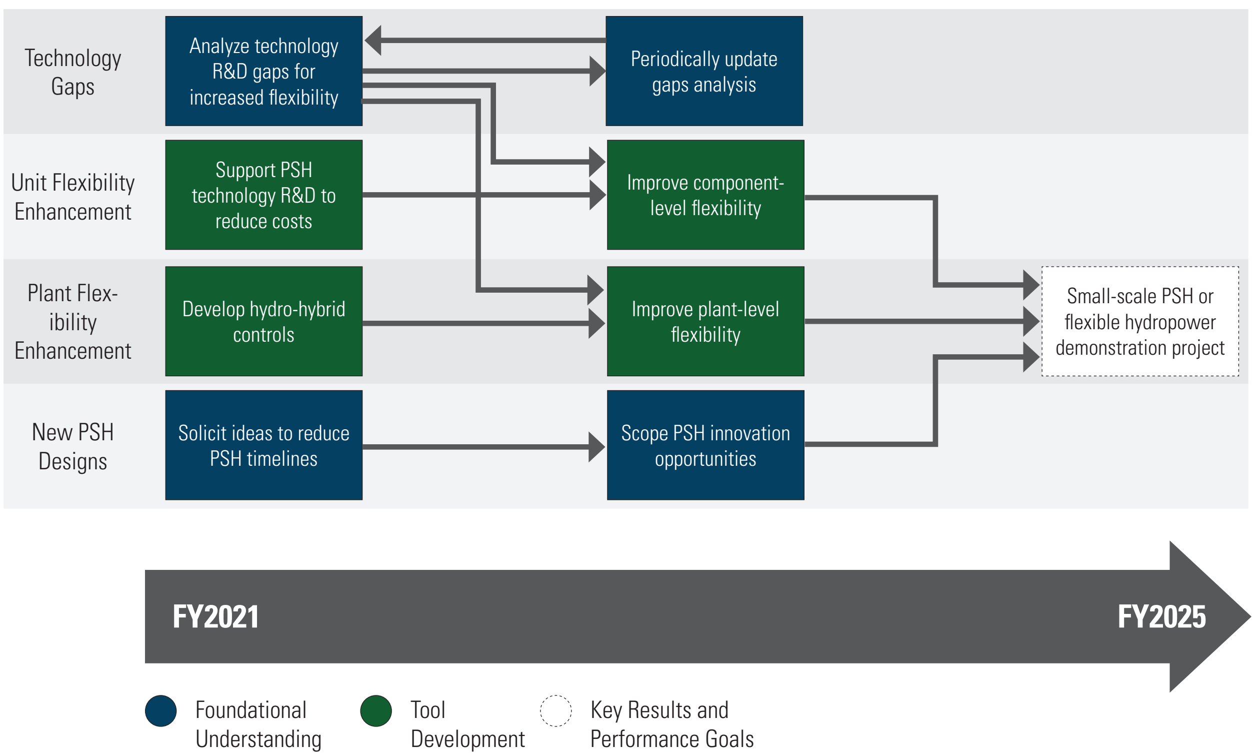
- **Technology Gaps**
  - **Analyze technology R&D gaps for increased flexibility**: Determine what technology gaps at the component- and plant-level could be addressed to enable increased hydropower flexibility.
  - **Update gaps analysis periodically**: Periodically update the gaps analysis to ensure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

- **Plant Flexibility Enhancement**
  - **Develop hydro-hybrid controls**: Develop 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.
- **New PSH Designs**
  - **Solicit ideas to reduce PSH timelines**: Solicit ideas from other industries and academia on how 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.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 19.

Figure 19. Sub-Activity 2.4 – Technology Innovation Research Priorities



Additional Details

The first technical objective is to identify and map out technology innovations that enable hydropower plants to improve provision of grid services. Work under this objective will take stock of the state-of-the-art hydropower technology, specifically focused on capabilities for enhanced flexibility or provisions of other emerging system needs. This bottom-up assessment of technology gaps will outline opportunities for targeted technology R&D and their respective impacts. Future work may enable greater flexibility, building on previous work in the portfolio,[58] and including rigorous assessment to determine viable innovation pathways.

Once gaps have been identified, this sub-activity will further develop technology solutions that enable enhanced flexibility at the unit level. 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, and/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. Previous work on this topic includes external funding opportunities for advanced PSH development and research into pump-turbines for geomechanical storage. In the future, this goal may be furthered with an investigation into hybrid hydropower use cases and technology R&D to enable increased flexibility at the unit level, such as turbine design or penstock/draft tube architectures.

Complementing Sub-Activity 2.3 – Operations and Planning, this sub-activity will develop technology solutions that enable enhanced flexibility at the plant level. This objective builds from the gaps 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. Innovations 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. Work is currently being done on the Hydropower and Energy Storage Systems project to combine hydropower with batteries, flywheels, or ultracapacitors to provide additional system services. More targeted technology R&D to enable increased plant flexibility is expected in the future.

The final technology objective in this sub-activity is to develop new technology concepts and approaches that overcome barriers associated with PSH deployment. There is little public information available about new designs that could offer benefits of pumped storage at competitive costs. To investigate such opportunities, this objective seeks radically new designs in PSH 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. Currently, a baseline report on reducing the time to commissioning of new PSH projects, including analytical work on reducing excavation costs and novel technology configurations, is in progress. Potential future work could include small-scale PSH testing and demonstration for innovative technologies.

[58] For example, the Energy Storage Technology and Cost Characterization Report provides a basis of understanding for which technology gaps prevent PSH from being competitive with other storage alternatives.

Opportunities for Hybridization of Hydropower Assets

As the energy mix evolves to increased diversity of resources, there is an opportunity to integrate these resources at the point of interconnection to better take advantage of their unique capabilities. HydroWIRES will perform valuation analyses to determine if pairing hydropower with different generating and/or storage assets can lead to a more reliable and flexible system than the standalone alternative. Examples of hydro-based hybrids include:

- **Hydro and Storage**: Integration of hydropower and other energy storage technologies provides synergies that increase the value of both asset classes and improves provision of grid requirements from existing hydropower plants. Adding energy storage technologies such as Lithium-ion batteries can increase the flexibility of hydropower over short to medium timescales, enabling it to provide frequency regulation; in a complementary way, hydropower provides a reliable and predictable source of generation for charging the energy storage devices. The benefits of hybrid hydropower and storage systems will vary based on the market/power system context. In restructured markets, the benefits are principally revenue-driven as a result of participating in additional ancillary service markets, such as frequency regulation. In regulated markets, the hybrid system can provide an alternative paradigm for utilizing existing hydropower plants to meet reliability requirements. In microgrids, the system can provide power quality stability, decrease cost of operation, and enable greater deployment and operation of variable generation resources.
- **Hydro and Floating Solar Photovoltaics (or "floatovoltaics")**: Hydropower's flexibility makes it amenable to balancing the variable generation of solar plants, and in some cases, physically co-locating solar PV by floating it on a hydropower reservoir can provide benefits. In addition to operational complementarities, there are advantages of floating solar over land-based systems, including reduced reservoir evaporation and higher PV efficiencies due to cooling. In the case of PSH, floatovoltaics also provide a renewable energy source in situ to offset pumping costs.

Hydropower Program Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity

Overview

The Hydropower Program supports analysis, research, and development in three areas: (1) modernization; (2) maintenance; and (3) cybersecurity. Modernization refers to upgrading or adding new hydropower system capabilities. In the next five years, the modernization portfolio will primarily focus on hydropower fleet digitalization. Digital transformation refers to the application of digital capabilities to not only solve traditional challenges for hydropower but also enable access to a new range of opportunities for the industry. This is the initial focus of the modernization work because it represents one of the broadest opportunities for improvement in the hydropower sector, with the potential to reduce operation costs, improve system performance through continuous assessment and predictions, and ensure inter-generational knowledge retention. Maintenance research focuses on understanding and improving the specific procedures surrounding the preservation of hydropower systems. Maintenance represents the broadest component of asset management, where routine servicing to the system will maximize the remaining useful life of the asset. However, performance degradation or risk of failure will eventually require that the component be refurbished (activities intended to remove operational damage and increase remaining useful life) or replaced. Cybersecurity research focuses on assessing the complex regulatory landscape and helping asset owners to determine the possible benefits of different cybersecurity investments. This work includes the development of cyber surrogate capabilities, which are systems designed to help identify intrusions into the hydropower network by assessing aberrant network traffic or inconsistencies in system signals/operation. This is particularly valuable given both difficulty in incident identification and the potential long period between a malicious action and its detection.

Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity consists of the following sub-activities:

1. Modernization: Integrating digital capabilities into the hydropower industry to streamline workflows, reduce risks, and reduce costs through holistic monitoring and management of hydropower systems, as well as enabling the hydropower operators to take full advantage of digital solutions appropriate for specific sites.
2. Maintenance: Baselining maintenance costs, improving condition assessment datasets, and benchmarking causes of hydropower plant outages.
3. Cybersecurity: Maintaining hydropower plant security as facilities become increasingly connected to both digital systems and broad communication and control networks.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 16.

Table 16. Fleet Modernization, Maintenance, Cybersecurity Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Develop and make publicly available hydropower digital twin[59] capabilities (e.g., numerical models, computational codes, and underlying physics/engineering data) appropriately scaled for a diverse range of hydropower plant characteristics and operational profiles. • Publish valuation assessment guidance to facilitate right-sized investments into hydropower digitalization, maintenance, and cybersecurity. • Complete initial phases of research on fatigue and wear mechanisms for high-impact hydropower components, including both conventional and advanced materials, which can reduce forced outage instances and help design the next generation of hydropower components. • Develop hydropower plant cyber surrogate capabilities[60] that can be integrated into existing cybersecurity processes and reduce hydropower plant vulnerabilities.
Follow-On Objectives (2026–2030)
• Asset owners and equipment designers widely utilize new, open-access digital twin capabilities in efforts to improve system/administrative scheduling and condition-based predictive maintenance. • Demonstrated use of new valuation methodologies in hydropower plant capital planning processes as well as the use of these capabilities to identify cost reduction and capability improvement opportunities. • Use of better articulated wear/fatigue mechanisms by asset managers in maintenance scheduling as well as the integration of these insights into plant dispatch strategies. • Integration of cyber surrogate capabilities into hydropower cybersecurity processes to facilitate the rapid identification cybersecurity intrusions and improve overall system security.

Additional Details

Dams and reservoirs serve many purposes beyond hydropower generation, including recreation, fish and wildlife support, flood management, agricultural irrigation, drinking water supply, and cooling water for thermal plants. The average U.S. hydropower facility has been operating for over 64 years,[61] and as the fleet ages, it is critical to modernize facilities and incorporate state-of-the-art capabilities into hydropower infrastructure to ensure the nation can continue to have access to the wide breadth of benefits hydropower provides. Modernization of electrical, mechanical, and civil systems can improve efficiency and generation, increase system and grid reliability, enable new value propositions, and ensure critical infrastructure security. Effective modernization research first requires the development of landscape assessments to clearly articulate the state of the industry. Landscaping assessments can occur in parallel to the development of industry accessible valuation capabilities to clearly outline the costs and benefits that modernization would represent. Both the landscaping and valuation efforts are high-impact, short-term activities. In addition, these efforts help highlight the opportunities for new impactful research in hydropower digitalization, maintenance, and cybersecurity. The development of new capabilities (both tools and technologies) is also an integral component of Activity 3 – Fleet Modernization, Maintenance, and Cybersecurity. The development of new capabilities recognizes the importance of supporting systems throughout their maturation. Demonstration of new capabilities performance and benefits is particularly critical to ensure a smooth transition to industry adoption.

[59] Digital twins are mathematical based representations of systems that can be used in a host of applications including operations planning, assessing the impact of market entry, and upgrade/modernization investments.

[60] Cyber Surrogate capabilities are systems designed to help identify intrusions into the hydropower network by assessing aberrant network traffic or inconsistencies in system signals/operation.

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

As stated above, digitalization will represent the initial focus of the modernization effort given its significant potential to improve outcomes. This research will adapt and adopt capabilities from other, relevant sectors where possible and will consider how the capabilities produced by funded research can advance outcomes in other industries. Digitalization solutions from other relevant sectors, such as other forms of power generation, includes advanced sensing and signals processing capabilities. However, in many instances these need to be adapted to recognize both the varying structure of hydropower plants and the distributed nature of hydropower facilities, whereas the "digital footprint" for other industries tends to be much more repetitive and localized. Solutions in this diverse and distributed space can then be transferred to other industries with similar issues such as transportation and water infrastructure.

Maintenance research focuses on understanding and improving the specific procedures surrounding the preservation of hydropower systems. Maintenance represents the broadest component of asset management, where routine servicing to the system will maximize the remaining useful life of the asset. However, performance degradation or risk of failure will eventually require that the component be refurbished or replaced. These maintenance practices balance the need to service equipment to ensure system availability/performance and limit the risk of failure with both constrained resources and the desire to limit outage of the plant to perform the maintenance. To help the industry better strike this balance, WPTO works to: (1) improve condition assessment to determine component health more accurately; (2) develop novel condition monitoring capabilities to better assess a wide array of critical components; and (3) advance system wear/fatigue modeling to better understand how O&M practices contribute to the loss and preservation of system life. The enhanced information provided by this effort can be integrated into existing industry asset management practices and will enable more accurate decision making.

Cybersecurity research focuses on assessing the complex regulatory landscape and helping asset owners to determine the possible benefits of different cybersecurity investments. Furthermore, cybersecurity research focuses on leveraging relevant technologic solutions from other industries as well as developing novel capabilities uniquely suited for the diversity of hydropower infrastructure. This work includes the development of cyber surrogate capabilities, which are systems designed to help identify intrusions into the hydropower network by assessing aberrant network traffic or inconsistencies in system signals/operation. This is particularly valuable given both difficulty in incident identification and the potential long period between a malicious action and its detection.

These research efforts are designed to produce studies that holistically represent the state-of-the-industry and convey the value proposition of effective security, digitalization, and maintenance. This work will help ensure that solutions produced are "right-sized" based on both the future benefits they can provide and their associated costs. "Right sizing" specifically refers to the fact that the solutions will be applicable to many different scales and characteristics of hydropower facilities. In the long-term, the security, digitalization, and maintenance efforts aim to safeguard increasingly interconnected hydropower infrastructure, improve the value of operational paradigms, and reduce operation and maintenance costs, while improving system performance.

Sub-Activity 3.1 – Modernization

Overview

This research focuses on two efforts—digital twin capabilities development and enabling digital transformation. The latter of these refers to the integration of digital capabilities into the hydropower industry to streamline workflows, reduce risk, and reduce costs through holistic monitoring and management of hydropower systems. The Hydropower Program's overall hydropower digital transformation work will focus on enabling the hydropower operators to take full advantage of digital solutions appropriate for specific sites. In the short term, the Hydropower Program will conduct an assessment to fully describe the range of digital solutions and their relative applicability to different hydropower facilities. The fundamental barriers to uptake are a basic lack of information, such as costs, benefits, and applications, and lack of industry consensus on the opportunities and processes to integrate digital solutions into hydropower systems. The information from this broad assessment will be leveraged in subsequent efforts, which will develop a means to document the value of digitalization for hydropower facilities to help reduce the risk of uncertain return on investment into digital systems. Research in this area will culminate with an effort to enable a broader digital transformation of hydropower. While prior efforts largely focus on analyzing the applicability and value of existing capabilities, this work will be targeted at developing new digital solutions (or adapting capabilities from other industries). Work in this space will include improving return on investment via the refinement of supply/demand forecasting for system dispatch, reducing operational costs through system automation and remote operation, and increasing safety for operations staff.

FY 2021–2025 Research Priorities

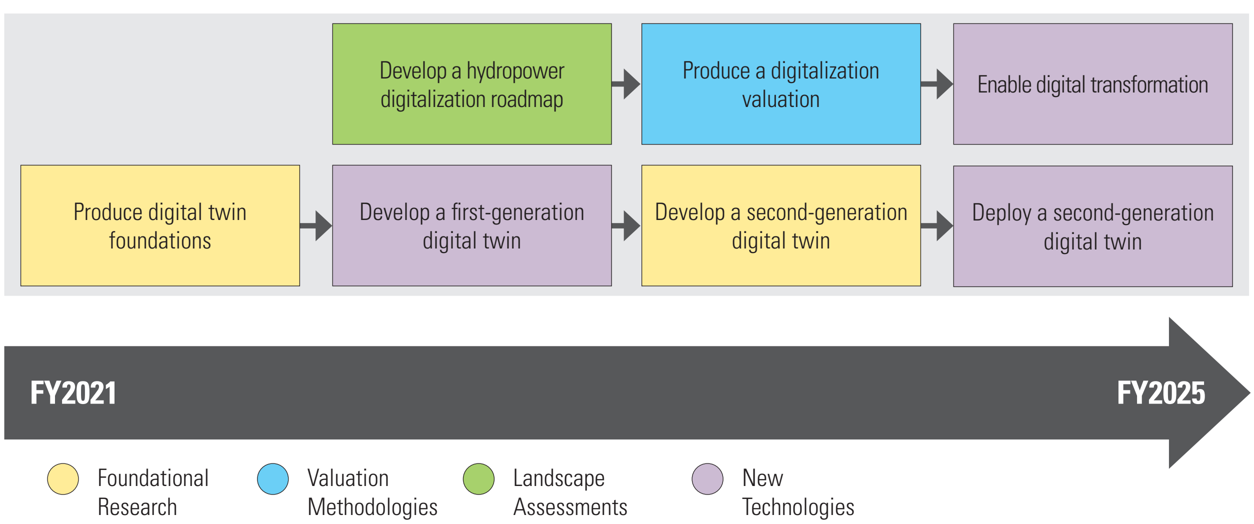
The following are the research priorities that will be emphasized within the Sub-Activity 3.1 – Modernization.

- **Develop a hydropower digitalization roadmap**: Assess the applicability of various digitalization solutions to the hydropower fleet and document the implementation and integration process.
- **Produce a digitalization valuation**: Produce an industry-accessible means to document the value of different digitalization opportunities.
- **Perform a digital transformation**: Leverage prior efforts to develop the capabilities necessary to enable digital transformation, drive-value propositions.
- **Produce digital twin foundations**: Produce the coupled mathematical models that represent hydropower plants to create the foundations of hydropower digital twins.
- **Develop a first-generation digital twin**: Utilize the digital twin foundations to develop a first-generation hydropower digital twin.
- **Develop a second-generation digital twin**: Utilize the lessons learned from the first-generation digital twin to refine the underlying principles and application processes.
- **Deploy a second-generation digital twin**: Deploy the second generation of hydropower digital twins.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 20.

Figure 20. Sub-Activity 3.1 – Modernization Research Priorities



Additional Details

As stated above, the modernization of hydropower plants entails a broad swath of options from exchanging legacy mechanical hardware for newer systems to installing next generation system controls. Given this wide range of opportunities, the Hydropower Program has elected to focus primarily on digitalization within the scope of the MYPP. This focus on digitalization is based on the wide range of opportunities that it presents to the hydropower community and that many facilities are in various stages of digitalization. It should be noted that in the future, the breadth of the modernization work will likely evolve or expand to encompass a broader range of research opportunities (contingent on budget availability). Hydropower plant digitalization research is focused on the conversion of legacy systems to integrated digital capabilities, and the use of this unprecedented volume of new data that this provides to significantly improve hydropower outcomes, such as reducing costs, improving reliability, and increasing revenue. As the hydropower industry enters a new century of service, traditional operational practices must be updated to enhance technological competitiveness and enable hydropower facilities to maximize performance under increasingly complex operational, social, and environmental considerations. System digitalization can enable this by not only increasing the efficiency of current practices, but also by enabling novel capabilities and benefits that hydropower plants were unable to unlock previously. However, it is important to recognize the importance of ensuring “right-sized” solutions—or solutions that appropriately balance the resources necessary to implement the capability, the value provided by the solution, and the ability of the organization to appropriately manage the capability—given that hydropower facilities operate over a wide range of sizes, operational constraints, maturity, and resource availability. Given the broad impacts and potential benefits of digitalization, there is also overlap with several other activities. Notably, digitalization can play a significant role in the design and monitoring of next generation hydropower (Sub-Activity 1.1 – New Technologies and Advanced Manufacturing), and digitalization of hydropower plant controls can potentially have significant effects on unit and asset flexibility (Sub-Activity 2.4 – Technology Innovation).

The other primary focus of research is the development of digital twin capabilities. These are extremely useful tools which have been leveraged in many other industries but have largely not been utilized for hydropower systems due to the diverse nature of hydropower plants and the disparate nature of data needed to inform these models. While digital twin capabilities have been investigated in a preliminary fashion for the hydropower industry, this approach to the research is limited to specific facilities only and is not widely applicable to other locations. The proposed R&D noted here is focused on developing publicly available underlying capabilities, which can then be applied to the broader hydropower fleet. These “open source” capabilities will facilitate the democratization of digitalization, as the publicly available nature of this information will allow owners/operators to better benefit from their own data as well as provide the hydropower industry with a common foundation upon which they can build a myriad of novel capabilities. Supported by prior efforts, (including HydroSource, mapping of Cyber-Physical Structures, and a partnership with the Hydropower Research Institute) WPTO now has the necessary insight and convening power to gather the requisite information as well as the scientific capabilities to develop solutions that will be applicable to the broader fleet. This work will initially be focused on investigating hydropower systems and developing the mathematic-/engineering-based models necessary to fully describe the broader hydropower fleet. These underlying models will be developed in such a way that will accurately describe generalized classes of hydropower facilities that can later be tailored to specific facilities using project-specific data and information to calibrate and train the models. Once the generalized models have been developed, the first-generation digital twin representations will be deployed to specific hydropower facilities to test the viability of the models. Then, the results (and lessons) will be utilized to further refine the tools to improve accuracy and increase broad applicability to other hydropower facilities. The second-generation digital twin will then be developed and deployed to a wider range of hydropower plants to provide the hydropower plant owners and operators with new and more valuable information necessary to improve hydropower plant value.

Sub-Activity 3.2 – Maintenance

Overview

Efforts in this sub-activity capitalize on a rich history of foundational, asset-management research funded by WPTO. This historic work includes significant effort in baselining maintenance costs, improving condition assessment datasets, and benchmarking causes of hydropower plant outage. This work entailed significant input and coordination with numerous owners, regulatory agencies, and industry groups. The initial effort moving forward will focus on transforming the broader historical research effort into a specific, high value, capability which owners and operators can use in their standard asset management decision-making process. In the immediate and medium term, this capability is aimed at articulating the impact of dispatch variability on system costs, condition, and reliability. Articulating the impact is important to the hydropower industry as operations are becoming increasingly varied to facilitate the integration of variable renewables. This work has particular applicability to Sub-Activity 2.4 – Technology Innovation (under Grid Reliability, Resilience, and Integration). However, this work exclusively focuses on the nuances of system fatigue and reliability reduction whereas HydroWIRES focuses on the broader universe of flexible operation. Hence, reduced-order maintenance-focused data and models will likely be incorporated into broader HydroWIRES efforts.

FY 2021–2025 Research Priorities

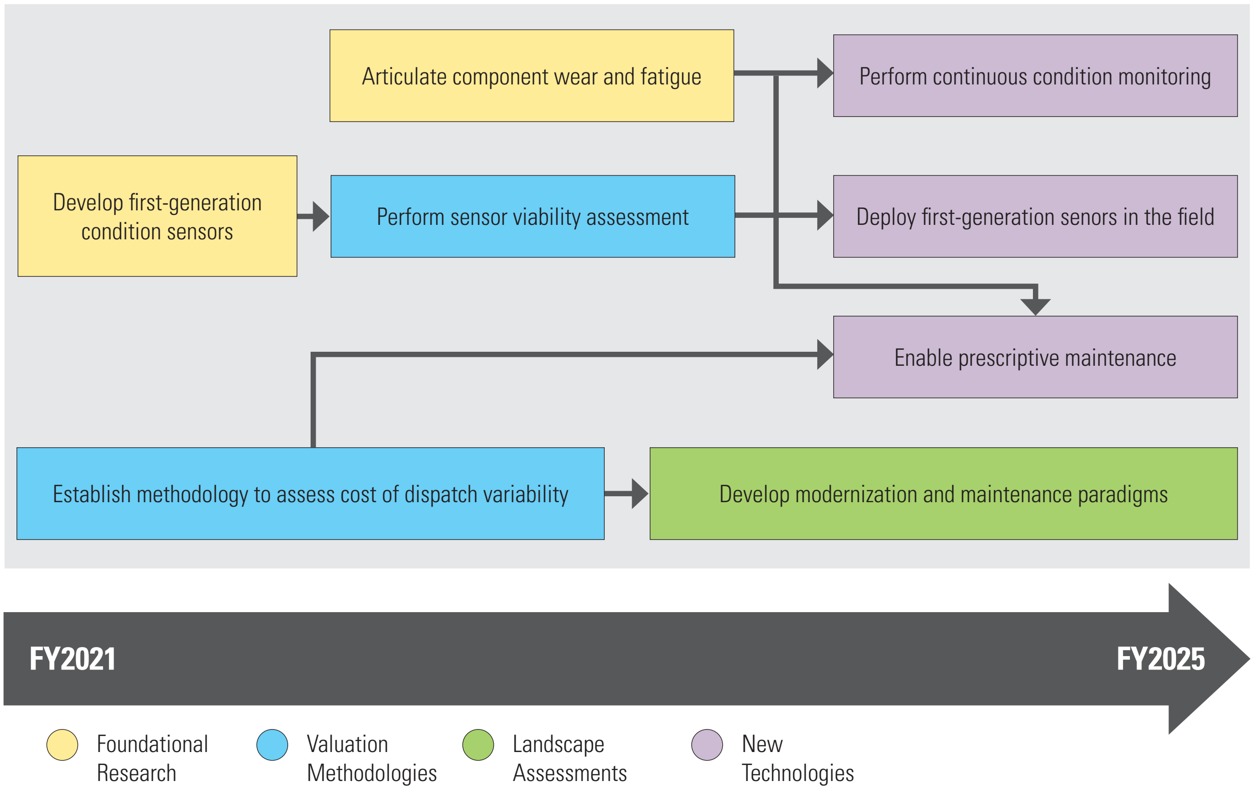
The following are the research priorities that will be emphasized within the Sub-Activity 3.2 – Maintenance:

- **Articulate component wear and fatigue**: Articulate the wear and fatigue mechanisms of critical hydropower plant components necessary to understand component reliability.
- **Perform continuous condition monitoring**: Create capabilities to continuously monitor asset condition and document operation within acceptable parameters.
- **Develop first-generation condition sensors**: Develop first-generation condition assessment sensors capable of improving and/or expanding monitoring capabilities.
- **Perform sensor viability assessment**: Assess the economic and performance viability of novel sensor capabilities.
- **Deploy sensors in the field**: Deploy sensors in the field to gather critical performance and reliability data.
- **Enable prescriptive maintenance**: Enable data-driven maintenance practices based on component health, risk of failure, and downtime coordination.
- **Establish methodology to assess cost of dispatch variability**: Create a methodology to assess the impacts of dispatch variability on cost, condition, and reliability.
- **Develop modernization and maintenance paradigms**: Produce guidance on the processes and trade-offs associated with modernization, overhaul, and maintenance decisions.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 21.

Figure 21. Sub-Activity 3.2 – Maintenance Research Priorities



Additional Details

Effective hydropower plant maintenance requires a combination of repairing and replacing system components as they age and lose effectiveness. Maintenance decisions must balance the risk of component failure and the associated cost of reduced performance against limited resources and outage planning. In addition, these decisions must be made under a range of uncertainties from both historic operation and current condition assessments. There is significant value to the hydropower industry from WPTO-funded research to develop data-driven solutions for asset maintenance planning and improving the understanding of the complex wear mechanisms of hydropower components. This research strategy will be effective in helping reduce the uncertainly and lost revenue potential associated with asset management decisions. Research reducing the O&M costs are particularly valuable for the hydropower industry, as the 2017 Hydropower Market Report indicated that O&M costs have grown 30 to 40 percent over the last decade for small, medium, and large hydropower facilities. This rate of increase significantly outstrips the growth of the Consumer Price Index.[62] Research in this area recognizes the site-specific nature of hydropower plant configurations, the diverse operational history, and the importance of engaging the broader hydropower industry and asset management community (including the Electric Utility Cost Group, the Center for Energy Advancement through Technological Innovation [CEATI], the North American Electric Reliability Corporation–Generating Availability Data System, and a host of utilities).

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

Information gathered through the application of the variability dispatch valuation methodology—as well as the broader asset management effort—will then be consolidated, along with other information, to produce industry guidance on maintenance and upgrade decisions. This guidance will clearly outline the decision making and administrative processes regarding maintenance and upgrade activates for various hydropower plant systems. This guidance will also help provide original equipment manufacturers with better visibility into the decision-making processes of asset operators and thereby provide more tailored solutions for future hydropower technologies.

In addition to this focus, the Hydropower Program is investing in sensors research to assess the condition of hydropower plants more reliably. The initial research will be targeted towards early-stage sensor concepts to gather fundamental data on performance, impact, and costs. In the medium term, the initial research will then be expanded to gather more detailed performance information and to document the ability of these sensors to provide sufficient benefit to justify their expense. Once the medium-term research has been performed, the Hydropower Program will partner with the hydropower industry and test first-generation sensors in the field to gather further information and to help build confidence regarding sensor efficacy and safety. The solutions developed from this initial deployment should be sufficiently mature to warrant commercial uptake to benefit the hydropower industry more broadly.

Finally, the Hydropower Program will begin efforts to better understand the fundamental wear and fatigue mechanisms of hydropower components. Full articulation of these processes is critical to assessing the remaining useful life of hydropower plant components and structures. While traditional efforts in this area have focused on a “top down” empirical modeling approach, data have been historically inadequate to fully document the processes. As a result, efforts will focus on a bottom-up physics- and experimental-based approach to ensure that system degradation is appropriately captured. This effort will begin with detailed investigations to the wear and fatigue mechanisms of high-impact components. The development of these models will help better articulate component reliability. The results of this effort will then be leveraged to develop a methodology to assess asset condition based on available data. This assessment methodology will recognize both the need to develop reduced order models, which do not require significant time and computational resources, as well as the fundamental lack of high-resolution historical data for a vast majority of components. The reduced order models will enable these assessments to be applicable to a majority of hydropower plants and thereby will have a broad impact on the hydropower industry.

Sub-Activity 3.3 – Cybersecurity

Overview

The cybersecurity sub-activity focuses on maintaining hydropower plant security as facilities become increasingly connected to both digital systems and broad communication and control networks. The work under this effort will involve the broad range of stakeholders in hydropower cybersecurity and leverage WPTO’s core hydropower technology capabilities with the broader cybersecurity expertise elsewhere in DOE, other federal agencies, and industry. Cybersecurity research focuses on conveying the complex impact propositions and process of hydropower plant security and then leveraging the lessons learned to produce novel technical capabilities—which the hydropower industry can apply to its diverse range of cyber structures. These efforts will initially entail a multi-year effort designed to articulate the value proposition of investing in cybersecurity upgrades. Created with the industry in mind, this methodology will enable ready comparison of these investments to other capital planning efforts, thereby enabling decision makers to efficiently dedicate resources. In addition, initial efforts during the multi-year period include documenting the status and trends of cybersecurity in the hydropower industry. This work will enable visibility on the complex hydropower cybersecurity landscape, a factor which has been widely acknowledged as a bottleneck to advancing the state of the art.

FY 2021–2025 Research Priorities

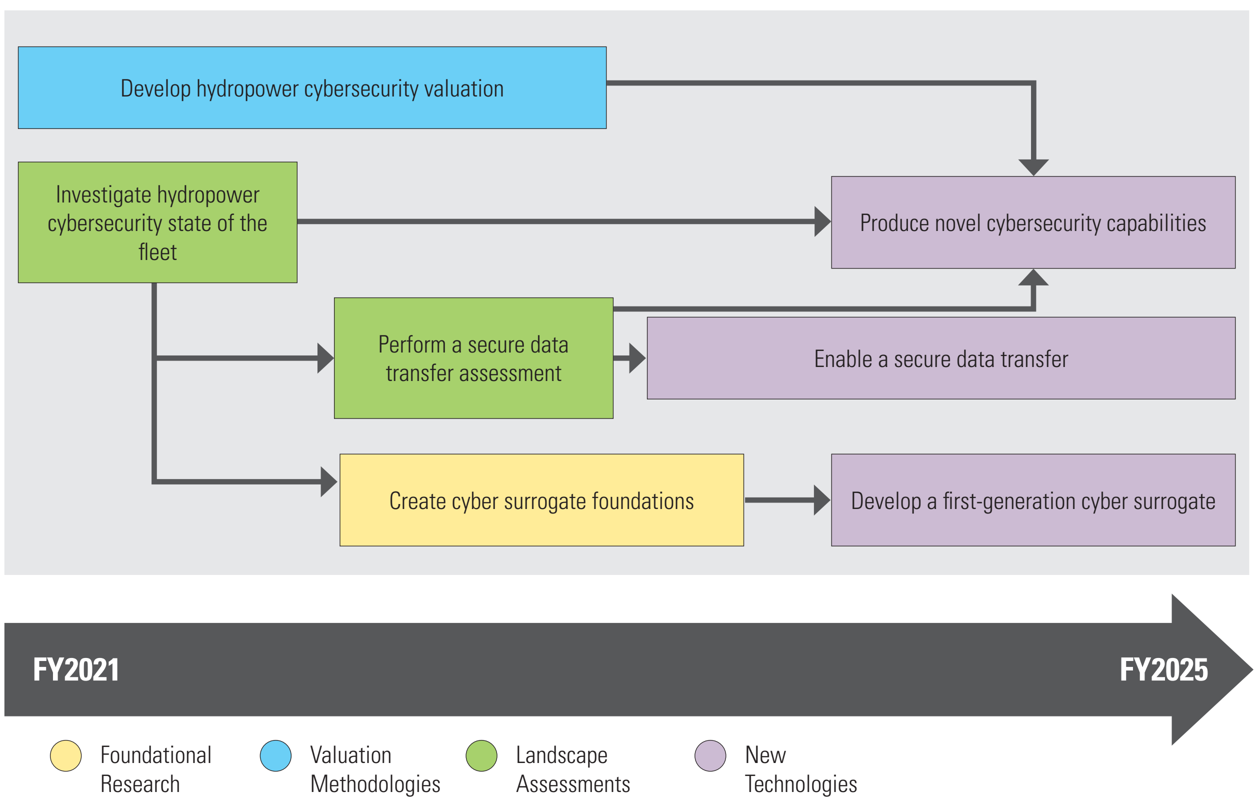
The following are the research priorities that will be emphasized within the Sub-Activity 3.3 – Cybersecurity:

- **Develop hydropower cybersecurity valuation**: Develop an industry accessible hydropower valuation method to enable informed investments in security improvements.
- **Investigate hydropower cybersecurity state of the fleet**: Investigate the hydropower fleet cybersecurity status and highlight opportunities for growth.
- **Perform a secure data transfer assessment**: Document existing capabilities for low latency data transfer and their applicability hydropower applications.
- **Enable a secure data transfer**: Enable and develop the use of low latency secure data transfer to be used in hydropower plant operation and decisions.
- **Create cyber surrogate foundations**: Create capabilities to document relevant system process foundation to developing a cyber surrogate.
- **Develop a first-generation cyber surrogate**: Develop first-generation cyber surrogate capabilities and assess its performance and develop lessons learned.
- **Produce novel cybersecurity capabilities**: Produce novel cybersecurity capabilities which can be integrated with a diverse set of preexisting cybersecurity process and structures.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 22.

Figure 22. Sub-Activity 3.3 – Cybersecurity Research Priorities



Additional Details

It should be noted that WPTO is making an active effort to coordinate efforts with other actors in this space, including the Department of Homeland Security (DHS); FERC; the Office of Cybersecurity, Energy Security, and Emergency Response (CESER); industry working groups; and individual owners. This coordination is foundational to ensuring uptake of the capabilities produced, as well as that the work sponsored by WPTO builds upon the office's unique capabilities and focuses on the most impactful areas in this space. Engagement with these partners is achieved in three primary ways: bilateral presentations of WPTO's and the other organization's portfolio followed by discussion of value proposition and next steps; presentations to working groups with broad representation such as CEATI's Infrastructure Protection and Security Interest Group and DHS's Dam Sector Cybersecurity Working Group; and engagement during the research process. The last of these is particularly important, as working with industry is foundational to getting the necessary information for research and has an additional benefit of facilitating uptake of the capabilities produced by WPTO.

This research will then help inform subsequent efforts focused around two high-value efforts that the Hydropower Program wishes to promote: secure data transfer and cyber surrogate development. Secure data transfer is extremely important because data transfer must be both high-speed (known as low latency) and secure for hydropower plants to take advantage of advanced analytics and cloud computing. While advanced analytics and cloud computing could be applied to a myriad of different hydropower systems, they are particularly applicable to fault detection and improved system dispatch. Initial research efforts will focus on documenting the state-of-the-transfer technology, its relative security, and its applicability to hydropower plants. In later stages of this effort, the research will be focused on demonstrating the application of this technology to hydropower facilities, providing insight into best practices, and integrating these capabilities with new technology.

In addition to data transfer technology, this sub-activity will begin developing cyber surrogate capabilities for hydropower facilities. These surrogates are designed to document the network and signal paradigms over a range of operating conditions and leverage an established baseline to act as an early warning system for network intrusion. Effective intrusion detection is particularly important as it can take many months to identify, a period in which the facility is uniquely vulnerable to malicious actors. Initial stages of this work will be focused on developing network communication and system operation baselines—mostly focused on operational technology components of the hydropower system—and abhorrent signal detection capabilities, which can be applied to a wide range of hydropower plants. Once this has been done, the prototype capability will be applied to a hydropower plant to help refine both the technology and the application process. The overall cybersecurity effort will then culminate in the development of active defense capabilities, which can be readily applied to the overall hydropower fleet. These active defense capabilities will help the hydropower industry move beyond its traditional layers of parameter-based defense and will provide dynamic and proactive security measures.

Hydropower Program Activity 4 – Environmental and Hydrologic Systems Science

Overview

While hydropower has tremendous value to the power system as a flexible, renewable resource, its long-term value is dependent on maintaining a high level of environmental performance across the fleet. The Hydropower Program develops new technologies, tools, and data to better understand and improve the environmental performance of hydropower facilities. WPTO's work focuses particularly on issues related to fish passage, water quality, and water release management. In addition, this activity area aims to provide a better understanding of potential climate impacts and risks associated with climate change and hydrologic variation. WPTO's initiatives seek to understand the physical risk to current hydropower and develop the climate risk strategies and decision-making tools to ensure future reliability, performance, and energy services provided by hydropower in supporting a 100% renewable future. Environmental and Hydrologic Systems Science focuses on: (1) developing monitoring and mitigation technologies to improve environmental performance; (2) supporting foundational and applied biological, environmental, and hydrologic systems science research to understand environmental impacts; and (3) establishing relevant standardized metrics to understand environmental impacts and improved performance.

Activity 4 – Environmental and Hydrologic Systems Science consists of the following sub-activities:

1. R&D to Improve Environmental Performance: Improving understanding of fish movement, habitat use, and survival through the development of advanced monitoring technologies, relevant metrics, and other impact assessment tools.
2. Hydrologic Systems Science: Addressing fundamental questions of hydrologic variation, impacts on ecosystems, and risks for operations and engineering of hydropower systems.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 17.

Table 17. Environmental and Hydrologic Systems Science Performance Goals and Objective

Key Results and Performance Goals (2021–2025)
• Complete field validations of novel and improved fish detection and tracking capabilities relevant for hydropower studies, including demonstration of environmental DNA and prototypes of acoustic telemetry tags for sensitive species and a self-powered acoustic fish tag. • Demonstrate innovative tools and technologies that are benchmarked for cost and performance, including innovative fish passage technologies and sensor systems. • Demonstrate real-time data collection, automation, and visualization to inform decision makers' choices to operate hydropower resources for enhanced environmental performance in water and species management. • Release a nationwide analysis and visualization platform that enables utilities and system operators to evaluate potential long-term water availability and climate change related risks to existing and new hydropower assets at meaningful local or regional scales. • Validate new technologies to more accurately characterize and model methane emissions from reservoirs and other water bodies.
Follow-On Objectives (2026–2030)
• A suite of demonstrated, cutting-edge tools and technologies for hydropower-specific environmental monitoring, mitigation, and decision-making that enable accurate data collection and predictive outputs with reduced cost and time and can be utilized for community developed standardized processes and FERC relicensing. • Quantifiable improvements in fish passage performance that can be linked to established fish population and restoration goals. • Documented improvements in real-time data collection and accuracy for species of concern and other environmental variables that inform hydropower operations and management. • Better understanding of the risks of long-term hydrologic variations to hydropower generation and flexibility and documented incorporation into licensing or other planning processes. • Accurate and widely agreed-upon characterization of methane emissions from U.S. reservoirs.

Additional Details

Efforts to improve sustainability and environmental performance of the nation's hydropower systems are inherently linked to modernization of the existing fleet, efforts to improve flexibility, and advancements necessary to develop additional low-impact hydropower. Additions of new hydropower may leverage existing infrastructure or be sustainably deployed in new areas if river functions and ecosystem services can be maintained or enhanced. Over the past decade, numerous advances in environmental monitoring technologies and data processing have occurred. Applied to hydropower, such techniques and tools enable more accurate evaluations of the potential environmental risks and impacts for species and water management.

Hydropower operations planning and investment need to appropriately incorporate advances in watershed science, hydrology, and river biogeochemistry to understand risks and opportunities for hydropower systems. Understanding the best available climate, hydrologic, and carbon cycle sciences will help advance our understanding of risks to hydropower generation and flexibility from long-term hydrologic variation, advance our understanding of water risks across plant and grid-scale energy systems, and develop methods to better assess, characterize, and contextualize reservoir methane emissions.

As noted earlier in this document, Activity 4 is crosscutting in nature and has many different ties to the work that will be undertaken in Activities 1-3.

Sub-Activity 4.1 – R&D to Improve Environmental Performance

Overview

The Hydropower Program provides information, data, and tools to the hydropower community that enable a better understanding of key environmental challenges, as well as technologies to monitor environmental performance and avoid, minimize, and mitigate impacts. This sub-activity is focused on improving understanding of fish movement, habitat use, and survival through the development of advanced monitoring technologies, relevant metrics, and other impact assessment tools. There is a large amount of synergy between these topics since monitoring and mitigation often go hand in hand and improvements are evaluated by relevant metrics.

Information from advanced monitoring technologies may also increase confidence in decision-making to reduce risk, provide better informed and more rapid impact evaluations, and provide more cost-effective solutions to better meet hydropower permitting and license requirements. Novel and applied monitoring and mitigation technologies have the potential to support the continued modernization of existing hydropower plants and inform basin-level planning and information needs to meet management objectives for healthy watersheds.

FY 2021–2025 Research Priorities

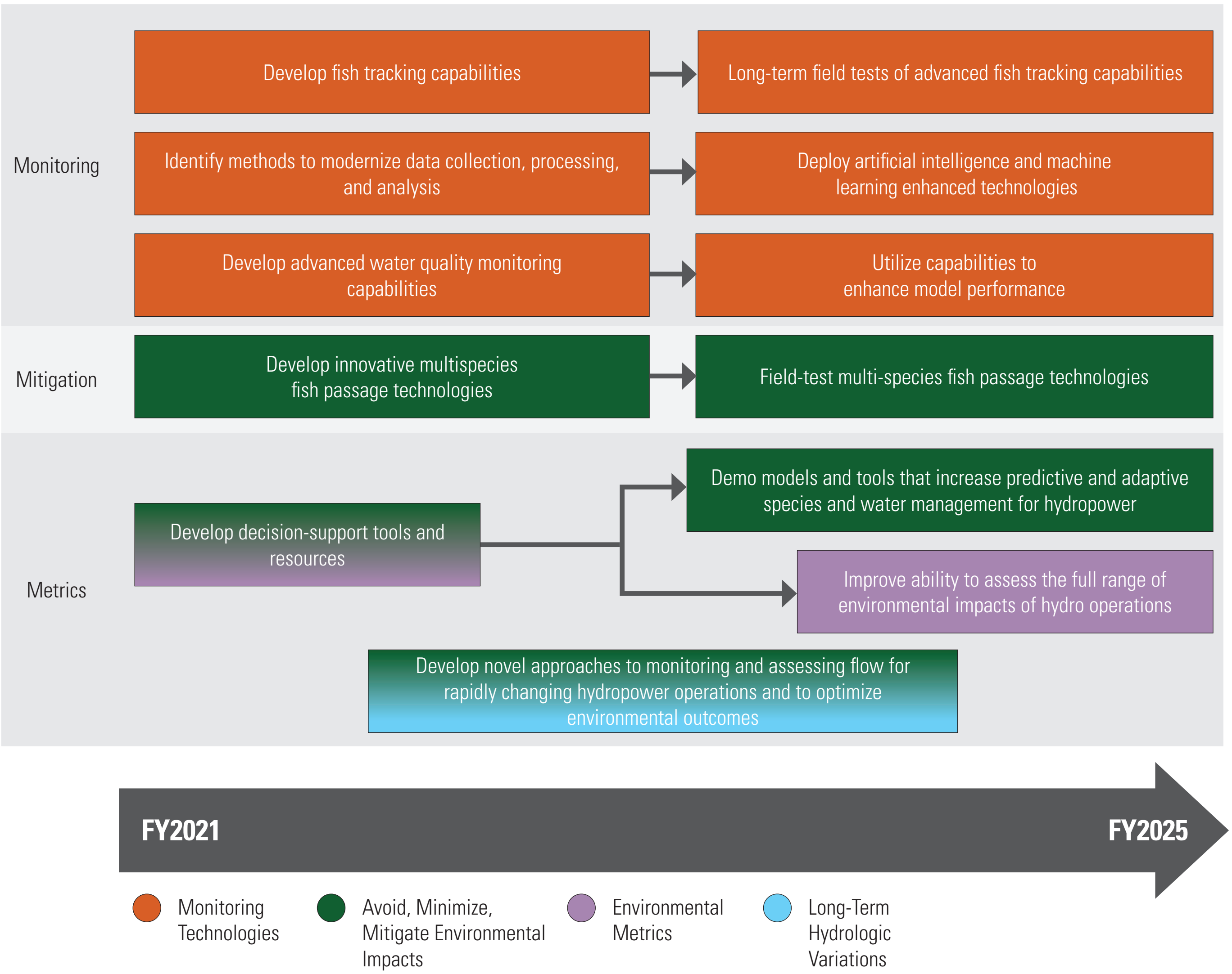
The following are the research priorities that will be emphasized within the Sub-Activity 4.1 – R&D to Improve Environmental Performance:

- **Monitoring**
    - **Develop fish tracking capabilities**: Provide more accurate and greater data for sensitive species over greater spatial and temporal scales.
    - **Long-term field tests of advanced fish tracking capabilities**: Conduct field tests to demonstrate advances in fish tracking capabilities.
    - **Identify methods to modernize data collection, processing, and analysis**: Identify and develop tools for data automation and investigate methods to apply artificial intelligence and machine learning for processing and analysis for rapid and real-time environmental assessments.
    - **Deploy artificial intelligence and machine learning enhanced technologies**: Demonstrate tools that utilize artificial intelligence and machine learning for environmental monitoring and quantify improvements in the data pipeline and cost reductions.
    - **Develop advanced water quality monitoring capabilities**: Research and prototype tools and technologies for more accurate and representative water quality measurements.
    - **Utilize capabilities to enhance model performance**: Develop more robust models and methods to inform real-time operations for improved water quality.
- **Mitigation**
    - **Develop multi-species fish passage**: Design and test innovative up- and down-stream fish passage technologies to support fish communities and prevent invasive species movements and investigate methods for relating technology choices to fish restoration goals.
    - **Field tests of multi-species fish passage technologies**: Quantify performance of innovative technologies and applied modeling capabilities to assess population-level impacts and restoration goals.

- **Metrics**
  - **Develop decision support tools and resources**: Provide information and science-based tools that utilize established environmental metrics and indicators.
  - **Access utility of tools in hydropower environmental assessments**: Demonstrate toolkits with hydropower stakeholders and assess capabilities to identify key environmental impacts and relevant mitigation methods.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 23.

Figure 23. Sub-Activity 4.1 – R&D to Improve Environmental Performance Research Priorities



Additional Details

WPTO efforts in this sub-activity are heavily focused on providing novel, fish tracking capabilities, advancing species detection methodologies, and providing novel sensors to assess core scientific and management questions. Activities also include developing applications to provide real-time and more robust data streams of key indicators of ecosystem health, such as dissolved oxygen. As technologies mature, the data may be applied to impact assessments and hydropower-specific monitoring for FERC licensing and compliance. The data may also be utilized to develop relationships for system-level understanding. The program regularly seeks both private and public partnerships to demonstrate the value of tools and real-time data for improved operations and management of fish passage, deployment of mitigation, and optimizing water releases for achieving both energy and environmental goals.

Monitoring

Since hydropower plants—and the environments they are deployed in—are extremely diverse, scientific knowledge gaps exist around biology, behavior, and interaction of many fish species with hydropower facilities. Core objectives for species monitoring include development of capabilities to monitor fish over larger spatial and temporal scales that may be realized through efforts to produce self-powered tags. Other tracking capabilities will be focused on integrating embedded sensors into tags to provide measurements of physiological and water quality variables that can correlate to health, habitat use and quality, and hydropower operations. The Hydropower Program will also focus on utilizing big data analyses and machine learning, collected with commercial-off-the-shelf technologies, which will support more rapid and cost-effective monitoring, as well as developing novel detection and sensor systems that utilize these techniques to enable more informed environmental management options.

Mitigation

Realizing the potential for future hydropower growth and optimization of the existing fleet will require overcoming several key technological, environmental, and market challenges. Novel and specialized technologies enable hydropower dams to cost-effectively reduce environmental footprints. The Hydropower Program's efforts to improve the environmental performance of hydropower include activities to avoid, minimize, and mitigate ecological impacts (e.g., water quality and quantity, up- and down-stream fish passage, biodiversity, Endangered Species Act-listed species, habitat, and instream flows). For example, to address water quality, WPTO is funding the development of technologies that may radically reduce water pollution risk, such as biodegradable oils and oil-free applications, as well as the development of tools for more robust methods of monitoring. In addition, to enable infrastructure longevity and address concerns of invasive mussels, this sub-activity is working towards solutions to prevent zebra and quagga mussel colonization and range expansion. Further, WPTO understands that variable and intermittent renewable energy integration call for more flexible hydropower operations (Activity 2 – Grid Reliability, Resilience, and Integration [HydroWIRES]), which may have a variety of different impacts on aquatic species and ecosystems. Therefore, the Hydropower Program will build upon studies to clarify the short-term effects hydropeaking (or the discontinuous releases of water through turbines to meet peak energy demands which causes downstream water flow fluctuations) on resources and assist in the development of novel monitoring approaches and flows for rapidly changing hydropower operations to achieve better environmental outcomes.

North America has a high diversity of fish species, including both migratory and non-migratory species. Such species of concern have a wide variety of upstream and downstream fish passage needs that are regulated at hydropower dams. Therefore, a core objective for species management is the development and evaluation of innovative fish passage technologies with an emphasis on multispecies passage to support resource agency biodiversity and fish restoration goals, fish protection, and adaptable passage for changing conditions. Fish passage technologies are assessed for environmental performance and benchmarked against evaluations of cost reduction pathways—particularly with respect to standard/modular designs, components, and applications of advanced and additive manufacturing (Sub-Activity 1.1 – New Technologies and Advanced Manufacturing) to reduce overall costs.

The Hydropower Program also supports foundational science through laboratory and field studies to assess ecological impacts—particularly the direct impacts of turbine passage to fish, and applications of advanced models and methods for evaluating population- and basin-level impacts. Furthermore, the program develops tools to enable more robust and real-time data collection for field evaluations of hydropower sites; computational fluid dynamics advancements that enable models of turbines and hydropower sites to be related to biological responses of fish; and applications of machine learning and artificial intelligence to automate and enumerate biological and environmental assessments.

Metrics

The Hydropower Program will leverage past efforts to identify appropriate environmental sustainability measures, metrics, and indicators of ecosystem health, and develop tools to identify and communicate key river functions during permitting, focusing attention on only relevant, potentially impacted resources. This sub-activity will pursue the development of widely accepted standardized practices to increase transparency in decision making, enable better environmental outcomes at lower costs, and reduce risk from environmental uncertainty.

Sub-Activity 4.2 – Hydrologic Systems Science

Overview

The Hydropower Program's hydrologic science portfolio addresses fundamental questions of climate change and hydrology, impacts on ecosystems, and risks/opportunities for operations and engineering of hydropower systems. Improving riverine ecological resilience and energy-water security requires better characterization of climate change variations in streamflow, snowmelt, and watershed storage, as result of changing weather patterns and long-term climate shifts. Better characterization of other important scientific gaps relevant to hydropower operations is also needed for climate adaptation. Areas of work within the Hydrologic System Science sub-activity mutually enhance hydropower production, energy security, water resilience, and overall ecosystem health by (1) incorporating scientific advancements, empirical studies, and modelling/simulation into our understanding of the water cycle and (2) identifying limitations and uncertainty of current methane formation analyses that inform future research areas for understanding potential reservoir emissions.

FY 2021–2025 Research Priorities

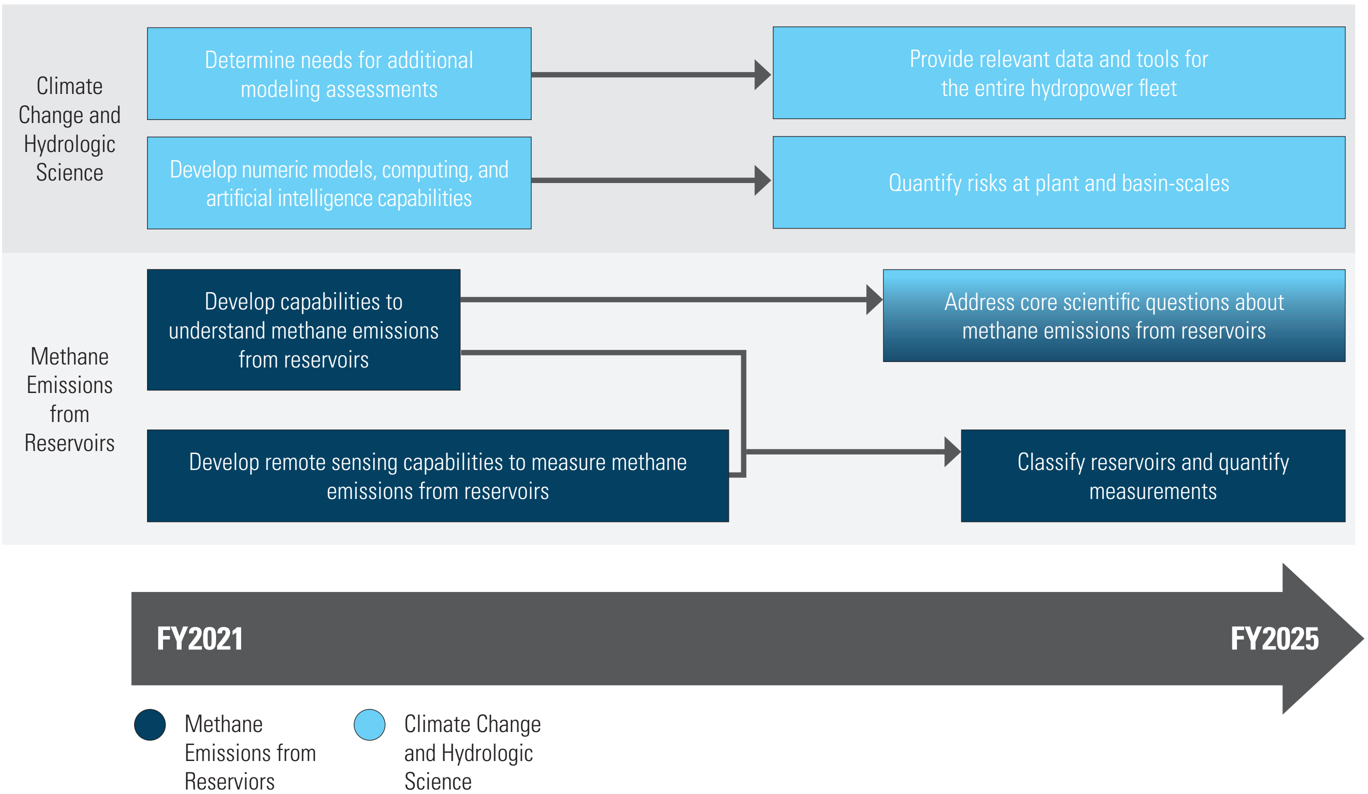
The following are the research priorities that will be emphasized within the Sub-Activity 4.2 – Hydrologic Systems Science:

- **Climate Change and Hydrologic Science**
  - **Determine needs for additional modeling assessments**: Assess the need to conduct additional modeling assessments or develop models with new capabilities.
  - **Provide relevant data and tools for the entire hydropower fleet**: Utilize modeling capabilities to clarify potential risks and uncertainties to better understand climate change and hydrologic variations.
  - **Develop numeric models, computing, and artificial intelligence capabilities**: Identify and apply advanced methods to increase understanding of basic hydrologic systems science and potential applications.
  - **Quantify risks at plant and basin-scales**: Develop tools for different user groups to investigate risks of climate change and evolving hydrology at different spatial scales.
- **Methane Emissions from Reservoirs**
  - **Develop capabilities to understand methane emissions from reservoirs**: Characterize the state of the science on methane emissions from reservoirs and other water bodies.
  - **Address core scientific questions about methane emissions from reservoirs**: Conduct foundational science on carbon transport and methane formation.
  - **Develop remote sensing capabilities to measure methane emissions from reservoirs**: Advance current and novel technologies to test and validate methane measurement capabilities for different types of reservoirs and water bodies.
  - **Classify reservoirs and quantify measurements**: Develop and utilize a reservoir classification scheme to assess risk and uncertainties of methane emissions.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 24.

Figure 24. Sub-Activity 4.2 – Hydrologic Systems Science Research Priorities



Hydropower Crosscut: Hydrologic Forecasting

Hydrologic forecasting focuses on progressing accurate and reliable riverine information to improve hydropower operations and strengthen basin-scale decision-making. Occurring over a wide range of timescales and integrated within hydropower processes at numerous decision points, operational forecasting of riverine streamflow, reservoir inflow, snowmelt, and other river ecosystem parameters are irrefutably important. WPTO's efforts will develop next generation hydrologic prediction models applicable to a broad range of locations and which leverage cutting-edge weather data, data assimilation techniques, cloud computing, novel remote sensing systems, and information from a host of sources.

There are important economic incentives for the hydropower industry to invest in new forecasting systems and methods. Specifically, where forecasts lead to clear market value in terms of revenue or avoided cost, and where advancements in forecast quality can affect operations, increase windows of reservoir optimization and overall system performance. In theory, advance foresight of variations in hydrologic parameters and reservoir levels, allows for better economic returns and optimal decision-making.

Advancements in forecasting can also influence the timing and nature of decision-making. Weekly, monthly, and seasonal forecasts products are evolving and there are interesting opportunities to consider these developments across water infrastructure planning and hydropower optimization. Developments in the fields of machine learning, big data, and artificial intelligence also could have implications for automating decisions or building decision-making around multiple and diverse datasets. Operational forecasting is an important strategic asset across the federal government, specifically at water mission agencies such as National Oceanic and Atmospheric Administration (NOAA) and United States Geological Survey (USGS) and represents a vibrant area to partner on future R&D activities for both industry and national interest.

WPTO considers forecasting as a crosscutting activity, negotiating programmatic connections across Environmental and Hydrologic Systems Science and the Data Access, Analytics, and Workforce Development, with some critical work relevant for HydroWIRES. Under Hydrologic Systems Science, the program will look to advance areas of hydrologic science, data production, and model prediction, with a focus on these areas across short and long-terms forecast products. Recognizing developments in water technology, spatial data integration, data access and curation, and the science of decision-making, forecasting is also a critical Data Access, Analytics, and Workforce Development activity with direct tie-ins to value (HydroWIRES Sub-Activity 2.2 – Capabilities and Constraints) and optimizing water infrastructure (water resilience). WPTO endeavors to utilize next generation hydrologic prediction models to impact the broader basin-scale/watershed space including reducing environmental impacts, improving hydropower plant performance and reliability, optimizing flexibility and grid value, informing risk-based decision-making, and long-term infrastructure planning.

Additional Details

A core objective of the program is to regularly evaluate the need for new models with capabilities to assess the effects of climate change on the U.S. hydropower fleet. Past efforts have focused on examining the potential effects of long-term climate trends on water availability for federal hydropower generation, based on the best available scientific information, and future. These efforts will extend and amplify analytical capabilities for non-federal, investor-owned hydropower facilities to understand future investment, operations, and business risks. The Hydropower Program also focuses on more foundational hydrologic work, particularly in the area of flow forecasting, by utilizing numerical modeling methods, high-performance computing, and machine learning to assess and manage future climate impacts to watershed-river-reservoir systems on streamflow, hydropower, and water temperature. The ultimate goal is to develop decision-making tools that provide a comprehensive understanding of water impacts and risks to both grid and hydropower operations, including sensitivities to varying climate-hydrologic drivers and infrastructure futures, ranging from individual generating assets and river reaches to regional- and national-scale threat assessments.

An emerging, complementary goal of the hydrologic science portfolio is utilizing the tools and capabilities developed and advanced to address the role of hydropower in responsible management of our water systems. As the interdependencies and subsequent risks in the power and water systems are better understood, so are the opportunities for integrated resilience. Given the position of hydropower squarely at the nexus of energy and water systems, the Hydropower Program seeks to understand how hydropower can serve as a tool to improve water resilience and security.

Methane Emissions

Numerous studies in past years have suggested that reservoirs and other waterbodies can serve as potential sources of methane emissions. However, many of these studies either focus on a handful of reservoirs, new reservoirs, a specific region, or conducted sampling with limited spatial and temporal diversity. As a result, large uncertainties remain in characterizing both the temporal and spatial variation of methane emissions from reservoirs. Providing more confidence in measurements and estimates is vital for understanding methane emissions for the U.S. hydropower fleet and the formation and cycling of this potent greenhouse gas. Other greenhouse gases (carbon-dioxide, nitrous oxide) are known to be produced in waterbodies and inundated areas as well. However, measured amounts in previous studies have been modest, and the transformation of molecules of organic carbon (with a global warming potential of one should carbon dioxide be produced) into methane (with a warming potential of more than 20) is the main issue of concern.

In this sub-activity, the Hydropower Program's goal is to characterize uncertainty in methane emissions from reservoirs by synthesizing the scientific research to date, identifying critical research gaps, and partnering with industry leaders and other NGOs to develop and improve new methodologies and technologies with the ability to collect both field-based and remotely sensed data on reservoir methane emissions.

Establishing foundational research questions for future scientific analysis will help to improve the understanding of methane emission uncertainty. It will be necessary to build partnerships with scientists, state and federal agencies, and practitioners for researching, disseminating, and improving the understanding of methane emissions from reservoirs. These partnerships are crucial to advancing the development of a classification scheme for reservoirs at low-, medium-, and high-risk of emitting methane and working with stakeholders to understand mitigation—a long-term goal for this sub-activity area.

Hydropower Program Activity 5 – Data Access, Analytics, and Workforce Development

Overview

As a technology-neutral, national research agency with access to some of the most advanced computing, data management, and analytics in the nation, DOE is well-suited to work closely with other agencies and stakeholders to improve the data landscape for important hydropower and river-related information. This can help enable the development and commercialization of new crosscutting analytical capabilities to weigh multi-objective tradeoffs and support stakeholder decision-making. Also, as a largely non-regulatory agency, DOE is in a unique position to help provide insights to identify areas with the greatest opportunity for hydropower regulatory process improvements. The Hydropower Program's efforts will focus on extracting lessons learned from the substantial record of development over the last century and will use its convening role to engage other federal agencies, tribes, the hydropower industry, and NGOs to share this information and develop ways to enhance stakeholder engagement and benefit regulatory processes. As the nation's energy and water systems become even more complex and intertwined, all of these goals aim to support improved decision-making and basin-wide management of river resources for multiple objectives, including energy, enabled by improved data and analytical tools. Lastly, WPTO has a unique vantage point given its strong partnerships across industry, academia, and the federal government. WPTO will leverage this unique perspective and expansive network to address another key challenge for the hydropower industry: its aging workforce. The Hydropower Program will expand on work conducted by the office to date in developing effective strategies to support STEM and workforce gaps in hydropower.

Activity 5 – Data Access, Analytics, and Workforce Development consists of the following sub-activities:

1. Data Access and Workforce Development: Identifying and improving access to valuable hydropower asset data, technology advances, and many other diverse types of dam and river-related information.
2. Data Analytics: Developing "evergreen" analytical capabilities that can be applied to a diverse range of hydropower-related investigations including basin-scale decisions, energy market applications, and hydropower relicensing processes.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 18.

Table 18. Data Access, Analytics, and Workforce Development Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Launch and improve the new externally oriented HydroSource online data portal with broad use-case capabilities. • Develop a standard suite of application programming interface (API) capabilities that will provide unprecedented access to power market information for the hydropower community. • Leverage machine learning and new big-data access approaches, in collaboration with FERC and other stakeholders, to increase access to information available in FERC's eLibrary. • Publish a report on the key issues on the time, cost, and uncertainty associated with U.S. hydropower regulatory processes. • Release a new hydropower-focused STEM/education portal and initiate new partnered efforts to provide data and informational support for high-priority hydropower workforce training needs. • Launch DOE's first-ever hydropower collegiate competition and hydropower-focused fellowship program, providing students of diverse backgrounds and disciplines the opportunity to develop key skills for a career in hydropower.
Follow-On Objectives (2026–2030)
• Significantly increased use of the HydroSource portal by a diverse set of stakeholders—beyond the current range of application—along with improved ease-of-use metrics and reviews from users. • Power market data are utilized by developers of new hydropower technologies to specifically target the greatest opportunities and approaches for growth and are incorporated into future technology development and project planning processes. • FERC and other stakeholders leverage eLibrary insights along with interdisciplinary big data approaches to improve licensing and relicensing study efforts while maintaining regulatory effectiveness. • Key issues identified in the U.S. hydropower regulatory process report are utilized by diverse hydropower stakeholders to agree upon and begin to operationalize regulatory process improvements. • Documented increases in hydropower early-career interest/opportunities and improvements in institutional knowledge-transfer landscape.

Additional Details

Although it is the oldest form of electricity generation in the country, there has historically been limited publicly available or easily accessible centralized data on the makeup, performance, costs, market participation, or regulatory best practices of the U.S. hydropower and pumped storage fleet. Accessibility and the ability to analyze a variety of other river and water data—including river ecology, flood control, hydrography, recreation, other socioeconomic uses, water quality, and water use—are limited. This limitation hinders the ability of diverse stakeholders to engage in integrated energy-water systems planning, particularly at the river-basin level. Improved access to existing data and new analytical capabilities that bridge multiple disparate sectors are also necessary to inform a well-designed long-term research strategy to support maintenance and expansion of the U.S. hydropower fleet, reduce its impacts, and identify ways to increase its contributions to grid reliability and resilience. A large amount of new information is also continually generated as the result of DOE-funded research, and this data must be transparent and made publicly available in a timely manner. Fundamentally, the Data Access, Analytics, and Workforce Development effort are designed to help address what is commonly known as the "80/20" situation regarding data analysis, where roughly 80 percent of time and resources are expended on accessing, aggregation, and preliminary data analysis, and 20 percent of resources are spent on solving the specific problem of interest. The development of centralized capabilities in this "80 percent" is important because they not only impact significant resource expenditures, but they can also help reduce redundancy across many different organizations involved in hydropower research.

Hydropower Permitting and Licensing

One of the more significant factors limiting the growth of U.S. hydropower is the length and uncertainty of the federal regulatory permitting process, most notably FERC licensing. A preliminary Oak Ridge National Laboratory licensing analysis of 49 projects in the FERC record indicates that the time from license application to license issuance ranged from 12.2 to 89.6 months with a mean time of 40.1 months.

As a non-regulatory agency, WPTO is in a unique position to evaluate and execute actions to advance effective licensing practices, share governance lessons between hydropower policies and practices, provide this information to stakeholders to better facilitate decision-making in the regulatory process, and take a higher-level perspective on the role of permitting in our national energy outlook. WPTO's role in this effort is exemplified by its successful facilitation of the memorandum of understanding (MOU) between FERC and the U.S. Army Corps of Engineers (USACE) to coordinate their dual regulatory authorities for private hydropower development at the USACE non-powered dams.

It is evident that regulatory processes associated with hydropower permitting are cost and time-intensive, and there is poor information and data available/accessible on regulatory process outcomes and drivers. As a result, WPTO is developing a suite of tools to assist not only federal regulators, but all stakeholders (e.g., hydropower developers, non-governmental environmental organizations, etc.) with navigation of the hydropower permitting process. Tools and data currently available include the RAPID toolkit (National Renewable Energy Laboratory), a comprehensive user-friendly guide to permitting regulations and best practices, in addition to a fleet-wide searchable database of hydropower environmental mitigation measures (Oak Ridge National Laboratory). WPTO's current efforts in the hydropower regulatory arena include development of an Environmental Decision-Support Tool (Oak Ridge National Laboratory) that would help stakeholders identify the most impactful and cost-effective studies necessary to determine the environmental impacts of proposed hydropower projects. Future efforts by WPTO to reduce the cost and uncertainty of hydropower permitting could include studies of the transferability of existing hydropower environmental impact data and a tool to search and identify significant environmental data and best licensing practices in the FERC eLibrary.

Finally, WPTO, with the assistance of a broad group of stakeholders from across the hydropower community, is currently conducting a comprehensive study of the entire federal permitting process for hydropower. This study will use both qualitative and quantitative analyses to determine the root causes for the costs and uncertainty associated with the process. While the study will stop short of making specific recommendations for regulatory process improvements, the study can be used by policy makers to identify the key areas of the process that need improvement.

Sub-Activity 5.1 – Data Access and Workforce Development

Overview

Data Access and Workforce Development focuses on identifying and improving access to valuable hydropower asset data, technology advances, and many other diverse types of dam and river-related information. The Hydropower Program also maintains information sharing platforms (the foremost being the HydroSource portal) to enable the dissemination and open exchange of information. There is also an increasing focus on work and coordination with other federal agencies and data-focused organizations to improve nation-wide coordination and access to river and water-related data. This takes the form of improving metadata structures and standards, database and data portal harmonization, and other big-data management improvements. Additionally, the Hydropower Program is committed to supporting the next generation of the hydropower workforce through access to educational materials and workforce development programs.

FY 2021–2025 Research Priorities

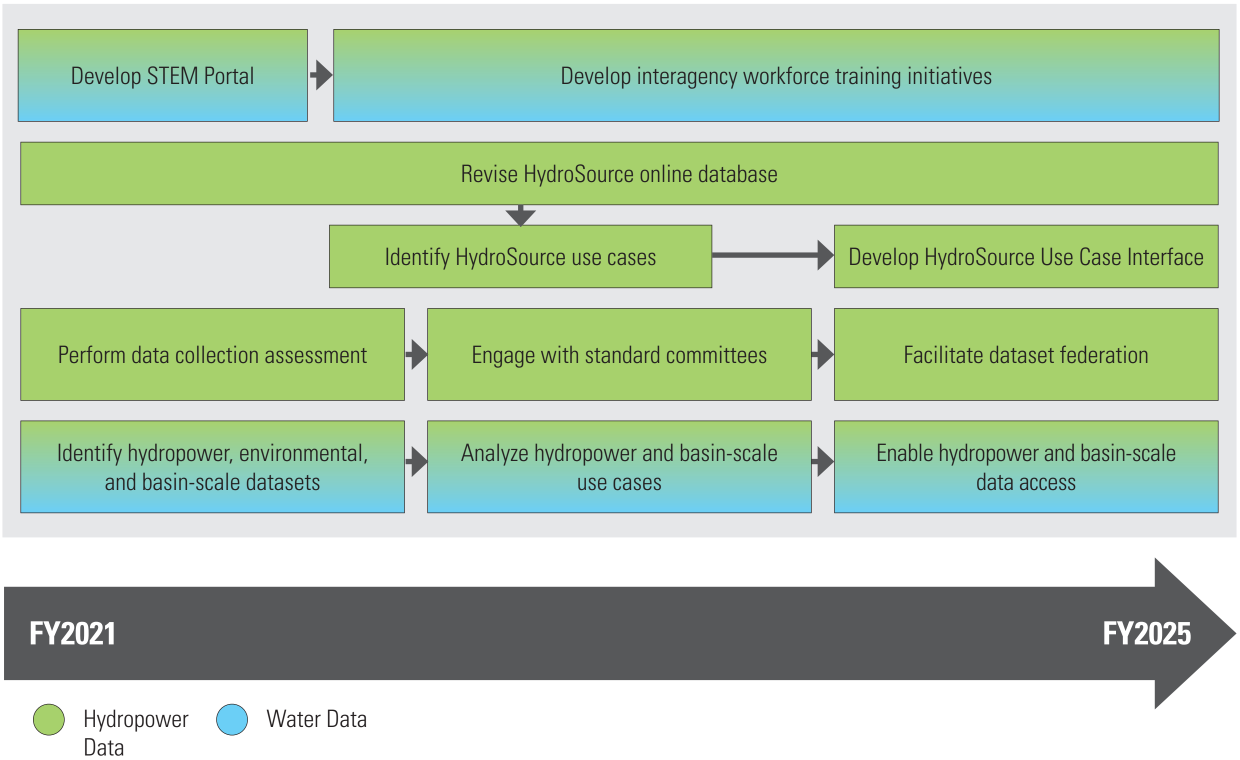
The following are the research priorities that will be emphasized within the Sub-Activity 5.1 – Data Access and Workforce Development:

- **Launch new workforce development programs for hydropower**: Establish DOE's first-ever hydropower collegiate competition and hydropower-focused fellowship program, providing students of diverse backgrounds and disciplines the opportunity to develop key skills for a career in hydropower.
- **Develop STEM portal**: Launch new, publicly available STEM portal for hydropower educational information and curricula.
- **Develop interagency workforce training initiatives**: Develop interagency and external partnerships that utilize information to support high-priority workforce training initiatives.
- **Revise HydroSource online database**: Continuously revise, improve, and expand the HydroSource database to provide state-of-the-art access to relevant hydropower data.
- **Identify HydroSource use cases**: Work with a diverse set of stakeholders to understand the range of use cases for the HydroSource Database.
- **Develop HydroSource use case interface**: Based on high-value use cases, develop user interfaces to collect relevant HydroSource data and synthesize it into the appropriate structure.
- **Perform data collection assessment**: Document the drivers and potential solutions to the collection of low data quality and low data availability.
- **Engage with standards committee**: Engage with the relevant standards committees to bring the process of improving data collection.
- **Facilitate dataset federation**: Develop a process to facilitate data federation and synthesis from multiple sources.
- **Identify hydropower, environmental, and basin-scale datasets**: Identify relevant datasets held by a diverse set of stakeholders along with the dataset characteristics.
- **Analyze hydropower and basin-scale use cases**: Analyze available datasets to identify a range of potential data uses cases and their associated value proposition.
- **Enable hydropower and basin-scale data access**: Work with appropriate partners to facilitate the broad availability of hydropower and basin-scale data.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 25.

Figure 25. Sub-Activity 5.1 – Data Access and Workforce Development Research Priorities



Additional Details

The flagship effort in this sub-activity is HydroSource—the most comprehensive repository of hydropower-relevant data in the United States. HydroSource was originally developed to primarily meet internal DOE analytical and research needs, but that focus is shifting to enhance publicly available access to information to serve the data needs of a diverse user base. A wide range of relevant stakeholders will be engaged to understand use cases for various types of information and the value proposition for different data needs. Based on use case information, access to the HydroSource data will be iteratively improved through the development of different graphical user interfaces to enable ready investigation of high value and crosscutting datasets. Ongoing research will also focus on enabling effective dataset synthesis. This data synthesis is critical for much of the data access work because analyses in this space requires low latency—or as small of a period of possible between data being collected and data being available for analysis—to access data located in a range of locations with diverse structures. This will initially be focused on engaging with stakeholders to help improve data collection quality and to develop necessary quality assurance and quality control capabilities. Once this has been addressed, WPTO will engage established data standards communities to ensure federation and synthesis capabilities reflect industry best practices. These capabilities will enable access to unified, federated, consistent, and correlated hydropower and other water-related datasets, most which are of diverse structure and resolution. This unification, federation, and correlation broadly refers to the issues associated with leveraging multiple, heterogeneous, datasets. Given that the data is structured differently it is first necessary to enable ready and consistent comparisons between the datasets before any insights can be taken away from them.

This sub-activity also entails improving access to multidisciplinary basin-scale information as hydropower interacts with and is influenced by a broad range of other water sectors. This effort will start by identifying the sources of basin-wide information that are most valuable to different stakeholder and user groups (e.g., specific types of river ecology, flood control, hydrography, recreation, other socioeconomic uses, water quality, infrastructure resilience and water use data) and the associated characteristics of the identified datasets. Once this has been completed, the available information will be assessed in coordination with stakeholders and other water-data-focused agencies and organizations to articulate the range of use cases that these data could enable and the associated value proposition. Based on the results of this assessment, data access and visualization capabilities will be developed in coordination with various data holders to enable access to the necessary information for the identified use cases.

Finally, this sub-activity focuses on developing and providing access to educational information and workforce development opportunities to support a vibrant and evolving U.S. hydropower workforce. There has been a noted lack of easily accessible, publicly available basic information on hydropower resources, technologies, environmental issues, opportunities, and linkages to a variety of other scientific and technical fields. Tools and best-practices to support knowledge transfer to incoming generations of workers are also needed. The Hydropower Program will also stand up its first-ever collegiate competition and hydropower-focused fellowship program, while also assisting efforts led by interagency or external partners to address the hydropower industry's workforce development needs.

Sub-Activity 5.2 – Data Analytics

Overview

Sub-Activity 5.2 – Data Analytics is focused on developing "evergreen" analytical capabilities that can be applied to a diverse range of hydropower-related investigations including basin-scale decisions, energy market applications, and hydropower relicensing processes. It should be noted that the capabilities (which can come in the form of open-source computer code, analysis processes, etc.) are the focus of this effort rather than the results of a discrete application of the capabilities. The development of these broadly relevant analytical capabilities will significantly reduce the time and resources needed to perform research in a host of hydropower applications funded not only by WPTO but also by a wide range of other stakeholders. This focus on a centralized set of capabilities however necessitates that the solutions will remain functional as they age. These "evergreen" capabilities—or capabilities that remain continuously relevant and functional—ensure the continued functionality of secondary applications and analysis dependent on these data analytics. Efforts in this sub-activity are focused on the development of a robust, centralized set of analytical capabilities which access information from a diverse set of repositories to synthesize results. One notable application in this space is the development of capabilities to readily access and analyze power market information. While this data and its analysis is extremely valuable to hydropower owners when planning for the future, equipment manufactures when targeting cost/capabilities, and developers when considering the rate of return for hydropower installations, the about of information required and its analytical process are complex and resource intensive. Advancements in this space would empower improvements in data driven decisions and allow a range of new actors to engage with the hydropower industry. While overall capabilities in this space have been developed to varying degrees, existing systems have been developed in an ad hoc fashion, with limited coordination across the hydropower and other relevant sectors. This effort focuses on the development of centralized, efficient capabilities to perform data manipulation, analytics, and visualization for high-value application. These open-sourced capabilities will hopefully enable improved decision-making based on expanded, relevant big data access without incurring the extensive upfront cost of developing new, custom capabilities.

FY 2021–2025 Research Priorities

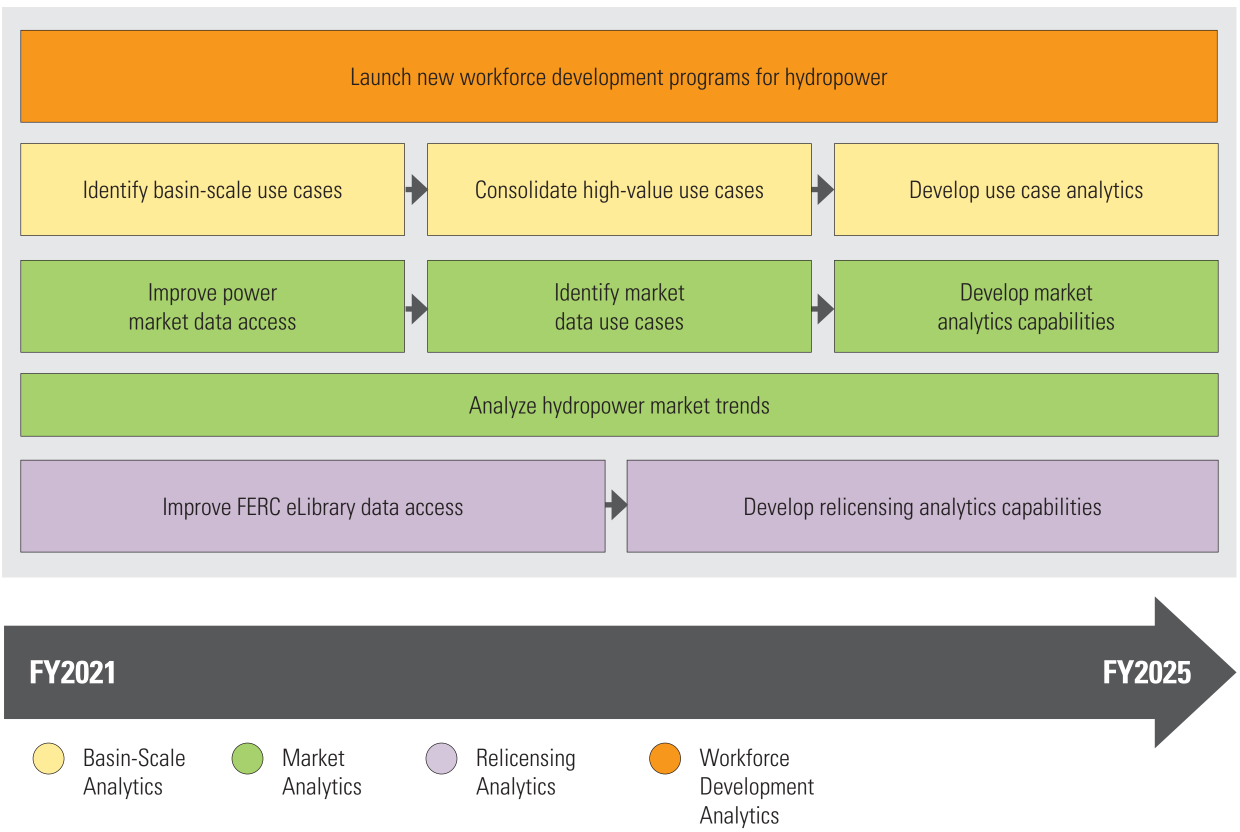
The following are the research priorities that will be emphasized within the Sub-Activity 5.2 – Data Analytics:

- **Identify basin-scale use cases**: Identify uses case and major data gaps for basin-scale decision analytics.
- **Consolidate high-value use cases**: Produce the capabilities to synthesize the diverse datasets necessary for the use case analytics.
- **Develop use case analytics**: Produce broadly accessible analytics around the identified use cases.
- **Improve power market data access**: Develop a common suite of tools to facilitate access to relevant power market data.

- **Identify market data use cases**: Document a range of use cases for power market data, in combination with other sources of information, and their associated impact.
- **Develop market analytics capabilities**: Produce broadly applicable analytics based on the identified used cases.
- **Analyze hydropower market trends**: Continue to analyze important trends in hydropower via the Hydropower Market Report.
- **Improve FERC eLibrary data access**: Leverage natural language processing algorithms to enable unprecedented access to FERC eLibrary data.
- **Develop relicensing analytics capabilities**: Leverage data from a diverse set of sources to facilitate the constant and efficient relicensing process.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 26.

Figure 26. Sub-Activity 5.2 – Data Analytics Research Priorities



Additional Details
Efforts in basin-scale analytics are focused on enabling planning through collaborative engagement processes and improved replicability. Work will initially be focused on documenting the range of use cases associated with basin-scale, energy-water planning efforts, their associated value proposition, and any relevant gaps in data necessary to enable these analytics. Once the documentation has been completed, the capabilities—needed to consolidate and source the data necessary to inform these analytics—will be developed, with priority being placed on high value proposition use cases. After this, use case analytics and visualization capabilities will be developed in coordination with relevant stakeholders. One of the important efforts in this space is efforts in reservoir inflow forecasting, as improved forecasting has the potential to improve a host of hydropower outcomes including system revenue,

reliability, and socio-environmental outcomes. This work will both inform and be informed by research in Sub-Activity 4.2 – Hydrologic Systems Science. Initial data analytics efforts in this space will focus on articulating the use cases and value metrics associated with inflow forecasting improvement because "improvement" can take numerous forms (including different timeframes and error reduction metrics) and should be targeted on improvements which have the most impacts. Armed with these improvement metrics, the development of new inflow forecasting capabilities in Sub-Activity 4.2 – Hydrologic Systems Science can target the highest value improvements in metrics. It should be noted that these metrics will be combined with the insights provided by research in Sub-Activity 2.2 – Capabilities and Constraints, which is focused on articulating the benefits that various improvements in inflow forecasting can have on the stability of the electric grid.

In addition to this effort, the Hydropower Program will aim to make power market data more readily available to the hydropower community. This data has significant potential to improve outcomes across a wide spectrum of current and planned hydropower outcomes—particularly when combined with other information, such as new-stream reach development potential when considering new hydropower development, or site-specific improvements in flexibility when assessing the rate of return of different capital investments. The initial phase of the work will entail engaging with stakeholders in both the hydropower industry and power markets. Once this has been done, a library of available, accessible data will be developed in an open-source environment. While this standard library is being developed, the Hydropower Program will continue to pursue its ongoing effort to document hydropower markets and trends in the Hydropower Market Report.[63]

The final effort in this sub-activity will work on providing information and tools in the hydropower relicensing process to ensure it is applied consistently and predictably. As hydropower plants continues to age, a considerable number will soon go through relicensing processes. While these are important regulatory requirements, they are also time and resource intensive to complete. For that reason, the Hydropower Program is working to improve efficiencies via big data access capabilities (by reducing the time and resources necessary to collect data). This will initially be focused on improving access to the FERC eLibrary, which acts as a central repository of information fundamental to any big data-based approach. This rich history of information will provide unprecedented visibility on consolidated licenses, which have the potential to evolve as conditions change. Once improved access to the FERC eLibrary has been completed, work to reduce the relicensing burden—while still maintaining standards—will be coordinated with a broad set of stakeholders. This effort will be explored with a robust stakeholder set and will be based around efficient approaches to obtaining new data, understanding the value of the collected data, and addressing delays in analyzing and processing that data within the existing regulatory framework.

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

Hydropower Strategic Partnerships and Crosscutting Activities Overview

Coordination and collaboration with other DOE offices and government agencies is essential to optimize federal investments, leverage resources, avoid duplication, ensure a consistent message to stakeholders, and meet national energy goals. WPTO's Hydropower Program maintains partnerships with other DOE offices and federal agencies as shown in Table 19.

Table 19. Summary of Collaborations Other DOE Offices and Federal Agencies

DOE Office	Collaboration Description
Office of Science	WPTO coordinates with the Office of Science on initiatives and advancements related to artificial intelligence and machine learning applications (Activities 4 and 5), including actions identified in the Office of Science's Artificial Intelligence Town Hall report. Work on modeling potential long-term hydrologic changes (Activity 4) is also coordinated with the Biological and Environmental Research program.
Artificial Intelligence and Technology Office (AITO)	WPTO plans to coordinate on initiatives and advancements related to artificial intelligence and machine learning applications (Activities 3, 4, and 5) with this new office. Artificial intelligence is critical to asset management, including machine condition monitoring and assessment, for potential improvements through image recognition and signals analysis.
Office of Electricity (OE)	WPTO works closely with OE through numerous efforts in HydroWIRES, and OE staff serve on the HydroWIRES Executive Board.
CESER	WPTO coordinates with CESER on cybersecurity research to streamline efforts and leverage existing capabilities.
Power Marketing Administrations (PMAs)	WPTO engages the Bonneville Power Administration and Western Area Power Administration (WAPA) in conversations to determine how WPTO's Hydropower R&D activities, most notably HydroWIRES (Activity 2), can be applied to real-world challenges faced by the PMAs on hydropower's role in grid resilience and flexibility. WPTO is currently engaging WAPA staff in a series of webinars to identify specific R&D projects of mutual interest.
EERE Office	**Collaboration Description**
AMO	Through Oak Ridge National Laboratory's Manufacturing Demonstration Facility, WPTO partners with AMO to jointly fund efforts by hydropower technology developers to discover ways of utilizing advanced manufacturing techniques for new and innovative components with an emphasis on cost reduction (Activity 1 – Innovations for Low-impact Hydropower Growth). WPTO also coordinates with AMO under the Water Security Grand Challenge on projects pertaining to hydropower's role in maintaining and enhancing the nation's water infrastructure.
Solar Energy Technologies Office (SETO)	WPTO collaborates with SETO on the North American Renewable Integration Study (NARIS), the North American Energy Resilience Model (NAERM), and staff regularly serve as merit reviewers for each other's external solicitations.
Wind Energy Technologies Office (WETO)	WPTO collaborates with WETO on several grid-system analysis projects.

Federal Agencies	Collaboration Description
USACE	WPTO has multiple long-standing collaborations with the USACE related to technology, sustainability, and modernization of the federal fleet that stem from the Sustainable Hydropower MOU (WPTO, USACE, and U.S. Bureau of Reclamation). WPTO continues to advance the Juvenile Acoustic Salmon Telemetry System, co-funded by USACE, and continues to utilize Ice Harbor Dam as a testbed for new technologies coming out of the national laboratories. In addition, WPTO staff facilitated an MOU between FERC and USACE to ensure an efficient process for non-federal hydropower development at Corps dams.
U.S. Bureau of Reclamation	WPTO has multiple long-standing collaborations with Reclamation related to technology, sustainability, and modernization of the federal fleet that stem from the Sustainable Hydropower MOU (WPTO, USACE, and Reclamation). For example, the recent Fish Protection Prize to develop new ideas and mature viable technologies to prevent fish from being entrained in diversions and intakes. WPTO and Reclamation regularly provide portfolio overviews to establish areas of mutual interest for collaborations, often resulting in WPTO supported technologies being demonstrated at Reclamation sites.
U.S. Department of Agriculture (USDA)	WPTO supports the MOU between USDA and DOE based on mutual interest in rural energy development and the development of technologies that support and advance rural and agricultural communities. Collaboration with USDA has highlighted opportunities for future mutually beneficial work.
FERC	WPTO works closely with FERC staff to provide technical information pertaining to its mission to determine environmental effects of proposed hydropower projects and to establish a more streamlined regulatory process for hydropower licensing. For example, WPTO staff facilitated an MOU between FERC and USACE to ensure an efficient process for non-federal hydropower development at USACE dams.
NOAA, U.S. Fish and Wildlife Service, USGS	Through the Federal Hydropower Working Group, WPTO regularly interacts with subject matter experts at NOAA, the U.S. Fish and Wildlife Service, and the USGS to understand regulatory technology transfer barriers and obtain feedback from researchers on topics related to species and water management, including fish passage and forecasting. In 2018 and 2019, WPTO and these agencies developed two Environmental R&D Summits to identify hydropower research needs and priorities. WPTO also engages with NOAA on inflow forecasting improvements, as accurate knowledge of streamflow timing and water availability is foundational to hydropower operation. NOAA manages the River Forecasting Centers, which provide riverine data and predictions to a wide range of stakeholders. WPTO is considering more formalized near-term collaborations on topics of mutual interest.

Energy Storage Grand Challenge

Building on DOE's Advanced Energy Storage and Grid Modernization Initiatives, ESGC is a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage. The vision for the ESGC is to create and sustain global leadership in energy storage utilization and exports in order to develop a domestic manufacturing supply chain that does not depend on foreign sources of critical materials.

The ESGC includes the following five tracks:

- The Technology Development Track will focus DOE's ongoing and future energy storage R&D around user-centric goals and long-term leadership.
- The Manufacturing and Supply Chain Track will develop technologies, approaches, and strategies for U.S. manufacturing that support and strengthen U.S. leadership in innovation and continued at-scale manufacturing.
- The Technology Transition Track will ensure that DOE's R&D output transitions to domestic markets through field validation, demonstration projects, public-private partnerships, bankable business model development, and the dissemination of high-quality market data.
- The Policy and Valuation Track will provide data, tools, and analysis to support policy decisions and maximize the value of energy storage.
- The Workforce Development Track will educate the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.

The Hydropower Program participates extensively in the storage challenge, primarily through the HydroWIRES initiative described in Activity 2. HydroWIRES R&D in Sub-Activity 2.1 – Value Under Evolving System Conditions contributes directly to the Policy and Valuation track and will be closely coordinated with the modeling improvements and valuation frameworks undertaken through the broader DOE effort. Likewise, the assessments of hydropower's ability and operational requirements to operate flexibly and provide grid services under different conditions, encompassed in HydroWIRES Sub-Activities 2.2 and 2.3, will directly inform the storage use cases and technology pathways developed in the ESGC Technology Development track. Lastly, new innovations in PSH, undertaken in Sub-Activity 2.4 – Technology Innovation, will be key elements of the broader storage challenge's work in both Technology Development and Manufacturing and Supply Chain.

Water Infrastructure and Resilience

Infrastructure and ecosystem resilience, water security, and energy-water system complexity are vital research areas for the hydropower community when thinking about the evolving long-term future of hydropower. It is important to consider hydropower systems, facilities, and other non-powered dams as multipurpose water infrastructure projects instead of solely viewing them as existing or potential future energy assets. Water resilience research by WPTO will advance tools, models, sensors, and other pioneering technologies to consider broad developments of water infrastructure and hydropower's unique position at the nexus of energy and water systems. DOE's previous crosscutting efforts on the energy-water nexus provided a strong basis of understanding for this work as well as the Water Security Grand Challenge and WPTO's activities supporting hydrologic systems science and data access and acquisition.

Over the past few years, the Hydropower Program has funded a number of small research projects looking at how hydropower infrastructure and research tools could improve water system resilience. Some of these early efforts include considering opportunities to realize value from integrating hydropower into irrigation modernization activities (Sub-Activity 1.3 – New Value Propositions); capitalizing on hydropower's benefits and services for local energy reliability, improved economic outputs, and restored water resources (Sub-Activity 1.3 – New Value Propositions); and understanding and mitigating water risk, especially in the power system (Sub-Activity 3.3 - Cybersecurity).

Near-term future activities would include new technology development and support, methods for incorporating resilience strategies in municipal water systems, and advanced modeling and forecasting for more accurate assessments of risk. The outcomes expected are a mix of both technology advancement and analytical frameworks for improvement of water infrastructure—recognizing DOE's capabilities to provide direct investments in novel technologies and advanced analytical and computational tools. The economic incentives specific to hydropower's infrastructure and technologies provide a compelling advantage to drive wider water infrastructure evolution and innovation.

In future funding years, WPTO will look to execute on new visualization and operational planning tools providing insight into specific energy-water interactions and drivers to demonstrate and facilitate cooperation and optimization across energy and water assets. A systems-level approach for mutual water resilience will be undertaken across water and energy sectors to solve challenges in communications and control at multiple levels and scales. The work would also undertake new water and power co-design/co-optimization demonstrations that realize system wide benefits. In addition, data acquisition and access underpin water security and resilience, and the availability of actionable information is imperative to the Hydropower Program's activities seeking to balance a wide range of factors (Sub-Activity 5.1 – Data Access and Workforce Development and Sub-Activity 5.2 – Data Analytics). Finally, the water resilience-focused activities will directly engage many of the river system predictions, models, and decision-making science advanced by WPTO's Hydrologic Systems Science activity. This can better inform hydropower's role under changing future conditions to improve management of our water infrastructure and strengthen river basins facing hydrologic variations and changing projections of water availability (Sub-Activity 4.2 – Hydrologic Systems Science). This strategic initiative will be encapsulated in a report that documents the research to date, stakeholder outreach and engagement, and a roadmap.

Other Key Partnerships and Collaborations

Federal

In 2010, DOE (through WPTO) signed an MOU with the U.S. Department of the Army (through USACE and the U.S. Department of the Interior (through the Bureau of Reclamation) to advance mutual goals for greater development and utilization of clean, reliable, cost-effective, and sustainable domestic hydropower generation. In 2015, the MOU was renewed for another five years to provide a framework for collaboration on the following topics: (1) technology development, (2) hydropower sustainability, (3) quantifying hydropower capabilities and value in power systems, (4) asset management, and (5) information sharing, coordination and strategic planning. Key accomplishments from this partnership include:

- Development of a national database of existing U.S. hydropower infrastructure.
- Demonstration and commercialization of Pacific Northwest National Laboratory's Sensor Fish and a microbattery powered fish tag for sensitive species.
- Establishment of an MOU between USACE and FERC for a streamlined regulatory process for adding power to USACE NPDs.

DOE has once again committed to working with USACE and the Bureau of Reclamation by signing a new MOU on August 24, 2020. This new MOU will leverage resources to facilitate enhanced collaboration and coordination on technology research, development, and demonstration, and identify and engage in mutually beneficial research projects that support the hydropower industry and the federal agency core missions. The MOU and resulting action plan will detail overarching topics to increase sustainable hydropower generation and flexibility, while identifying a specific set of activities that the agencies will collectively undertake. These commitments were designed to represent a new approach to hydropower development that will result in clean, renewable power generation. Five topic areas were developed and include: (1) Asset Management, (2) Value of Hydropower, (3) Workforce, (4) Water Supply Reliability, and (5) Environmental Outcomes.

WPTO continues to partner with the Bureau of Reclamation on fish protection, a major challenge to hydropower and water users. For example, in a 2019 prize competition—the Fish Protection Prize—crowdsourced ideas to reduce fish entrainment impacts at water diversions and intakes. Selected ideas are incubated at national laboratories to prepare concept stage winners for technology advancement and commercialization. An ongoing prize contest that aims to mature viable concepts is currently being led by WPTO in partnership with the Bureau of Reclamation and supported by experts from USGS, NOAA, and the national laboratories.

Building off these past successes, WPTO is working with the MOU partners to discuss potential collaborations and aligned R&D opportunities. The Federal Inland Hydropower Working Group (FIHWG)—comprised of 15 federal agencies with roles in hydropower—was formed as an outcome of the MOU. WPTO will evaluate opportunities to collaborate more closely with FIHWG partners, such as NOAA, USGS, U.S. Forest Service, and Environmental Protection Agency, to leverage resources and/or accelerate beneficial outcomes through partnerships on specific topics. These strategic partnerships could support demonstration of new WPTO-developed technologies and more flexible operating regimes at federal facilities. Furthermore, these partnerships can facilitate applications of advanced manufacturing of legacy hydropower parts components, and support uptake of advances in Environmental R&D and Hydrologic Systems Science areas (e.g., development of advanced water quality and other sensor packages, fish passage research, flow forecasting, hydrologic modeling).

International

U.S.-Norway Memorandum of Understanding

In February of 2020, DOE and Norway's Royal Ministry of Petroleum and Energy made a commitment to collaborate on hydropower R&D by signing an Annex to an existing MOU on energy research. This MOU Annex brings together WPTO and the Norwegian Research Centre for Hydropower Technology to plan and coordinate hydropower R&D activities; develop, share, and implement results; increase understanding of hydropower's role in the future energy mix; and provide input to international discussions regarding hydropower.

Hydropower faces similar challenges and opportunities in the United States and Norway, and both countries are committed to enabling hydropower to support their respective electricity systems. Collaborative R&D under this Annex may include research in a number of areas:

- Markets and value
- Hydropower plant capabilities and constraints
- Monitoring and control technologies
- Environmental design solutions
- Environmental impacts and tradeoffs
- Flexible operations and planning
- Technology innovation.

Discussions between DOE national laboratories and Norwegian researchers have already identified specific opportunities for collaboration. Comparing capabilities of Norwegian and U.S. power system models is underway in order to identify opportunities for co-developing models and benchmarking model performance. Other work will include collaboration on digitalization, asset management, and component fatigue/wear modeling. In the environmental arena, there could be opportunities for collaboration on fish tags, environmental sensing using environmental DNA, and balancing environmental objectives with flexible operations. In the future, a formal researcher exchange program could benefit some or all of these efforts.

IEA Hydropower Technical Collaboration Programme

WPTO is actively involved in the IEA Hydropower Technology Collaboration Programme (TCP), supporting a number of annexes. HydroWIRES efforts are closely aligned with annex IX: Valuing Hydropower Services, and WPTO is actively engaged in this work stream. Environmental and new development efforts in WPTO support Annex XII: Hydropower and Fish, and Annex XVI: Hidden Hydro, respectively. WPTO also serves as a Deputy Chair of the Hydropower TCP Executive Committee.

International Pumped Storage Forum

The International Pumped Storage Forum, co-funded and led by the United States, aims to provide a platform to understand and shape the role of PSH in future power systems. Through the establishment of a multi-stakeholder network, the forum seeks to serve all stakeholders to expand and transfer best practice and experience with the aim of delivering sustainable, affordable and reliable power for all, while contributing to climate mitigation goals. The forum engages in activities such as, but not limited to, the following areas:

- Improve understanding of the role of PSH in providing storage and flexibility services, and the capabilities, values, costs, and potentials of PSH in addressing the needs of future power systems.
- Explore the full value of PSH's wider services beyond the power system, such as regulating water availability for society, industry, and agriculture, reducing the impact of flood and drought, and helping to adapt to climate change.
- Develop guidance and tools to support the design of market and policy frameworks that appropriately compensate and incentivize PSH development.
- Support the R&D of innovative and complementary technologies to enhance PSH.
- Ensure that all PSH development is sustainable and aligned with good environmental, social, and governance practice.

6 MARINE ENERGY MULTI-YEAR PROGRAM PLAN

Marine Energy Program MYPP Organization and Structure

The following sections detail FY 2021–2025 plans within each activity and sub-activity area in the Marine Energy Program and are organized as follows:

- Activity 1 – Foundational R&D
- Activity 2 – Technology-Specific System Design and Validation
- Activity 3 – Reducing Barriers to Testing
- Activity 4 – Data Access, Analytics, and Workforce Development.

Each activity area section includes the following components:

- *Activity Overview*: This subsection contains a brief overview of the activity area and scope of effort.
- *Key Results and Performance Goals (2021-2025)*: This subsection highlights certain significant outputs or products within the activity area that are expected within the next five years. The key results and performance goals are critical to achieving the program's 2026-2030 objectives. The list of key results and performance goals is not intended to be comprehensive and may not include every output produced within the five-year timeframe.
- *Follow-on Objectives (2025-2030)*: This subsection identifies short-term outcomes that the program aims to achieve by 2030, resulting from the successful completion of the 2021-2025 Key Results and Performance Goals. These follow-on objectives logically lead to the intermediate and long-term outcomes and ultimate impacts defined in the program's logic model.
- *Additional Details on Activity*: This subsection provides additional background information, context, and details on the program's activity area, such as links or interdependencies between or among the activities/sub-activities.
    - *Sub-Activity Overview*: This subsection summarizes the various elements that the sub-activity covers and highlights major areas of work to achieve overall activity performance goals and follow-on objectives. A flow diagram illustrates the timing and sequencing of major areas of work.
    - *Sub-Activity FY 2021–2025 Research Priorities*: These are the main efforts the Marine Energy Program intends to support within the sub-activity.
    - *Sub-Activity Timing and Sequencing of Research Prioritie*s: A visual representation of the timing, sequencing, and relation of different research priorities to each other.
    - *Additional Details on Sub-Activity*: Additional background information, context, and details on the program's planned efforts within the sub-activity.

Marine Energy Program Activity 1 – Foundational R&D

Overview

In order to reach cost-competitiveness with other energy resources, marine energy technologies need to see dramatic cost reductions over the next 10-20 years. The Marine Energy Program's Activity 1 – Foundational R&D supports research to drive these cost reductions, both through improving the device performance and reducing costs of existing device designs and by developing new capabilities that can allow for entirely new designs and approaches to harnessing the energy in natural water bodies. These early-stage R&D efforts are typically applicable to a wide range of device archetypes and, in some cases, cut across multiple technology types (e.g., wave, tidal, ocean current).

Activity 1 – Foundational R&D consists of the following sub-activities:

1. Advanced Materials and Manufacturing: Focusing on basic and applied science in materials and manufacturing that can be used by the marine energy industry to increase longevity/reduce operations and maintenance costs, reduce capital costs, and improve energy capture performance.
2. Controls: Enabling broad implementation of advanced control systems across the marine energy industry to dramatically improve performance and reduce cost of marine energy converters.
3. Numerical Modeling: Developing experimental and numerical methods to measure and predict device performance that are needed to design and optimize the next generation of marine energy technologies and lower the cost of marine energy.
4. Components: Optimizing conventional and next-generation subsystems and components with high potential for cross-cutting multiple energy conversion systems and technologies, as well as emphasizing advanced components and systems that are capable of operating in complex marine environments with limited operation and maintenance requirements.
5. Resource Characterization: Providing key information on the opportunities, constraints, and risk for marine energy projects, as well as understanding the value and potential of marine energy technologies.

These sub-activities have been identified to have the highest potential impact on device performance and/or cost. Research undertaken in each of these areas is necessary to understand the difficult and complex ocean environment, drive long-term innovation and cost reduction in different scales of devices and arrays, and ultimately achieve the cost reductions and performance improvements required for deployment of marine and hydrokinetic technologies at scale.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 20.

Table 20. Foundational R&D Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Evaluate applicability and performance of composite and other novel materials for marine energy converter systems and subsystems, such as wave energy converter hulls and tidal energy converter blades. • Develop power take-off (PTO)/control system co-design methodologies and partner with technology developers to pilot the use in marine energy converter device design processes. • Validate foundational modeling tools with data from ongoing water testing projects. • Disseminate high fidelity data sets and models through upgrades of the Marine Energy Atlas and DOE interface to cloud computing services and functional web-based application tools. • Complete resource measurements and assessments in support of marine energy projects to enhance the resilience of specific remote communities. • Test new and important component technologies that support significantly improved IO&M (e.g., wet-mate connectors and distributed energy conversion technologies). • Advance power electronics technologies that support integration of marine energy devices into power at sea and coastal community microgrid system applications.
Follow-On Objectives (2026–2030)
• Integrated, in-water systems testing completed for new, high-priority materials, power electronics, and other components. • First generation in-water tests completed of device designs documented to have used PTO/control system co-design methodologies and tools. • Early technology readiness levels (TRL) system testing of distributed-energy-conversion technology archetypes. • Widespread utilization (along with positive ease-of-use metrics and value reviews from users) of validated foundational modeling tools.

Additional Details

In general, marine energy technologies are at an early stage of development due to the fundamental scientific and engineering challenges of generating power from dynamic, low-velocity, and high-density waves and currents while surviving in corrosive ocean environments. To address these challenges, the program invests in early-stage R&D specific to marine energy applications to generate knowledge relevant for industry to develop innovative components, structures, materials, systems, and approaches to manufacturing. The Marine Energy Program's early-stage foundational R&D focuses on addressing scientific and engineering challenges that facilitate breakthroughs for broad, industry-wide benefits. The Marine Energy Program defines foundational research as research on problems or topics that have broad relevance across large portions of the marine energy industry and often cut across technologies or resource types. A primary value of this type of research is that it enables exploration of complex scientific problems beyond the scope of a single issue, technology design, or narrow area for a greater long-term impact to the industry at-large.

WPTO's marine energy R&D portfolio makes broad investments in foundational research that will increase fundamental knowledge, foster opportunities for breakthroughs, and provide technology options for future advances in marine energy capabilities and systems. The Marine Energy Program seeks to balance risk, opportunity, and potential marine energy impact. The Marine Energy Program's foundational R&D focuses on: (1) advanced materials and manufacturing; (2) controls; (3) numerical modeling; (4) components; (5) resource characterization; and (5) crosscutting R&D. These focus areas are critical cross-cutting elements to WPTO's marine energy R&D

portfolio in order to understand the difficult and complex ocean environment and drive long-term innovation and cost reduction in different scales of devices and arrays. Foundational R&D is a priority area in the near- and mid-terms because resulting data and knowledge from this research will inform many different types of system design improvements. The Marine Energy Program intends to drive innovation in multiple areas. Innovative components, like types of generators, and materials that are capable of operating in the complex marine environment with limited O&M requirements are needed to further the development of commercial marine energy technologies. The Marine Energy Program supports R&D led by industry, academia, and national laboratories to meet these challenges.

Foundational R&D investments provide technology building blocks that can be leveraged by private U.S. marine energy developers for technology improvements and, ultimately, successful commercialization. U.S. marine energy developers are generally small, specialized companies that do not have resources to make large investments in foundational science and engineering. The Foundational R&D activity area supports the development of new, cutting-edge technologies to improve device system performance and establish a strong, competitive industry in the United States.

Sub-Activity 1.1 – Advanced Materials and Manufacturing

Overview

New material capabilities have the potential to drive significant cost and performance improvements in marine energy technologies through increased energy capture performance and reduced costs. Material properties that increase resistance to corrosion or biofouling can have a significant impact on long-term efficiency and O&M costs, while new materials or manufacturing processes can allow for entirely new device shapes, designs, and approaches to energy conversion. This sub-activity comprises basic and applied science into materials and manufacturing that can be used by the marine energy industry, focused on advances that can (1) increase longevity/reduce operations and maintenance costs; (2) reduce capital costs; and (3) improve energy capture performance.

FY 2021–2025 Research Priorities

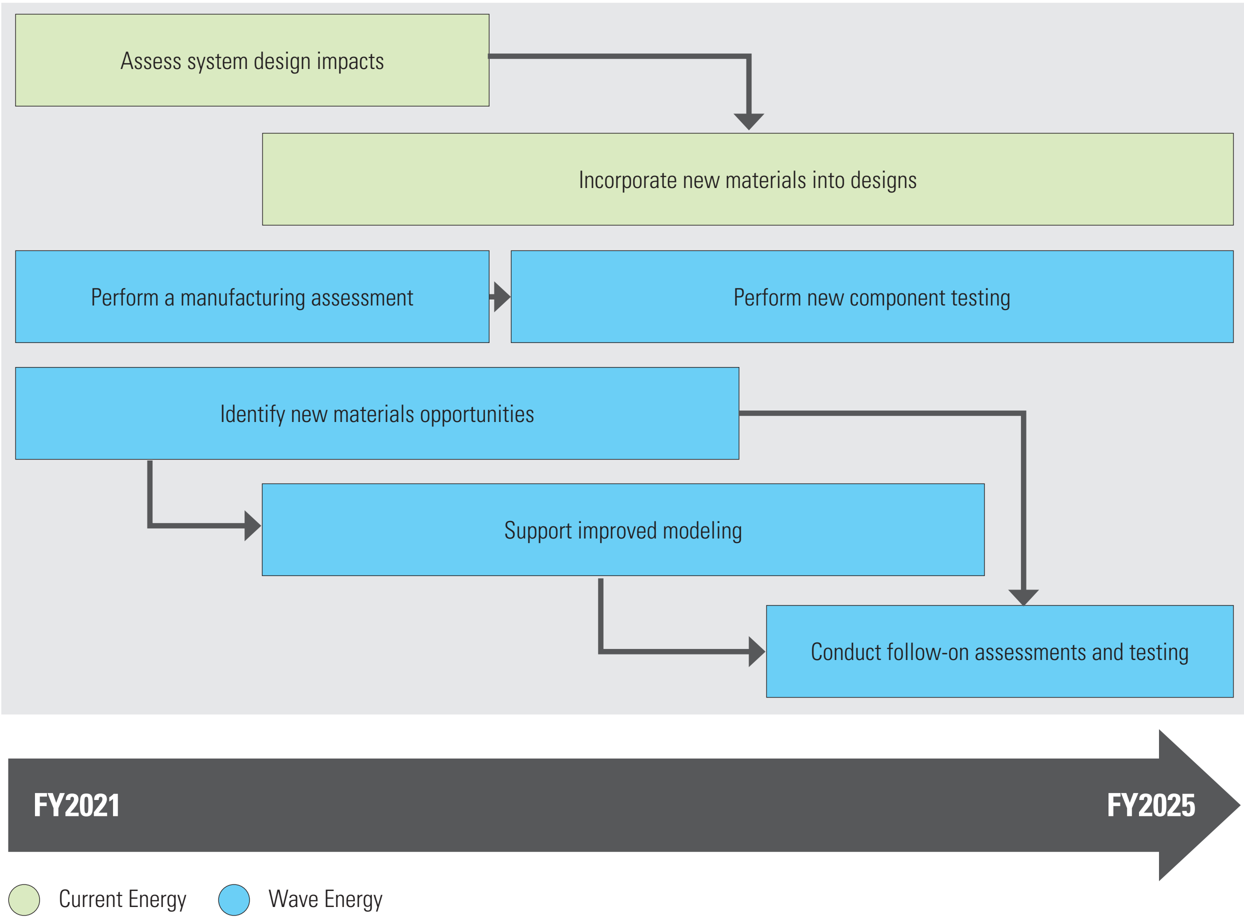
The following are the research priorities that will be emphasized within the Sub-Activity 1.1 – Foundational R&D:

- **Assess system design impacts**: Investigate potential design system impacts for current/tidal energy converters using novel materials and manufacturing materials.
- **Incorporate new materials into designs**: Incorporate novel carbon fiber materials into current/tidal energy converter designs.
- **Perform a manufacturing assessment**: Assess feasibility of additively manufactured wave energy converter components by evaluating potential time savings and quality of finished products. Evaluate the LCOE impact of the additive manufacturing technology with respect to incorporating thermoplastics or other thermosets/resins in WECs.
- **Support improved modeling**: Extend existing numerical modeling capabilities to analyze novel/unconventional material and coating performance.
- **Conduct follow-on assessments and testing**: As needed, further characterize and test materials that show potential for increased performance or reduced costs.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 27.

Figure 27. Sub-Activity 1.1 – Advanced Materials and Manufacturing Research Priorities



Additional Details

Advanced materials are enablers of technologies needed to construct devices for converting the tremendous energy available in water motion into usable electricity. The maritime environment is harsh and marine energy systems need to survive and thrive over long periods of time in order to be cost-effective. Material selection for a marine energy device is important as it has significant impacts on performance, capital equipment costs and operational costs. This sub-activity focuses on basic and applied science into materials that can be used by the marine energy industry, which has different constraints and performance requirements from other maritime industries. The challenges of cost/performance trade-off related to marine energy devices are addressed by utilizing the recent and continuing developments in advanced materials such as carbon fibers and thermoplastic composites, as well as manufacturing technologies such as additive manufacturing. Impacts of the research includes effects on LCOE since materials can impact the price/pound of the marine energy structure, manufacturing, O&M, reliability, and safety.

Marine energy devices will need to reliably operate for 20 or more years in harsh environments of oceans and rivers. These operational parameters place severe performance requirements of structural integrity and durability on the selected materials. Furthermore, water uptake into the material volume and deposition of marine organisms on surfaces create additional performance challenges. This sub-activity plans to support continued R&D to evaluate performance of materials and biofouling protection for devices in marine energy environments. Additionally, consideration will be given for R&D with new applications to marine energy, such as utilization of light weighting and integrated computational materials engineering to evaluate and develop materials with optimal combinations of characteristics to meet the needed performance requirements. Since operation and maintenance costs contribute significantly to the total device LCOE, these research areas focus on reducing this cost.

A significant part of the device capital expenditure cost is in its two main components: the energy-capturing structure and the electricity-generating structure called the PTO. While some of the materials considerations for the energy-capturing structures were discussed above, additional impactful R&D focusing on the PTO is also considered in this sub-activity. Further considerations are also given to new and emerging designs aimed at integrating these two parts in the WECs by utilizing for example flexible membranes and a concept called dielectric elastomer generator. Several materials and manufacturing challenges emerge that need to be addressed before the unconventional WECs with flexible membranes can become commercial devices. This sub-activity will explore the potential of these devices by supporting R&D that synthesizes new polymers, possibly by using nano-scale particles to modify the mechanical and electric conductivity characteristics.

Using advanced materials in marine energy devices requires properly characterizing the materials to determine their performance limits. This in turn requires knowledge of the hydrodynamic loads that act on the devices in the harsh marine environment as well as the materials response to those forces. This sub-activity will therefore support development of tools to calculate those forces and testing methodologies to characterize the material properties and their thresholds.

Sub-Activity 1.2 – Controls

Overview

Advanced controls and controls co-design research remains a major programmatic focus for current energy converters (CECs) and WECs. Previous studies[64] have shown that advanced controls improvements can provide significant increases in energy capture at varying timescales with recent tests doubling the energy capture for WECs over previous methods.[65] And controls have the ability to impact more than energy capture as well. Control systems can reduce both fluctuation frequency (from a large range of incoming wave frequencies or wave periods) and magnitude (from a large range of wave heights), thereby reducing cyclic loading, fatigue potential, and high stress occurrences. Controls can affect the amount of structural design margin needed to better estimate the amount of structural material and reduce capital expenditure. Control systems also effect in-water fatigue loading, impacting operational expenditure. Co-design involves designing and balancing requirements for the control of an marine energy system simultaneously with the design of other systems. The controls system and having a system that is controllable should not be an afterthought but be considered at the earliest stages of design analysis.

FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the Sub-Activity 1.2 – Controls:

- **Perform wave energy controls experiments**: Conduct multiple, diverse studies that consider control design approaches and device variables to produce publicly available data on controls system performance.
- **Advance sensor packages**: Develop and improve sensor packages to improve data collection on controls system performance in laboratory and open-water settings.
- **Perform opportunistic analysis of open-water test data**: Establish partnerships with developers and researchers to aggregate and analyze information on controls system performance from tests not directly funded by DOE.
- **Support third-party comparative analyses**: Support comparative and longitudinal studies of wave energy controls system efficacy by neutral third parties.

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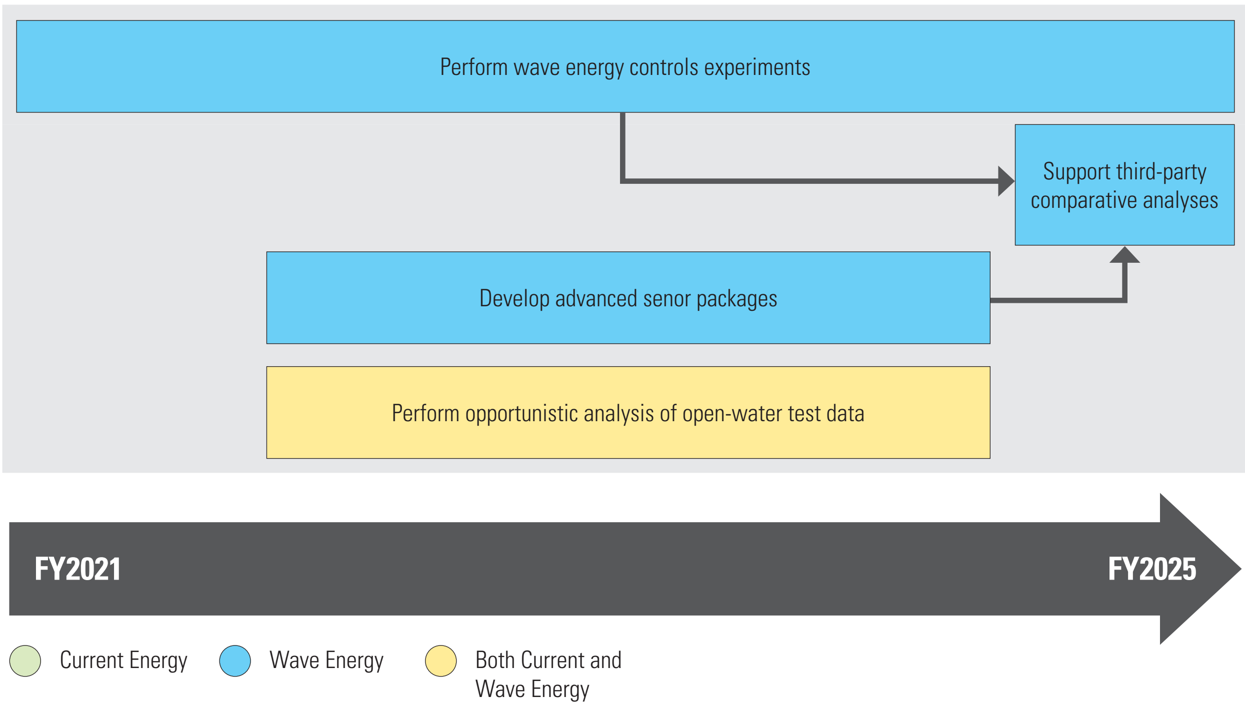
64 Dallman, A., Jenne, S., Neary, V., Driscoll, F., Thresher, R., and Gunawan, B. 2018, “Evaluation of performance metrics for the Wave Energy Prize converters tested at 1/20th scale.” https://www.osti.gov/biblio/1492503-evaluation-performance-metrics-wave-energy-prize-converters-tested-scale.

65 Bacelli, G. and Coe, R, 2020. “Comments on Control of Wave Energy Converters.“ https://ieeexplore.ieee.org/document/9005201.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 28.

Figure 28. Sub-Activity 1.2 – Controls Research Priorities



Additional Details

Controls and controls co-design strategies and technologies are being leveraged from other industries (e.g., aerospace and defense) that can maximize power production over a range of ocean conditions. Other priorities include improving and validating modeling tools and methodologies needed to optimize device and array performance and reliability across operational and extreme conditions. During early-stage R&D, targeted government support can generate knowledge benefits applicable to marine energy technology development and deployment by industry, as well as broader knowledge spillover benefits from innovations in materials, sensors, and modeling capabilities.

Controls are of particular importance in WEC design as these systems are often physically large, must be capable of surviving extreme weather events, and must navigate the trade space of spectrum, intensity, and occurrence. Existing WEC designs produce power efficiently over a narrow band of the full wave frequency spectrum. Wave energy tends to be concentrated at lower frequencies which often translates to low-speed, high-torque PTOs that are physically large and often requiring speed increasing mechanisms such as gearboxes. To achieve commercial viability, WECs must be able to absorb and produce power efficiently across a broad range of frequencies. Projects are developing and validating control strategies to increase power output of WEC devices. To make the difficult leap from theoretical studies to deployable WEC hardware, WPTO has multiple investments performing research on control algorithm development, numerical simulation, and scaled model testing.

WPTO seeks to enable broad implementation of advanced control systems across the marine energy industry to dramatically improve performance and reduce cost of marine energy converters. Investments will be targeted to build a portfolio that can provide foundational knowledge to industry on a broad range of key elements related to PTO and control system design.

Sub-Activity 1.3 – Numerical Modeling

Overview

Physical modeling and testing of scaled marine energy devices in the water, whether tank or open ocean, is complicated, expensive, and can involve long timelines. Numerical modeling partially ameliorates these burdens and accelerates multiple design iterations. Models empower developers to make appropriate design choices based on improved understanding of important fluid-structure interactions, energy capture and conversion, and structural load response, including device/array interactions with the marine energy resource and resultant effect on economic and environmental considerations. The complex fluid-structure interactions between marine energy devices and the marine environment govern device performance and survival and the environmental effects of marine energy devices. The Marine Energy Program supports the development of experimental and numerical methods to measure and predict device performance that are needed to design and optimize the next generation of marine energy technologies and lower the cost of marine energy.

FY 2021–2025 Research Priorities

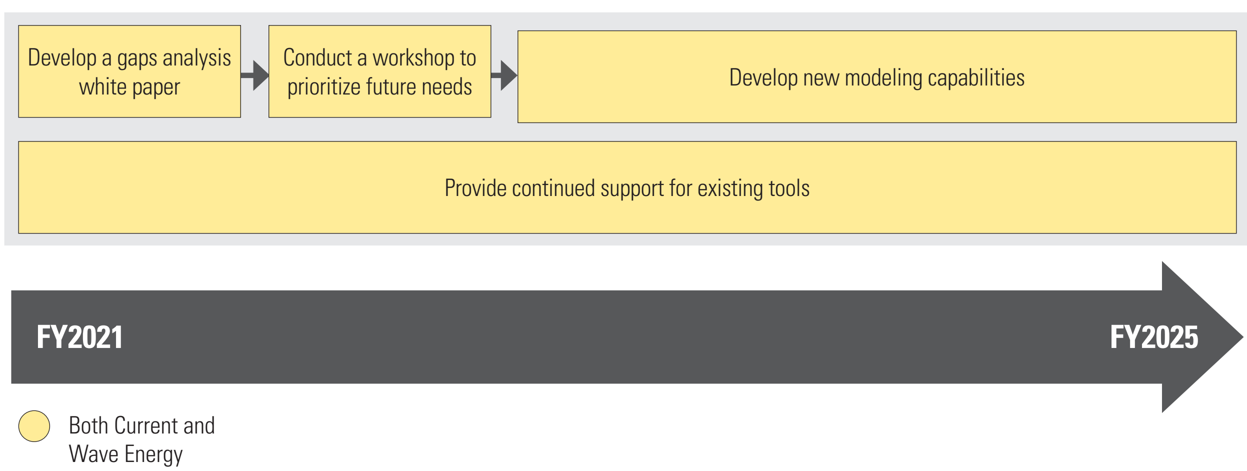
The following are the research priorities that will be emphasized within the Sub-Activity 1.3 – Numerical Modeling:

- **Develop a gaps analysis white paper**: Compile a document assessing existing marine energy software capabilities.
- **Lead a workshop to prioritize future needs**: Leverage the gaps analysis white paper to facilitate a workshop discussion with industry, universities, and researchers to determine what analytical capabilities are either missing or insufficient, and identify the priorities associated with developing these capabilities.
- **Develop new modeling capabilities**: Develop new tools and higher fidelity modeling capabilities using the priorities list established in the gaps analysis workshop.
- **Provide continued support for existing tools**: Maintain existing capabilities and functionality for marine energy numerical modeling tools.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 29.

Figure 29. Sub-Activity 1.3 – Numerical Modeling Research Priorities



Additional Details

WPTO works to stay informed on the continued development of international marine energy tools and commercially available models. International collaboration projects under the OES[66] through International Electrotechnical Commission (IEC) Technical Committee (TC) 114 (IEC TC 114)[67] are future opportunities WPTO can leverage to catalog other numerical tool sets and capabilities.

A quintessential project in this investment area is the development of the wave energy converter simulation tool (WEC-Sim), an open source numerical modeling code initially developed between 2012-2017 by the National Renewable Energy Laboratory and Sandia National Laboratories. Because existing commercial modeling codes were closed source and many were originally developed for offshore oil and gas and naval architecture applications, they were limited in their ability to accurately model wave energy converter dynamics and power performance. WEC-Sim provided other researchers and industry with an essential open-source tool to model wave energy devices.

Between 2021-2025, the WEC-Sim team will continue to disseminate the code (through outreach and publications), host training courses (in person and via webinar) and maintain the GitHub repository (by responding to user questions, merging pull requests, adding features, and resolving bugs). This effort supports DOE's missions by reducing the barrier of entry to new developers and innovative technologies. Success is measured by adoption of the WEC-Sim code by the wave energy community at large. WEC-Sim simulations are being used by OES Task 10.2 for its code verification and validation study.

Over the next five years, development work will continue for extreme conditions modeling (ECM). Efforts will include disseminating the WEC Design Response Toolbox (WDRT) through publications and training courses, conducting a set of WEC design load case studies using the ECM framework and accompanying tools, and developing a best practice document that describes the suggested framework for WEC design load analysis.

Between 2021-2022, WPTO will plan for an in-depth numerical modeling workshop where a broad and comprehensive range of industry stakeholders and other researchers will come together to evaluate existing capabilities, associated costs, challenges, and gaps. The workshop report will provide recommendations for the most impactful R&D that can be conducted to assist industry. Outcomes will be used to inform the strategy for maintenance of existing numerical modeling capabilities as well as future numerical modeling work.

Sub-Activity 1.4 – Components

Overview

Components research will continue to be a central priority for future marine energy R&D. Typical components in most marine energy systems include moorings, PTO systems, power conditioning, generators, speed-increasing mechanisms, control system hardware, seals, bearings, hydrofoils, or other prime movers. Current and past research in this sub-activity area has sought to optimize conventional and next generation subsystems and components with high potential for cross-cutting multiple energy conversion systems and technologies. Research has also emphasized advanced components and systems that are capable of operating in complex marine environments with limited operation and maintenance requirements. Past R&D efforts and experience have shown that power-to-weight ratio (PWR) and availability are central to lowering LCOE and increasing the value proposition for non-electric application of marine energy systems. Improvements in PWR can be achieved by increasing the energy capture and conversion efficiency of the device or by reducing its weight. Improvements in availability can be achieved through reduced maintenance, and improved reliability and survivability. Challenges and costs are amplified by the marine environment and therefore improvements to PWR and availability directly impact LCOE, and indirectly though IO&M (vessel availability and capability requirements, special purpose equipment such as cranes, etc.).

[66] International Energy Agency, 2016. "Wave Energy Converters Modelling Verification and Validation." https://www.ocean-energy-systems.org/oes-projects/wave-energy-converters-modelling-verification-and-validation/.

[67] Additional information on International Electrotechnical Commission Committee 114: https://tc114.us/.

FY 2021–2025 Research Priorities

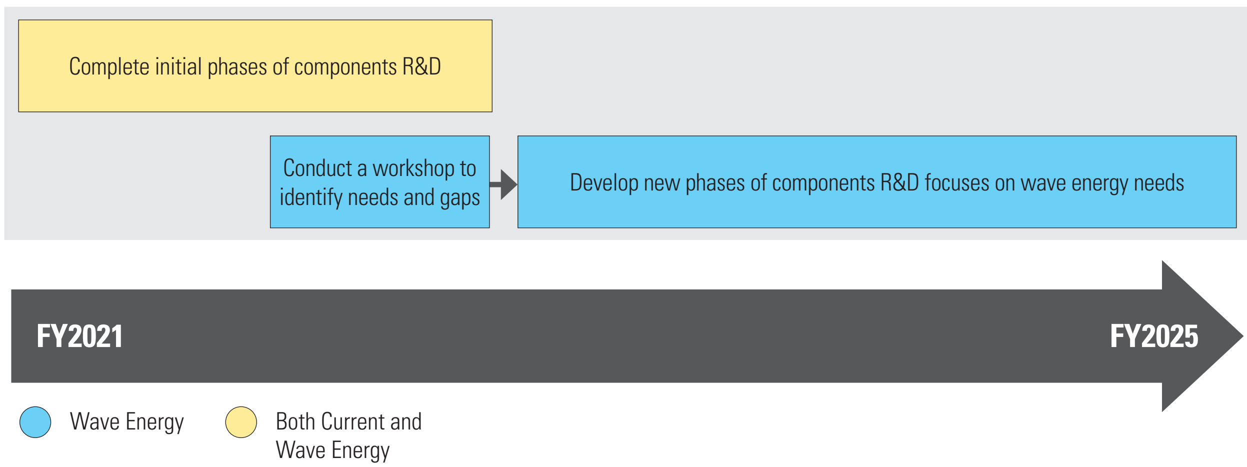
The following are the research priorities that will be emphasized within the Sub-Activity 1.4 – Components:

- **Complete initial phases of components R&D**: Continue work on conventional and next-generation PTO and energy conversion component research and testing.
- **Lead a workshop to identify future needs and gaps**: Engage with stakeholders in a workshop to identify gaps and opportunities to strategically prioritize resources for high-impact solutions in wave energy.
- **Develop new phases of components R&D focused on wave energy needs**: Develop targeted opportunities based on needs, gaps, and priorities.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 30.

Figure 30. Sub-Activity 1.4 – Components Research Priorities



Additional Details

Marine energy resources have large ranges in intensity and present other fundamental difficulties for designing systems to efficiently capture usable energy. These systems often operate in low-speed, high-torque environments resulting in large machines and the need for speed increasing mechanisms, such as gearboxes, which increase system complexity and maintenance requirements. Ongoing R&D includes magnetic gears and springs, magnetically geared generators, hydraulic pumps, and direct drive PTO concepts. As well, traditional means of energy capture and conversion require the use of components and storage elements, to translate energy into a usable form, that may not be optimal or optimized for the marine environment. Past R&D has shown great potential for incorporation of power conversion systems using wide band gap semiconductor devices, superconducting generator technologies, advanced control systems, and materials with enhanced conductivity for application in marine energy. Past experience has also shown mooring and umbilical systems are costly and often site and technology specific, which limit the useful life and ability to use across multiple systems and technologies. Ongoing research has largely focused on modeling and simulation capabilities for these systems. Current and past efforts have also sought to leverage technologies and innovations from other industries (e.g., hydropower, aerospace, defense, on and offshore oil and gas, offshore wind, and transportation) to accelerate the development of impactful solutions in marine energy, and to identify opportunities for co-development and optimization of shared components and subsystems (e.g., transmission, storage, power conditioning, etc.). While this approach facilitates rapid iteration and design evolution, considerable challenges exist with adaptation, integration, and application with marine energy technologies.

Future research efforts in this sub-activity area will target innovations and advancements which specifically address the challenges and opportunities highlighted above. Research activities will continue to support iterative improvements to conventional and next generation component and subsystems which reduce component size and complexity, increase modularity and standardization, and incorporate innovations in materials, controls, and manufacturing. Future efforts will also work to accelerate the development of components and subsystems which will facilitate rapid innovation and adoption of marine energy technologies in the PBE space.

Sub-Activity 1.5 – Resource Characterization

Overview

Resource characterization is fundamental to marine energy R&D, given the relatively early stage of the international industry and lack of convergence on device archetypes. Resource characterization provides key information on the opportunities, constraints, and risks for marine energy projects, in particular, (1) where resources (with target properties of magnitude and quality) are found; (2) how resources could enable different marine energy applications or project types (across scales, including grid and distributed); and (3) what challenges and opportunities resources pose, and in what time frame. The amount of energy capture relies upon not only the magnitude of these resources, but also other resource attributes, including speed, direction, and variability: technology development, optimization, and siting are all guided by characterization of a variety of resource attributes. Resource characterization is also critical for understanding the value and potential of marine energy, such as its predictability, and complementarity with other energy resources.

FY 2021–2025 Research Priorities

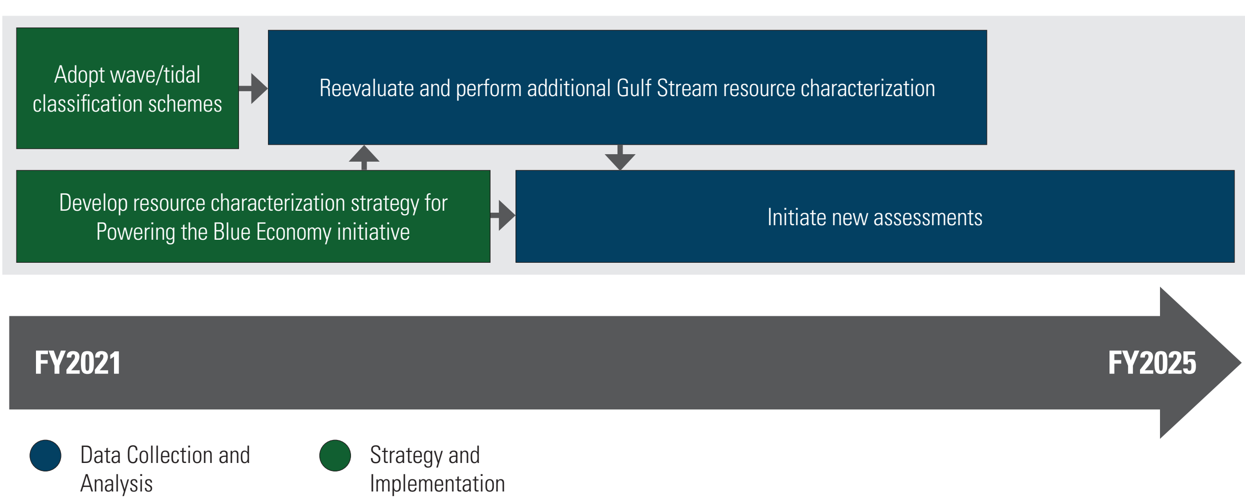
The following are the research priorities that will be emphasized within the Sub-Activity 1.5 – Resource Characterization:

- **Develop resource characterization strategy for the *PBE Initiative***: Determine additional data or analysis needed to characterize new PBE market opportunities.
- **Adopt classification schemes**: Develop wave/tidal classification schemes for IEC standards to streamline technology development and commercialization processes.
- **Initiate new assessments**: Support the development of new assessments for marine-powered desalinization and other emerging community-scale market opportunities.
- **Reevaluate and perform additional Gulf Stream resource characterization**: Evaluate and conduct Gulf Stream characterizations, incorporating feedback from industry.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 31.

Figure 31. Sub-Activity 1.5 – Resource Characterization Research Priorities



Additional Details

This sub-activity encompasses research and measurements, modeling and tool development, and data products and their dissemination and implementation. Measurements include both in-situ and remote observations and data processing. Some of these measurement data also feed into models. Modeling efforts include model development, refinement, and validation to generate high-resolution unstructured models of data sets that include a variety of statistics and resource parameters that characterize tidal, current, and wave resources in different geographic regions. Both measurements and models account for variability and extreme conditions that impact device performance and survivability. Measurements and data from models are shared across institutions and publicly through multiple formats including databases, maps, interactive tools, and publications. Users include developers and regulators, among others. Determining and sharing the types, variability, extent, and patterns of resources continues to be an important activity that supports technology development and optimization at multiple scales.

Resource characterization is cross-cutting; it informs and is informed by efforts across other areas of the program. For system development, marine energy resource assessments and characterizations are used to optimize devices and arrays. Resource characterization models and tools also inform how barriers to testing could be reduced. Resource characterization is critical for grid-scale and PBE initiatives as it underlies the development and efficacy of marine energy technologies across regions and scales.

Marine Energy Program Activity 2 – Technology-Specific System Design and Validation

Overview

R&D in the Technology-Specific System Design and Validation activity area focuses on (1) supporting the design, manufacture and validation industry-designed prototypes at multiple relevant scales; (2) improving methods for safe and cost-efficient installation, grid integration, operations, monitoring, maintenance, and decommissioning; (3) supporting the development and adoption of international standards for device performance and insurance certification; (4) supporting the early incorporation of manufacturing considerations into device design processes; and (5) leveraging expertise, technology, data, methods, and lessons from the international marine energy community and other offshore scientific and industrial sectors.

Activity 2 – Technology-Specific System Design and Validation consists of the following sub-activities:

1. System Design and Laboratory Testing: Designing, manufacturing, and testing proof-of-concept systems in laboratory and ocean settings to understand performance characteristics, identify and mitigate reliability risks, and provide data to inform future R&D to improve early-stage designs across the industry.
2. Open Water Testing: Validating systems in open water settings, resulting in data to inform future R&D and improve early-stage designs across the industry.
3. PBE: Developing new, marine energy-enabled technologies to address and relieve power constraints in markets and applications in the blue economy.
4. Standards Development: Developing and adopting international standards through the IEC.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 21.

Table 21. Technology-Specific System Design and Validation Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Complete initial field-testing for modular current energy converter systems that capture hydrokinetic river energy in low-flow environments (less than 2 m/sec) and can incorporate and advance IO&M techniques, which require only limited use of port and deployment vessel infrastructure. • Complete first year-long field tests of wave energy converter device designs in fully energetic wave environments (likely at the PacWave facility). • Complete at-sea, pre-commercial demonstrations of newly developed marine energy-powered ocean observing systems and desalination systems. • Concept refinement, design, and small-scale prototype testing of new wave energy system concepts with high techno-economic potential. • Establish U.S. capabilities for third-party certification of compliance to IEC Technical Specifications to include Power performance assessment, Assessment of mooring systems, Electrical power quality requirements, and Measurement of mechanical loads at PacWave wave energy test facility, and Power performance assessment of Current Energy Converters tested with the Mobile Test Vessel.
Follow-On Objectives (2026–2030)
• New, commercially available marine energy-powered ocean observation systems are deployed for a variety of uses. • Wave powered desalination systems are deployed for the first uses in disaster recovery or international development scenarios. • Documented improvements in energy-water system resilience and security for a number of targeted remote communities, enabled by marine energy systems. • International standards developed for device performance and insurance certification for grid-scale and blue economy market applications. Standards use established as best practice for all device tests and deployments. • First in-water, integrated system tests for newly developed wave energy device concepts. • Design and testing of megawatt (MW) scale current energy converter devices/arrays that incorporates installation, operation, and maintenance lessons.

Additional Details

Activities aligned with this area of work have increased steadily since the Marine Energy Program's initiation, as more component technologies have been developed and more devices have steadily matured. Focus in this area is expected to increase in the near to mid-term, eventually becoming the most significant area of focus within the Marine Energy Program, particularly as new facilities and capabilities become available to conduct in-water prototype testing more efficiently. In the long term, assuming sustained efforts to integrate new technologies into systems and test prototype devices produce successful results, prioritization of these activities would decrease slightly, as attention shifts to efforts focused on array-scale challenges and innovations. Still, persistent, long-term support of a critical mass of activities in this area will remain important to continually test and validate new innovations being introduced throughout in the industry.

Historically, investments to improve performance and reduce costs for multi-device arrays have comprised a small portion of the Marine Energy Program's portfolio, as efforts have been more focused on Foundational R&D and improving the performance of individual devices. Fewer efforts have thus far been dedicated to solving array-scale issues that could also influence how early-stage device designs are evaluated (e.g., considerations of IO&M issues, array interactions, and potential limitations of manufacturing large numbers of devices at scale). As discussed above, efforts focusing on addressing relevant array and plant-scale issues are expected to increase over time slowly and steadily, to the point where they will represent a much larger focus of the Marine Energy Program in the long term.

For industry to advance marine energy technologies beyond smaller-scale prototypes requires not only tank testing, but also open water validation of performance and efficiency, as well as reliability, especially in extreme sea states. Due to complexity in the wave physics of high-energy sea states and the fluid dynamics of sub-sea currents, even simple marine energy prototypes must be validated in open water to acquire data that accurately reflects system performance. This validation is expensive and time consuming due to the unique challenges of the marine environment, and it is generally beyond the capacity of pioneering technology companies that comprise the industry. Furthermore, industry-wide testing specifications and standards are still under development, leading to inconsistencies in how results are reported and ultimately making comparisons in performance data more challenging. Marine Energy Program support for in-water testing facilitates greater consistency between test protocols, test results, and accessibility of test data. The Marine Energy Program will continue ongoing research to develop and evaluate next-generation wave and current system designs, supporting and assessing promising components and early-stage integrated systems through national laboratories and university research, as well as industry partnerships for prototype development and validation.

Through support of device design and testing, the Marine Energy Program has demonstrated cost and performance baselines and improved device-specific efficiency and reliability. The Marine Energy Program has also provided critical, third-party validated data to inform continued early-stage research into new designs, materials, and systems. The Marine Energy Program is committed to investment in early-stage R&D that enables the domestic marine energy industry to advance toward achieving cost competitiveness with local hurdle rates in early adopter markets, including “power at sea” and “resilient coastal community” (RCC) applications, while working toward long-term cost-competitiveness at the utility scale. This will be accomplished by focusing on design concepts that have the potential to increase energy capture and annual energy production of devices, improve reliability and availability, and reduce capital and operating and maintenance costs if further developed and deployed by industry.

Sub-Activity 2.1 – System Design and Laboratory Testing

Overview

The Marine Energy Program’s System Design and Laboratory Testing strategy to help catalyze marine energy development focuses primarily on technology research and design tools to support the efforts of industry to reduce cost and improve performance of marine energy technology concepts at the system, rather than component, level. This research involves designing, manufacturing, and testing proof-of-concept systems in laboratory and ocean settings to understand performance characteristics, identify and mitigate reliability risks, and provide data to inform future R&D to improve early-stage designs across the industry. WPTO is committed to investment in early-stage R&D that supports the domestic marine energy industry to advance toward achieving cost competitiveness with local hurdle rates in near-term markets, where the cost of energy can be near or over $1 per kWh electricity while working toward long-term cost-competitiveness at the utility scale. This will be focused on design concepts that have the potential to increase energy capture and annual energy production, improve reliability and availability, and reduce capital and operating costs if further developed and deployed by industry. Key to this process, this sub-activity includes validation of the computer modeling tools and methodologies developed in Sub-Activity 1.3 – Numerical Modeling, which are needed to optimize device and array performance and reliability across operational and extreme conditions.

FY 2021–2025 Research Priorities

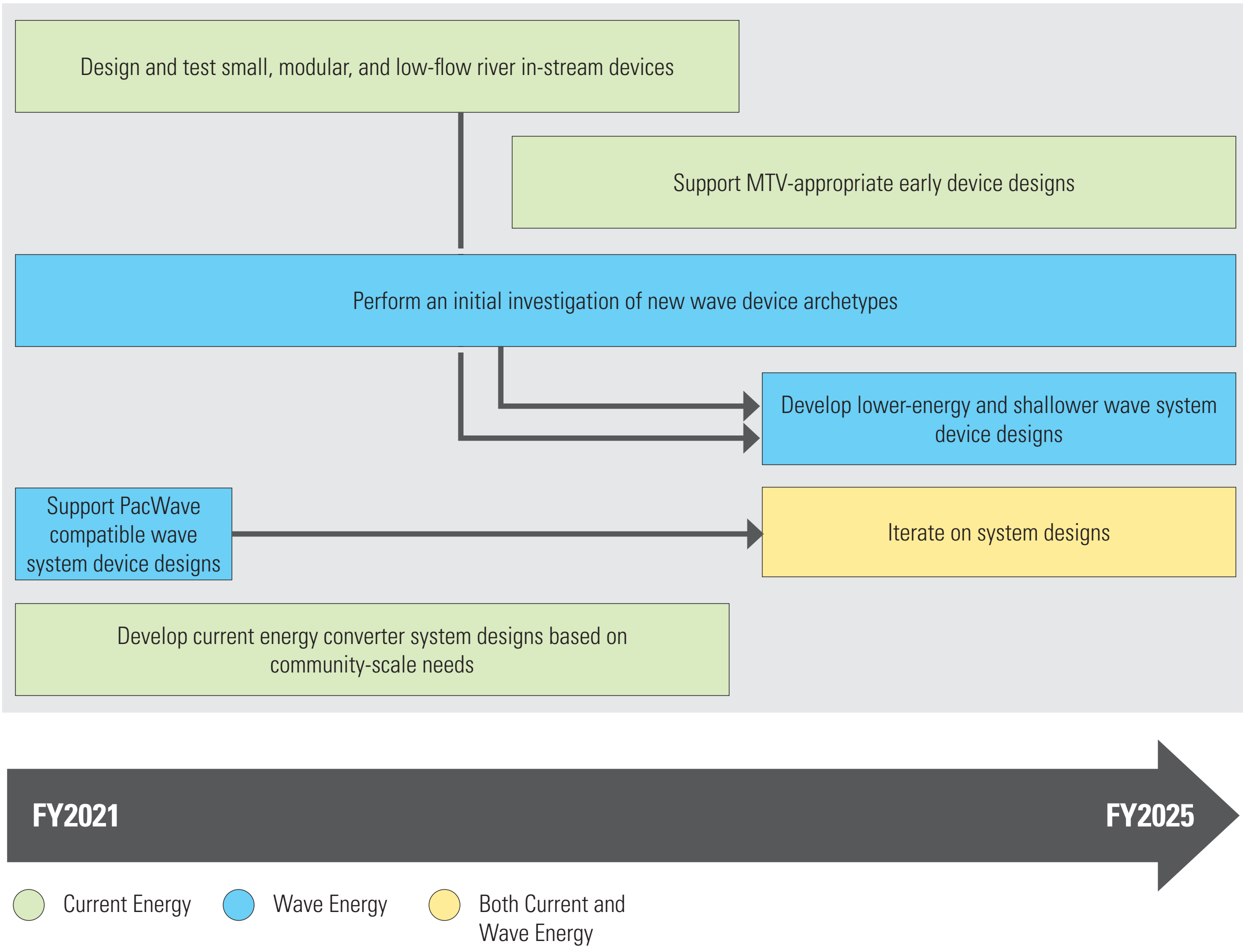
The following are the research priorities that will be emphasized within the Sub-Activity 2.1 – System Design and Laboratory Testing:

- **Design and test small, modular, and low-flow river in-stream devices**: Design and test modular CEC systems that can be efficiently installed and retrieved without the need for significant port or on-site infrastructure and specialized vessels.
- **Support mobile test vessel (MTV)-appropriate early device designs**: Enable CEC system designs whose prototype field validation could utilize the MTV, a fully mobile test platform capable of operations in locations with limited infrastructure support in multiple open-water flow conditions and geographic locations.
- **Perform an initial investigation of new wave device archetypes**: Investigate new wave device archetypes, including flexible, non-rigid-body materials and distributed PTO systems.
- **Develop lower-energy and shallower wave system device designs**: Perform laboratory and tank testing of novel WEC designs with high techno-economic potential.
- **Support PacWave compatible wave system device designs**: Perform system design and laboratory testing of larger wave energy converter devices compatible with a fully energetic wave resource, such as PacWave.
- **Develop current energy converter system designs based on community-scale needs**: Develop current energy converter system designs for the Energy Transitions Initiative (ETI) and microgrids, including energy-storage systems and appropriate community selection.
- **Iterate on systems designs**: Incorporate data analysis and lessons learned from wave and current energy testing to iterate on device designs, which will inform crosscutting foundational R&D innovations and optimization in components (materials, controls, and foundations/anchors), maintenance, and supply chain.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 32.

Figure 32. Sub-Activity 2.1 – System Design and Laboratory Testing Research Priorities



Additional Details

Systems Design and Testing R&D activities will also include a focus on design concepts that have the potential to serve existing or emerging ocean-based technologies that can advance the nation's military, commercial, and scientific capabilities. These include power for remote coastal communities and Department of Defense installations with high electricity costs, charging for ocean-based sensors and underwater vehicles, and non-electric uses like desalination. Development and testing for these applications will provide critical data and experience that will accelerate design improvements and cost reductions for grid-connected power generation.

Previous projects have enabled the marine energy industry to progressively test new designs for wave, current, and tidal energy converter components and systems to enable the performance and reliability improvements required for cost reductions. WPTO's wave energy portfolio has evolved from focusing specifically on component level advancements in controls, structures, and PTOs to the projects focused primarily on innovation and design improvements at the system level. This iterative and systematic design process is necessary to achieve the Marine Energy Program goals for continuous improvements in LCOE.

Designing wave, current, and tidal energy converter systems that meet rigorous marine energy design standards is a goal and a critical step on the path to grid-scale testing at fully energetic environments such as PacWave for wave devices, as well as technology commercialization. The system designs will be verified through rigorous design reviews. There is a focus on WEC designs that are capable of two years of continuous testing and operations utilizing relevant physical characteristics and wave climate. The designs must incorporate the

IEC Technical Specifications (TS) and the Institute of Electrical and Electronics Engineers standards to ensure that designs are final and fully ready to utilize for future shipyard fabrication and open-water testing via future funding opportunities. The development of international standards is critical to increase investor and stakeholder confidence, and reduce project insurance costs, by incorporating best practices developed in related marine industries that have proven designs and operations. Lessons learned and data collected during PacWave testing will be used to inform further development of standards as well as the next generation device designs to expeditiously advance wave energy technologies.

Sub-Activity 2.2 – Open Water Testing

Overview

In order for the marine energy industry to improve performance and reliability of WEC devices and more efficiently extract the maximum energy from the available wave resource, open water testing in a relevant environment is required. The Marine Energy Program's strategy to help catalyze marine energy development focuses primarily on technology research to reduce cost and improve performance of marine energy technology concepts. The open water testing sub-activity focuses on further understanding performance characteristics, as well as identifying and mitigating reliability risks, of the proof-of-concept systems developed under the system design & testing sub-activity. This is accomplished by validating those systems in open water settings, resulting in data to inform future R&D and improve early-stage designs across the industry.

This testing validates modeled system designs to increase energy capture and annual energy production, improve reliability and availability, and reduce capital and operating costs. Research in this area will support industry to overcome the unique challenges of operating, potentially in deep water, to extract the oscillatory and highly energetic the wave energy by supporting wave energy convertor system design, development, and testing at locations such as the Navy's Wave Energy Test Site (WETS) in Hawaii and Scripps Institution of Oceanography off the coast of California; and assessing cost and performance drivers for WEC and farm systems.

FY 2021–2025 Research Priorities

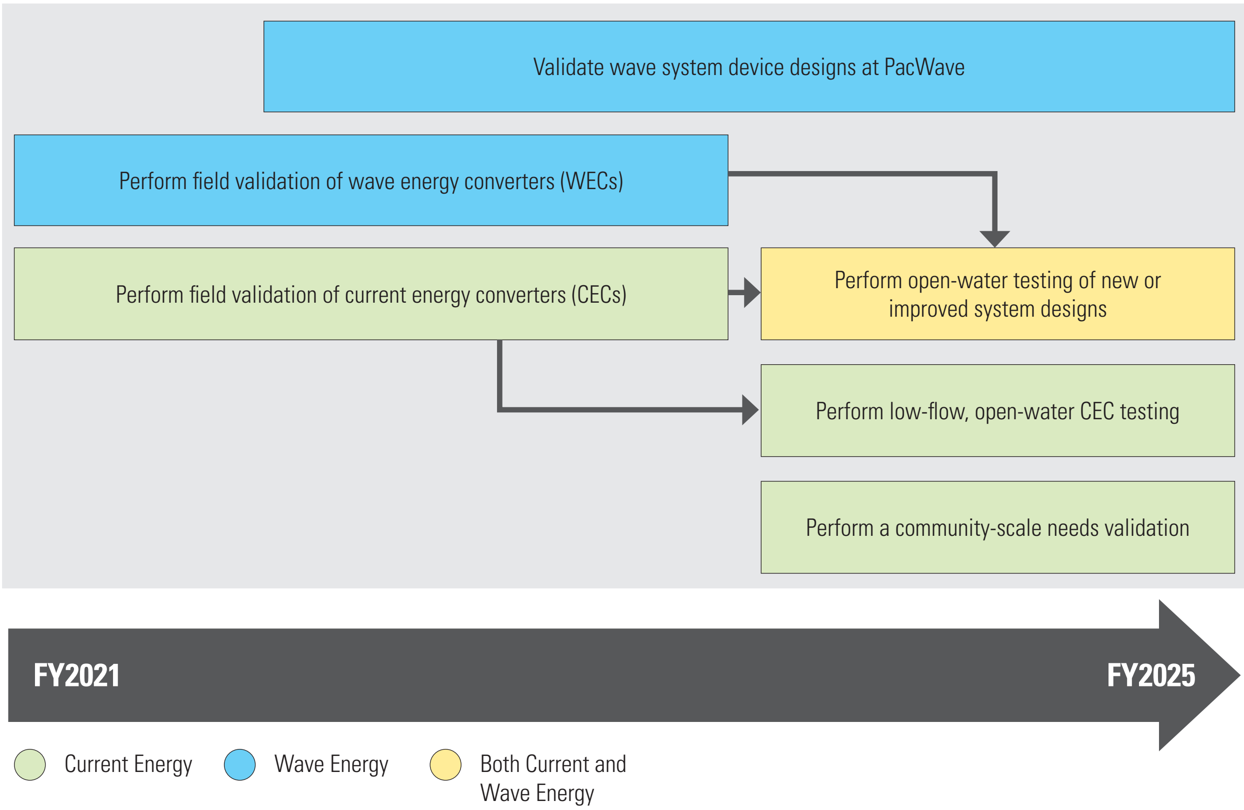
The following are the research priorities that will be emphasized within the Sub-Activity 2.2 – Open Water Testing:

- **Validate wave system device designs at PacWave**: Perform grid-connected field testing of WEC devices in open water at PacWave.
- **Perform field validation of WECs**: Perform open-water field testing of WEC devices in resources that produce less than 20 kW of annual average power (e.g., WETS, Scripps).
- **Perform field validation of CECs**: Perform open-water field testing of current and tidal energy converter devices at locations such as Roosevelt Island Tidal Energy and Igiugig.
- **Perform open-water testing of new or improved system designs**: Test novel and revised wave and current energy technologies for improved performance and reliability, as well as reduced IO&M costs.
- **Perform low-flow, open-water CEC testing**: Perform field testing of CEC optimized for different flow characteristics, such as low-flow environments.
- **Perform a community-scale needs validation**: Perform field testing of CEC system designs for ETI and microgrids, including energy-storage systems, at communities.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 33.

Figure 33. Sub-Activity 2.2 – Open Water Testing Research Priorities



Additional Details

Activities in this area will inform performance estimates to validate numerical models for sub-MW annual average power systems. This will in turn improve American Electric Power estimates and inform performance optimization opportunities. Additionally, testing in this sub-activity area informs refinement of operation and maintenance strategies for single device and array systems, which in turn will identify O&M cost reduction opportunities to decrease LCOE.

A process similar to that described above for wave energy technologies also applies to improve performance and reliability of CECs; validation of tidal and current energy capture devices in open water is required to more efficiently extract the maximum energy from tidal, ocean current, and river current resources. Continued R&D to overcome unique current energy challenges is anticipated by supporting current energy convertor system design, development, and field testing in multiple open water flow conditions, including locations in Alaska, New York, and Maine. Work in this sub-activity to design, fabricate, and test CECs will also be used to inform preliminary work to better understand the desired characteristics and requirements for a CEC test facility in the United States—for example, what are the best characteristics of the point of integration between the test facility and grid, what are the desired resource characterizations for test facility, and what are the critical risks to permitting the facility. Efforts focusing on addressing relevant array and plant-scale issues are expected to slowly and steadily increase over time, through collaboration with other DOE offices interested in extracting energy from current and tidal resources, testing of innovative CEC designs, and informing improvements in deployment and retrieval techniques.

Sub-Activity 2.3 – Powering the Blue Economy

Overview

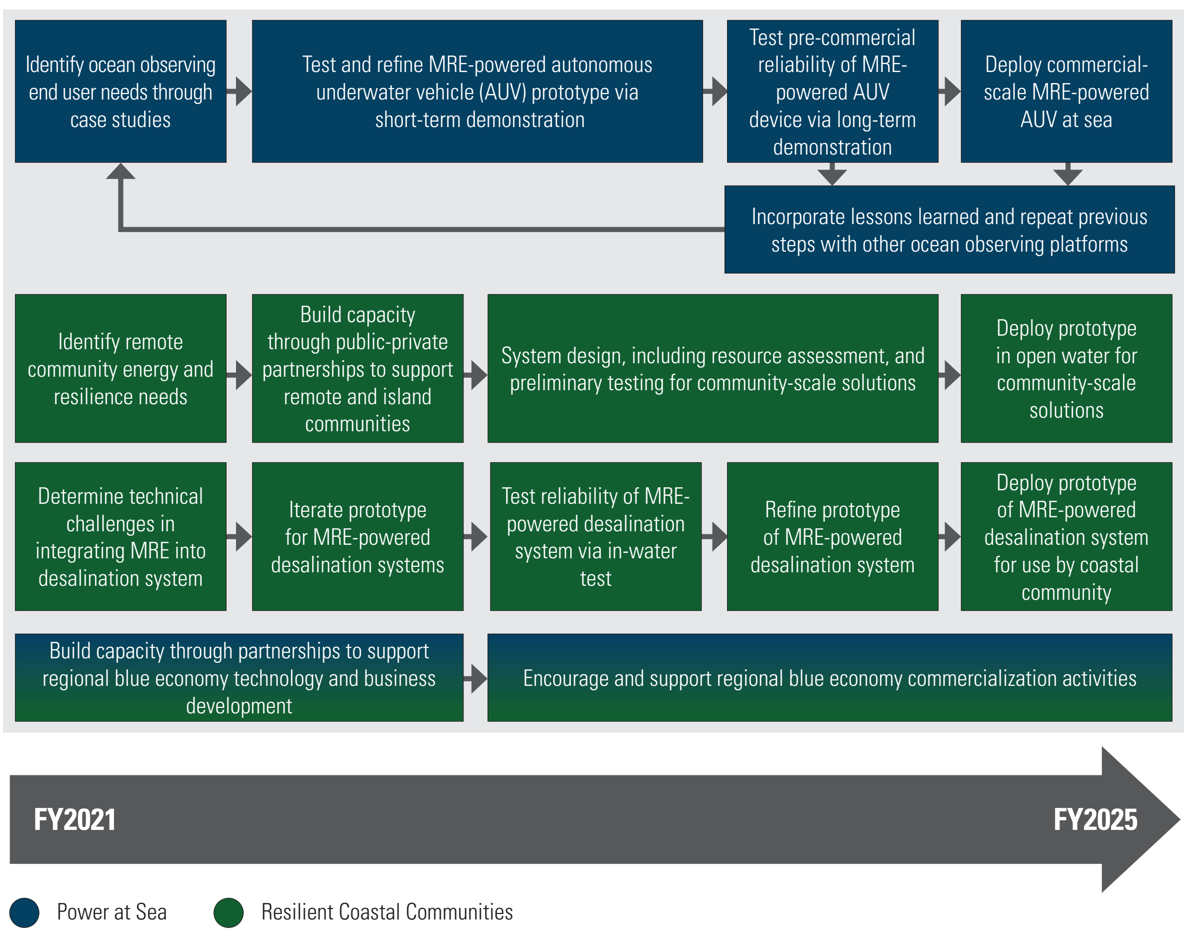
The PBE initiative seeks to develop new, marine energy-enabled technologies to address and relieve power constraints in markets and applications in the blue economy. This will be accomplished by focusing on the R&D of technologies that address the power requirements of multiple different coastal and maritime markets. There is enormous potential to support existing needs of mature markets like ocean observing, while also potentially creating new markets by relieving the energy constraints. Previous analysis[68] has shown that marine energy resources could be particularly well-poised to address power constraints in the blue economy because they are abundant, geographically diverse, energy dense, predicable, and complimentary to other energy sources. Since 2017, WPTO has been building a portfolio of R&D to better understand energy constraints and requirements in the blue economy, established partnerships to advance marine energy solutions in the blue economy, and launched activities to support the R&D of prototypes to realize the potential of an ocean energy-enabled blue economy.

While PBE is a specific sub-activity within marine energy, the success of PBE will also include work that draws from foundational R&D, technologies will be supported through testing and infrastructure, and ultimately lessons learned from PBE will be critical to translating findings for grid-scale marine energy applications. More information on PBE, including the goals, key principles, and partnerships critical to success of this initiative can be found in the detailed PBE section.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 34.

Figure 34. Sub-Activity 2.3 – Powering the Blue Economy Research Priorities



[68] U.S. Department of Energy, 2019, "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets." https://www.energy.gov/eere/water/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets#pbereport.

Additional Details

While PBE is a specific sub-activity within marine energy, the success of PBE will also include work that draws from foundational R&D, technologies will be supported through testing and infrastructure, and ultimately lessons learned from PBE will be critical to translating findings for grid-scale marine energy applications. There are three focus areas within PBE, including:

- **Power at Sea**: From ocean exploration and navigation to aquaculture, many marine-based applications and markets are located far from shore and sometimes in deep water. Delivering power to these systems can be expensive and difficult but powering these systems with energy derived from the ocean offers a cost-effective alternative. Markets considered within this focus area include ocean observation, underwater vehicle charging, marine aquaculture, marine algae, and seawater mining.
- **RCC**: Marine energy can help support coastal communities, making them more resilient in the face of extreme events such as tsunamis, hurricanes, floods, or droughts. Many marine energy applications are ideally suited to coastal development by offering relatively easy access for installation and operation and maintenance activities, providing a predictable and uninterrupted energy supply, and potentially reducing land requirements needed by many land-based energy solutions. Markets considered within this focus area include seawater desalination, coastal resilience and disaster recovery, and isolated communities.
- **Crosscutting Activities**: In addition to market and application specific work conducted under the Power at Sea and RCC focus areas, there is key crosscutting research that is needed to enable marine energy-powered systems for the blue economy, including but not limited to storage integration, reliability measures, mooring designs, and the development of small-scale marine energy systems. Additionally, these crosscutting activities include creating partnerships necessary for the commercialization of all PBE applications and supporting the development of incubation and entrepreneurial support networks and programs.

Power at Sea

As a focus area within of PBE, Power at Sea activities target energy innovation to both augment existing offshore activities and enable future offshore missions or markets. To better understand the engineering and R&D challenges for these markets and applications, the development of case studies where clear end user needs identified are instrumental in identifying foundational R&D needs. This deep analysis of customer needs and the identification of R&D to address these needs is key for both marine energy integration into existing deep offshore platforms and applications like integration of marine energy into existing offshore observation platforms as well as future consideration for providing power at sea for new offshore activities like deep offshore aquaculture. The core focuses within Power at Sea include defining energy needs for various activities or missions at sea, supporting development of prototypes that are ready in the near-term and reduce design iteration timelines, and identifying potential commercialization pathways for novel solutions. Some of the major elements of work related to Power at Sea goals include:

- Undertake case studies that examine the functional requirements of existing applications, like ocean observing platforms currently deployed, and identify key challenges to the development of these systems for at-sea applications.
- Build on the results of the joint NOAA-DOE Ocean Observing Prize, which was launched in 2019, to advance the development of marine energy-powered ocean observation platforms, including the recharging of autonomous underwater vehicles. This includes refining and maturing solutions that are supported through the prize through mechanisms like interagency solicitations.
- Develop deployment-ready prototypes in partnership with the ocean observing community, including working with federal partners like NOAA to build systems that meet the needs of this community.
- Develop R&D and understanding needed to develop devices could serve multiple end-uses, where a marine energy system could be deployed to serve multiple markets, like ocean observing, aquaculture, and desalination all through electricity delivery.

Resilient Coastal Communities

As a focus area of PBE, RCCs supports energy innovation for remote coastal and island communities with a focus on end-user needs, emergent blue economy markets, and technology optimization. Identifying R&D challenges and building the foundations of collaborations and partnerships are fundamental to success of RCC objectives. Core focus areas are technology optimization in remote communities, system integration, and energy storage. Some of the major elements of work related to RCC goals include:

- Build connections, partnerships, and capacity for remote coastal and island communities to consider their energy planning and resilience goals with the ability to orient around evolving marine energy R&D questions and the deployment of marine energy devices.
- Test marine energy devices in a variety of remote communities to validate grid-forming and baseload generation capabilities, integrating and hybridizing energy services.
- Demonstrate and commercialize wave powered desalination for disaster recovery, military applications, international development, or other specific water market segments as cost-competitive with existing systems.
- Identify designs and research for integrated energy systems (microgrids, energy storage, and hybrid renewable systems) for coastal and island systems focused on local industries, transportation, conservation, and resilient systems.
- Develop key connections with blue economy finance and accelerators to support adoption of technologies ready for deployment.

Crosscutting Activities

In addition to the above targeted activities, the PBE initiative includes crosscutting activities aimed at developing platform R&D to support marine energy-powered systems and grow the capabilities to connect end-users and customers with new technological solutions across the blue economy. These activities include:

- Identifying crosscutting R&D needs through the undertaking of market-specific use case studies for marine energy.
- Designing strategies to enable the adoption of marine energy technologies for a large customer base and blue economy markets, including conducting analysis to demonstrate the value of these systems for the customers.
- Forging partnerships with other agencies to enable the uptake of marine energy enabled devices.
- Establishing partnerships to encourage entrepreneurial training and growing an ecosystem to support the incubation of blue economy industries.

Sub-Activity 2.4 – Standards Development

Overview

The standards development sub-activity focuses on the development and adoption of international standards through the IEC. These standards have proved critical in the development of related renewable technologies (e.g., wind), so pursuing them for early-stage technology like marine renewable energy is likely to advance the development here as well. Internationally accepted standards for marine renewable energy are currently being developed through IEC TC 114. These international standards can accelerate economic growth by reducing barriers to global trade and enabling companies to enter new markets more quickly and cost-effectively. Additionally, standards can help governments write regulations that have the input of the industry and ensure safety for consumers. Standards also facilitate international collaboration, provide high-quality, reproducible test results, improve the quality of the devices, stimulate innovation, lower development risk to investors, increase transparency to regulators and public, and, ultimately, reduce costs. WPTO will also continue to support U.S. participation in other international bodies, like OES, to foster international collaboration in the marine energy sector.

FY 2021–2025 Research Priorities

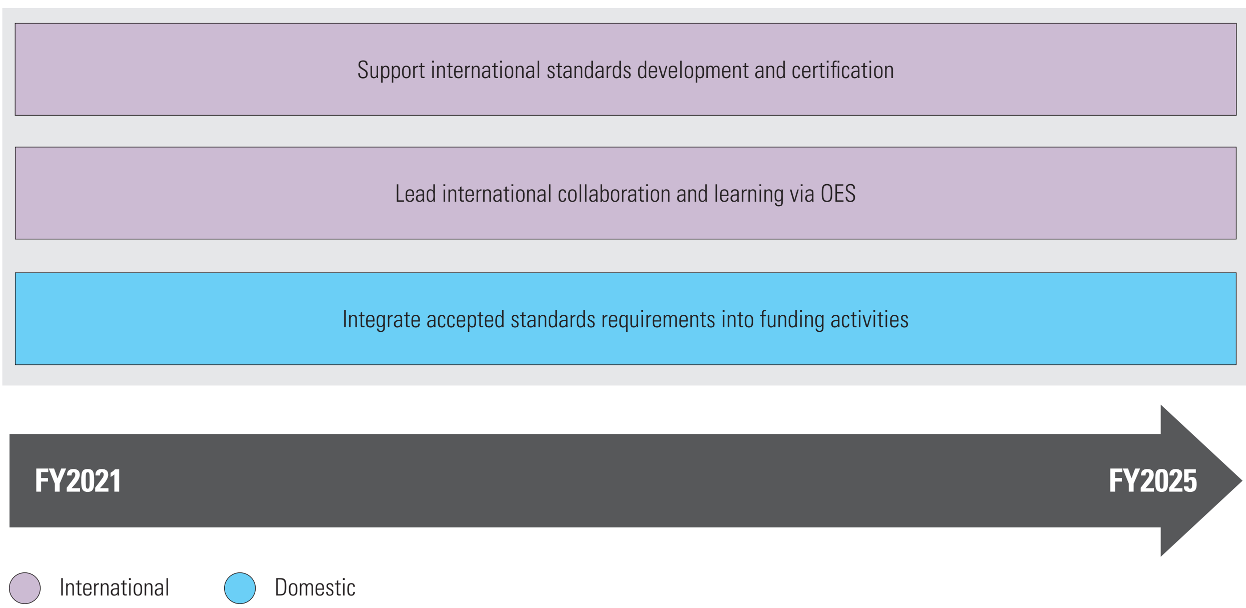
The following are the research priorities that will be emphasized within the Sub-Activity 2.4 – Standards Development:

- **Support international standards development and certification**: Continue to support U.S. involvement in TC-114 standards development and IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications certification activities.
- **Lead international collaboration and learning via OES**: Continue to lead U.S. involvement in the growing OES technology collaboration.
- **Integrate accepted internationals standards into funding activities**: Encourage and/or require funding recipients to utilize international standards during their DOE-funded projects.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 35.

Figure 35. Sub-Activity 2.4 – Standards Development Research Priorities



Additional Details

Accordingly, WPTO will continue to support U.S. experts to enable participation in the U.S. Technical Advisory Group and IEC TC 114, ensuring U.S. priorities are represented. Additionally, WPTO will encourage standards and conformity in assessment-relevant WPTO projects to feed into the international standards process through DOE expert participation, data sharing, and communicating lessons learned. As more standards are written and tested, WPTO will increase participation equivalently as well as track usage to supplement the data collected by the U.S. National Committee and the IEC. WPTO will advocate for standards to be incorporated into WPTO project planning when appropriate, ensuring that the draft technical specifications are put into practice and future iterations incorporate any lessons learned.

In the future, WPTO will consider the role of standards in developing and demonstrating non-grid, smaller scale marine renewable energy devices, and follow best practices established during the development of grid-scale standards to ensure lessons learned are incorporated as standards are used in the field. Additionally, WPTO will consider other relevant standards such as environmental standards in other maritime markets, like aquaculture when developing devices of a relevant scale.

Marine Energy Program Activity 3 – Reducing Barriers to Testing

Overview

Testing marine energy technologies is inherently more complex, expensive, and time consuming than for land-based energy generation technologies. The already slow pace of design and in-water testing cycles is further exacerbated by the limited availability of testing infrastructure at various scales, complex and time-consuming permitting processes, and expensive environmental monitoring (again, driven by being in-water). These challenges severely limit the ability of technology developers to quickly assess the performance of devices and components, innovate solutions where necessary, and iteratively test the next generations of devices. Because of the complex physics of the ocean wave and current environments, marine energy prototypes must be tested in real-world environments to fully characterize their performance and reliability. These challenges associated with testing, deploying, and optimizing technologies in a timely and cost-effective manner must be overcome to accelerate the pace of marine energy technology development. This activity area supports national assessments of testing infrastructure and needs, the development of testing facilities (including open-water, grid-connected and non-grid connected facilities) and NMRECs, instrumentation hardware and software dedicated to high resolution data acquisition, as well as environmental data collection.

This activity area connects to all other activity areas within the Marine Energy Program. Test infrastructure enables developers to iterate on their design and advance systems towards commercialization (Activity 2 – Technology-Specific System Design and Validation). Through testing, early-stage foundational research and models are also improved and validated (Sub-Activity 1.3 – Numerical Modeling). Furthermore, critical performance and cost data is collected during testing and is widely distributed to support industry to the greatest extent possible (Sub-Activity 4.1 – Data Access and Workforce Development).

Activity 3 – Reducing Barriers to Testing consists of the following sub-activities:

1. Testing Infrastructure Access and Development—Laboratory Facilities: Reducing barriers to laboratory testing and validation for technology innovation.
2. Testing Infrastructure Access and Development—Open Water Testing: Developing a pre-permitted, grid-integrated, open water test facility to provide marine energy developers a fast and streamlined process to install and test large-scale devices in a relevant ocean environment.
3. Environmental Research and Instrumentation Development: Gaining a greater understanding of the potential environmental risks associated with marine energy technologies through environmental monitoring technology and tool development, and targeted environmental research studies and data collection.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 22.

Table 22. Reducing Barriers to Testing Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Complete a minimum of 100 technical support actions under the Testing Expertise and Access for Marine Energy Research (TEAMER) initiative in collaboration with U.S. universities and national laboratories. • Develop a U.S testing network of at minimum 30 facilities, including a range of capabilities across traditional marine energy research facilities as well as new incumbent facilities with interdisciplinary expertise including non-grid applications. • Identify testing infrastructure gaps, including needs for non-grid applications, at universities and the national laboratories and, as appropriate, address those needs through infrastructure upgrades and development of new capabilities. • Commission, initiate testing, and gain accreditation for the PacWave grid-connected, open-ocean, wave test facility. • Demonstrate the improved technical performance of seven environmental monitoring technologies in relevant marine energy environments while opportunistically collecting data on acoustic outputs, electromagnetic field signatures, benthic habitats, and marine organism interactions with marine energy devices.
Follow-On Objectives (2026–2030)
• Significantly reduced timelines of design iterations for developers and researchers working in the marine energy industry, ultimately accelerating the iterative R&D process. • Validate cost and performance of devices through industry standards, providing confidence to regulatory, investor, and insurance communities. • Adoption of best practices for environmental monitoring technologies resulting in more consistent data collection across projects and greater confidence in the conclusions about the level of risk of specific environmental concerns.

Additional Details

At this time, open water testing capabilities are limited for all variations of marine energy technologies (wave, ocean current, tidal, river current). Gaps also exist in smaller scale tank testing for systems and components. In some cases, a new capability is required, and in other cases, upgrades to existing facilities or equipment are required to enable higher fidelity testing in support of industry needs. This activity area supports efforts to ensure a robust suite of testing capabilities at all levels of technology development are available to industry to help improve device performance and reduce costs and timelines associated with permitting. Providing industry with access to an economical, world-class infrastructure is an important part of WPTO's long-term marine energy strategy. There is a distinct inefficiency associated with developers independently investing in either their own or separate testing facilities, and through strategic investments, this activity area will enhance and enable broader industry usage of testing facilities while reducing costs to both developers and to WPTO.

Sub-Activity 3.1 – Testing Infrastructure Access and Development—Laboratory Facilities

Overview

This sub-activity focuses on the strategic investments made by WPTO to support reducing barriers to laboratory testing and validation to achieve technology innovations. marine energy device developers often face challenges raising the capital needed to conduct necessary laboratory and tank testing, as facilities with the necessary infrastructure are relatively rare, costly, and difficult to access. This challenge slows the pace of design iterations required to reduce LCOE, as appropriate testing infrastructure is critical to verifying and validating design assumptions and numerical models. By providing access to testing facilities and expertise on how to perform experiments in controlled environments and numerical modeling in operational and extreme conditions, as well as making investments to upgrade and improve existing facilities and capabilities, testing costs are reduced and more robust testing at smaller scales is enabled. This in turn supports work in the Foundational R&D activity area and Technology-Specific System Design and Validation activity area by:

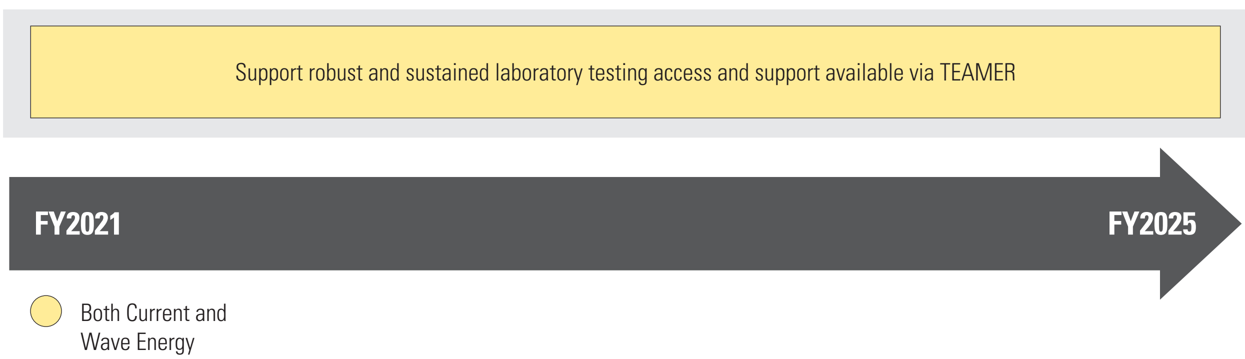
- Informing design decisions at an early stage.
- Validating numerical and analytical models through testing of physical models.
- Increasing credibility and comparability of performance test data.
- Enabling use of common performance metrics and testing standards.
- Providing world-class research and testing expertise to improve marine energy technologies.

FY 2021–2025 Research Priorities
The following are the research priorities that will be emphasized within the Sub-Activity 3.1 – Testing Infrastructure Access and Development—Laboratory Facilities:

- **Support robust and sustained laboratory testing access and support available via TEAMER**: Oversee the release of two to four requests for technical support per year for the initial period for the TEAMER program; expand the testing network; identify any additional infrastructure needs/gaps; and, as appropriate, address those needs.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 36.

Figure 36. Sub-Activity 3.1 – Testing Infrastructure Access and Development—Laboratory Facilities Research Priorities



Additional Details
Insufficient laboratory validation and measurements of components and systems can lead to potential in-water deployment failures, propagation of design errors, and slow technology advancement. To prevent this and maintain water power mission readiness, investments in this sub-activity area include facilities and testing capabilities infrastructure, such as dynamometers, hardware-in-the-loop equipment, micro-grid infrastructure, and structural and materials bench testing capabilities. As marine energy technologies advance in maturity and new design concepts are developed, laboratory testing capabilities must also be maintained and advanced.

To be impactful, these well-maintained facilities, advanced capabilities, and expertise must also be accessible. To facilitate this access, this sub-activity includes work to support a multi-year test campaign in collaboration with U.S. universities and national laboratories for early-stage marine energy systems. This initiative leverages the robust network of lab, university, and government facilities and maintains capabilities to perform cutting edge research, while simultaneously emphasizing component and system early learning opportunities via advanced numerical modeling and analysis. Researchers leveraging and supported through this network will also identify gaps in testing needs through an ongoing, iterative assessment of the available network facilities.

Sub-Activity 3.2 – Testing Infrastructure Access and Development—Open Water Testing

Overview

As the marine energy industry continues to advance technologies towards commercialization, there is an ongoing need for testing at all levels of technological development, including large-scale devices in the open water. Marine energy converter prototypes must be tested in real-world environments to fully characterize and validate the performance, reliability, maintainability, and potential environmental impact. However, open water testing can be the most expensive and cumbersome of all, requiring complex and time-consuming permitting processes, and expensive environmental monitoring. DOE supports the development of a per-permitted, grid-integrated, open water test facility—PacWave, off the coast of central Oregon—to provide marine energy developers a fast and streamlined process to install and test large-scale devices in a relevant ocean environment.

FY 2021–2025 Research Priorities

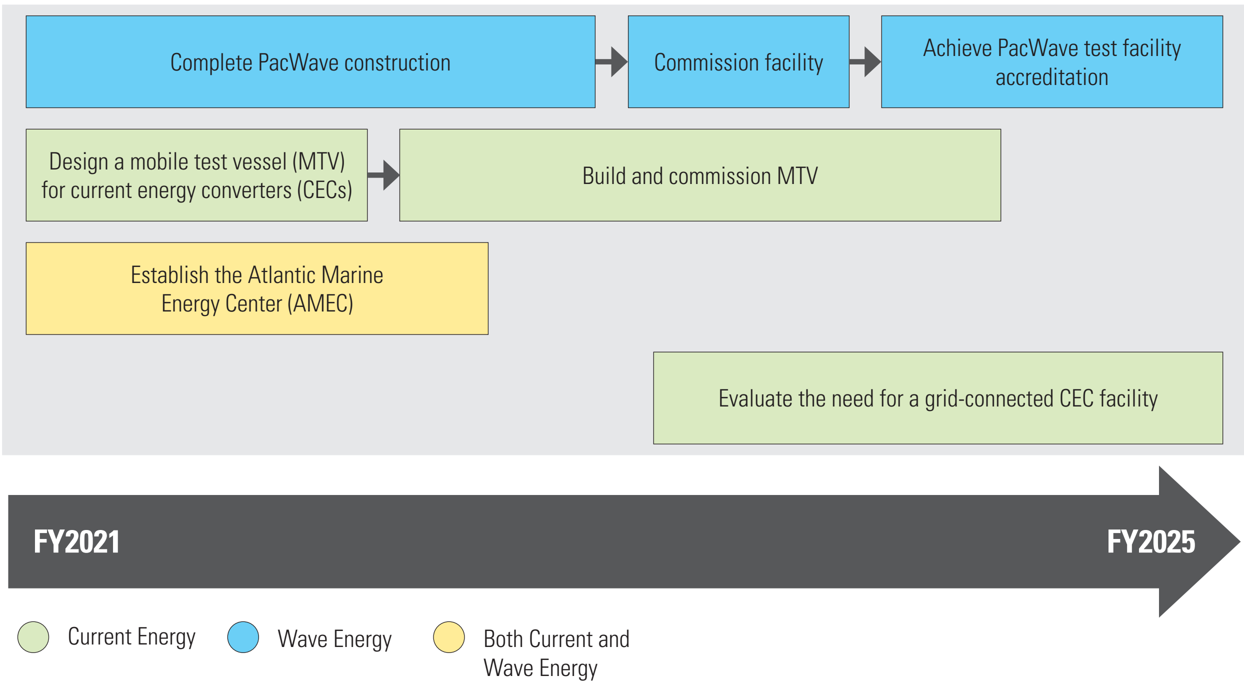
The following are the research priorities that will be emphasized within the Sub-Activity 3.1 – Testing Infrastructure Access and Development—Open Water Testing:

- **Complete PacWave construction**: Complete a first-of-its-kind, state-of-the-art, grid-connected test facility to evaluate utility-scale WEC performance, environmental interactions, and survivability. The facility will also be suitable for WECs that are not equipped to be connected to the grid.
- **Commission facility**: Successfully prepare systems and facilities to be 100% operational, including the development of accreditation strategies with the vision to accommodate the world's WEC needs.
- **Achieve PacWave test facility accreditation**: Qualify and train staff within the first year of device testing operations, which will be led by National Renewable Energy Laboratory, in partnership with the European Marine Energy Centre.
- **Design an MTV for CECs**: Design an MTV that will accommodate a variety of CEC systems to be tested and accredited by nationally and internationally recognized standards.
- **Build and Commission an MTV**: Fabricate an MTV which will be recognized as an accredited testing facility for leading and developing CEC technology.
- **Establish Atlantic Marine Energy Center**: Establish Atlantic Marine Energy Center (AMEC) that will be operated by a university or university-led consortium, with a focus on advancing the commercial availability and application of marine energy technologies by providing additional choice of and access to test facilities in the Atlantic region.
- **Evaluate the need for a grid-connected CEC facility**: Evaluate industry need, characteristics, and costs for a MW-scale, open-water, grid-connected CEC test facility (ocean current and/or tidal).

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 37.

Figure 37. Sub-Activity 3.2 – Open Water Testing Research Priorities



Additional Details

Providing the marine industry with access to economical, world-class infrastructure is an important part of WPTO's long-term marine energy strategy to reduce costs of testing. WPTO will collaborate with WETO where possible to address similar research needs. As a continued effort to reduce the barriers of testing to further develop the marine energy industry, WPTO selected the University of New Hampshire—partnered with various universities, national labs, and the European Marine Energy Center—to develop an AMEC on its campus. This facility will conduct marine energy testing, help address the need for ongoing research into marine energy, and support the PBE initiative.

There are currently three additional NMRECs, established through past WPTO funding: (1) the Pacific Marine Energy Center led by the University of Washington, Oregon State University, and University of Alaska, Fairbanks; (2) the Hawaii National Marine Renewable Energy Center led by the University of Hawaii; and (3) the Southeast National Marine Renewable Energy Center led by Florida Atlantic University.

During the past decade, increased interest in marine energy activities along the East Coast has resulted in the creation of an initial base of capabilities throughout the eastern U.S. By leveraging work done to date, establishing the new AMEC will support and further develop the marine energy industry in this region. AMEC will be established and operated by an institution of higher education or a university-led consortium with a focus on advancing marine energy technologies in the Atlantic region of the U.S. Applicants must have access to and utilize the marine resources in the eastern U.S.

Similar to the existing NMRECs, AMEC will (1) serve as a coordinating body on the East Coast and develop a robust strategy for supporting commercialization of marine energy; (2) conduct R&D relevant to marine energy; and (3) provide research capabilities and access to test facilities for developers.

Testing infrastructure investments have mainly focused on the ocean's wave energy, including the construction of the utility-scale PacWave wave energy test facility. Nevertheless, testing infrastructures that mainly focus on wave energy are of great importance reducing the barriers for testing due to the wide range of energy characteristics each specific location provides.

WPTO has identified a gap in the U.S. marine testing capabilities, specifically in testing CECs. Existing testing infrastructure in the U.S. can only accommodate small scale CECs with rotors 2-3 meters in diameter. There is a need for a mobile testing capability that can accommodate CECs with up to 8-meter diameter rotors for testing turbines under different flow conditions in a wide range of test conditions. Since CEC technologies are utilized in river, tidal and ocean environments, the mobile testing capability shall be adaptable for utilization at river, tidal and ocean test sites in a wide variety of current speeds, depths, wave conditions, and bottom types.

To address this gap, as part of the DE-FOA-0002234, WPTO will be funding an open water, non-grid connected mobile testing capability for CECs. Specifically, to design, fabricate, test, maintain and operate a mobile CEC test vessel in accordance with IEC TC 114 with a focus on IEC TS 62600-200 and IEC TS 62600-300 which define the power performance assessment requirements for CECs. This MTV will help accelerate CEC technology development by providing timely opportunities to test in multiple open water flow conditions, with anchoring capabilities for both ocean and river water depths and operate in current speeds up to 4 m/s and be capable of operations in locations with limited infrastructure support, such as remote Alaskan communities, or areas where installation of larger civil works is difficult, prohibitively costly, or environmentally unacceptable.

Sub-Activity 3.3 – Environmental Research and Instrumentation Development

Overview

As relatively new and novel technologies, marine energy devices have raised a number of questions in the regulatory and research communities about potential environmental effects and any unintended consequences of deployment. Understanding the impacts of single devices is important not just for future commercial deployment but also helps obtain the necessary permissions to demonstrate and test initial prototypes in public waters. Significant investigation of these potential issues over the past decade has improved our understanding of the issues and indicated that the ultimate likelihood of risks from a single marine energy device or small array is low.[69] While many uncertainties have been addressed via this research, some uncertainties remain. Focusing on uncertainties has historically led to perceptions of high risk and applications of the precautionary principle by marine energy technology regulators, resulting in higher costs and timelines associated with permitting. The Environmental Research and Instrumentation Development sub-activity focuses on gaining a greater understanding of the potential environmental risks associated with marine energy technologies through two work streams: 1) environmental monitoring technology and tool development, and 2) targeted environmental research studies and data collection.

FY 2021–2025 Research Priorities

The following are the research priorities that will be emphasized within the Sub-Activity 3.3 – Environmental Research and Instrumentation Development:

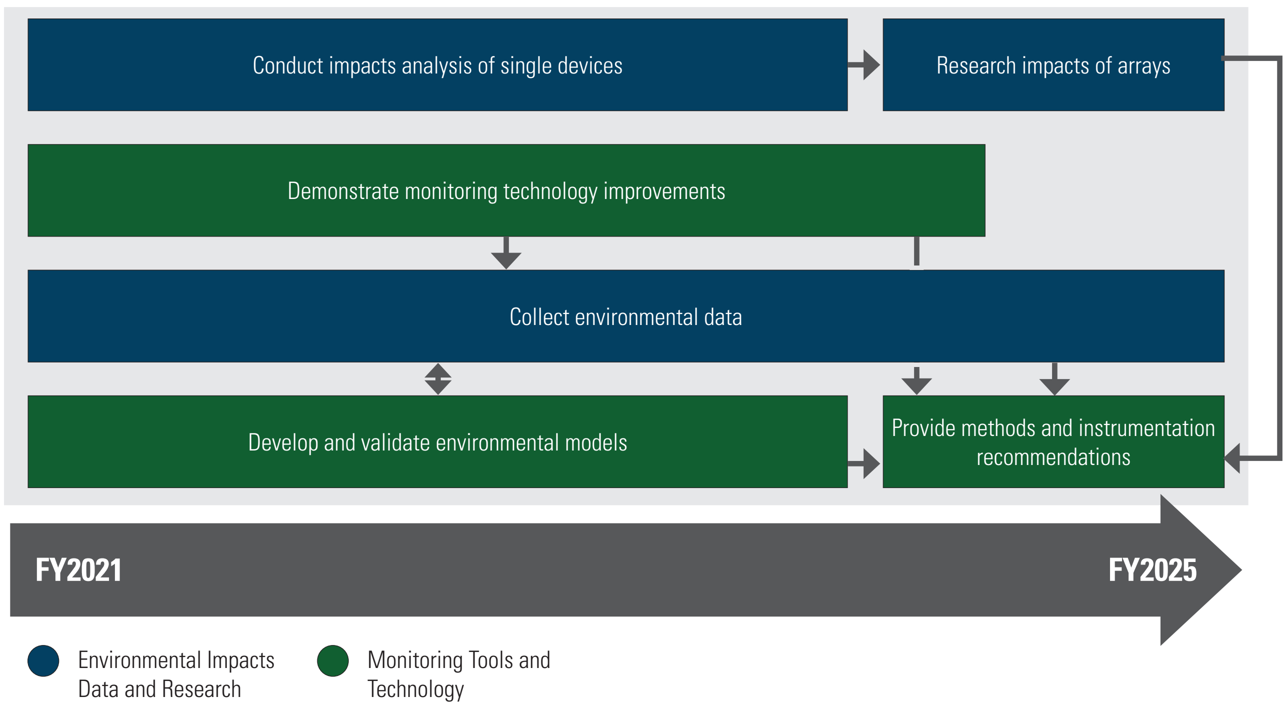
- **Conduct impacts analysis of single devices**: Conduct targeted research for the environmental impact of single devices or small arrays.
- **Research impacts of arrays**: Begin targeted research on possible environmental impacts of larger arrays and population-level impacts.
- **Collect environmental data**: Collect relevant environmental data prior to installation where feasible and as marine energy, or other relevant industries' (e.g., offshore wind), deployments occur.
- **Complete environmental model development and validation**: As new data is collected, ensure transferability and usability for validation of existing models.

[69] Copping, A.E. and Hemery, L.G., 2020. "OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES)." https://tethys.pnnl.gov/publications/state-of-the-science-2020.

- **Demonstrate monitoring technology improvements**: Demonstrate improvements in environmental monitoring technologies and develop new tools to fill remaining gaps.
- **Provide methods and instrumentation recommendations**: Support the development of recommendations for methods and monitoring instrumentation to be used in environmental assessments.

Timing and Sequencing of Research Priorities
The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 38.

Figure 38. Sub-Activity 3.3 – Environmental Research and Instrumentation Development Research Priorities



Additional Details
The Marine Energy Program also supports the development of numerical modeling tools to help assess potential effects when empirical data is insufficient to address regulatory concerns. Modeling work also benefits from and overlaps with efforts under Sub-Activity 1.3 – Numerical Modeling, as some of the same underlying codes can be utilized for multiple objectives like assessing both array energy extraction efficiency and changes to benthic habitat or beach formation processes for instance. Specifically, modeling efforts address marine energy produced sound, changes in circulation patterns, wave heights and nearby habitats as well as the refinement of encounter and collision risk models for interactions of marine mammals, fish, and seabirds with marine energy devices.

Additionally, there are ongoing efforts to develop and evaluate the environmental monitoring technology necessary to collect and process the data needed to understand potential environmental risks. Existing oceanographic equipment does not always have the ability to meet specific regulatory requirements or may not perform well in harsh marine energy environments. To reduce the cost of and enable environmental monitoring of deployed devices, the Marine Energy Program supports technical improvements to monitoring technologies and data processing tools. Additionally, continuing efforts will identify the most appropriate tools and methodologies for data collection and analysis in marine energy environments. Best practices will be formulated to promote more standardized data collection across projects and enable greater confidence in the data transferability among sites and devices. This will allow future projects to benefit from the invaluable environmental data that has been collected by previous projects.

The program also supports targeted research efforts in laboratory and field settings to gain a greater understanding of specific environmental risks. While current research focuses primarily on effects from a single device or small arrays on individual organisms (fish or marine mammals), future efforts will begin to address potential effects of larger arrays and population level impacts. To complement the research efforts, there will be a concerted effort to support the collection of relevant environmental data around deployed marine energy devices to provide the information necessary to retire or mitigate concerns.

Efforts will also focus on identifying collaboration opportunities with DOE's WETO as well as other federal or state agencies to address similar research needs marine energy and offshore wind share many of the same potential environmental concerns and may greatly benefit from coordinated efforts to develop and test environmental monitoring and mitigation technologies.

Marine Energy Program Activity 4 – Data Access, Analytics, and Workforce Development

Overview

As a public research agency and the primary funder of U.S. marine energy R&D, DOE is uniquely capable of aggregating and disseminating objective and accurate information about marine energy. The Marine Energy Program ensures that data and analysis produced are easily accessible and useful to multiple audiences, such as technology developers, researchers, regulators, or students. Improved access to and use of data, tools, and STEM resources or programs can lead to: (1) improved awareness of marine energy technology advances and lessons learned; (2) reduced cost, time, and uncertainty around the marine energy permitting processes; and (3) increased opportunities for students to develop skills needed to enter the marine energy workforce. In the long-term, these outcomes can support innovation, increase the development and testing of devices at scale, provide a greater understanding of opportunities for marine energy across the blue economy, enhance energy resilience of coastal and river communities, improve marine resource management, and prepare a skilled workforce to advance marine energy into the future.

Activity 4 – Data Access, Analytics, and Workforce Development consists of the following sub-activities:

1. Data Access and Workforce Development: Aggregating and providing access to marine energy data and informational resources created through WPTO's funded projects, improving the connectivity of WPTO's databases to other U.S. and international data portals, and increasing opportunities for students to develop skills needed to enter the marine energy workforce.
2. Data Analytics: Leveraging data to produce lessons learned and useful analysis across a range of topics.

Performance Goals and Objectives

The key results, performance goals, and follow-on objectives are summarized in Table 23.

Table 23. Data Access, Analytics, and Workforce Development Performance Goals and Objectives

Key Results and Performance Goals (2021–2025)
• Publish an assessment of marine energy industry and researcher data needs. • Collect, analyze, and publish data from the existing in-water testing projects to generate new foundational understanding of marine energy devices and identify promising areas for additional research. • Complete integration of publicly available, WPTO-funded marine energy databases with interconnected search functionality. • Launch a new marine energy permitting toolkit to improve regulators' access to and understanding of information about marine energy resources, devices, and potential environmental effects. • Release a new marine energy STEM portal consisting of educator and student resources and curricula. • Improve targeted outreach with the intention of diversifying the pool of students participating in WPTO workforce development programs such as the graduate student research fellowship and Marine Energy Collegiate Competition.
Follow-On Objectives (2026–2030)
• Increased usage of WPTO-developed data, along with supported marine energy databases and toolkits (including the Marine Energy Environmental Toolkit, Marine Energy Permitting Handbook, and State of the Science Report) by a diverse set of stakeholders (along with positive value and ease-of-use metrics collected from users). • Dramatic improvement in regulators' access to useful marine energy data, helping to reduce uncertainty, improve their ability to assess risk, and achieve efficiency gains when permitting projects. • Measurable and significant increases in use of marine energy STEM portal by educators and individuals. • Measured improvement in the diversity of students and student teams participating in WPTO's fellowship programs and Marine Energy Collegiate Competition, including minority students as well as students from minority-serving institutions, such as historically Black colleges and universities, Hispanic-serving institutions, and tribal colleges.

Additional Details

Given the nascent stage of the marine energy industry and with relatively few open water test or deployments to date, there is a lack of validated, publicly available, and usable data and analyses regarding many different aspects of marine energy technologies. Existing data are found in disparate locations, which creates access and discoverability challenges for marine energy researchers and developers, regulators, investors, potential supply chain vendors, and the general public. In addition, there are few resources and programs to help students and those interested in pursuing possible clean energy careers gain familiarity with these technologies. This workforce challenge is exacerbated by infrequent testing and demonstration of new technologies, meaning interested individuals, and the marine energy community overall, rarely have opportunities to gain real-world experience. Improved access to and usability of data and analyses produced by WPTO-funded projects, as well as the development of new educational resources and programs, are needed to reduce uncertainty around marine energy technologies, maximize the impact of federal R&D, and support long-term marine energy industry growth.

Sub-Activity 4.1 – Data Access and Workforce Development

Overview

The Data Access and Workforce development sub-activity primarily focuses on aggregating and providing access to marine energy data and informational resources created through WPTO's funded projects, improving the connectivity of WPTO's databases to other U.S. and international data portals, and providing the next-generation of marine energy innovators access to the industry and workforce development opportunities. Data Access efforts focus on identifying, aggregating, and providing public access to data produced by projects across the Marine Energy Program, including both technology-specific projects and technology-agnostic projects (the latter largely representing data and tools developed under the Foundational R&D activity area) as well as educational resources for students and educators. A large amount of new information is generated as the result of DOE-funded research, and these data must be quickly and transparently made available. This requires collaborating across the portfolio, developing, and ensuring use of best practices for formatting and curating content, implementing metadata structures and standards, creating, and maintaining database and data portal interconnectivity, enhancing usability, and other data management issues. Additionally, with the United States becoming an emerging leader in marine energy, international collaboration is important to ensure that our data is available internationally, and to connect U.S. marine energy stakeholders with international partners to learn from what has been done in other countries. Additionally, the future of marine energy is dependent on the availability of a skilled workforce, which WPTO supports by offering workforce development programs such as a collegiate competition and fellowship opportunities, which are advertised and disseminated through WPTO's main data portal. To achieve success in this sub-activity, WPTO continuously seeks stakeholder feedback and continues to adapt data access projects to meet the needs of the greatest number of users.

FY 2021–2025 Research Priorities

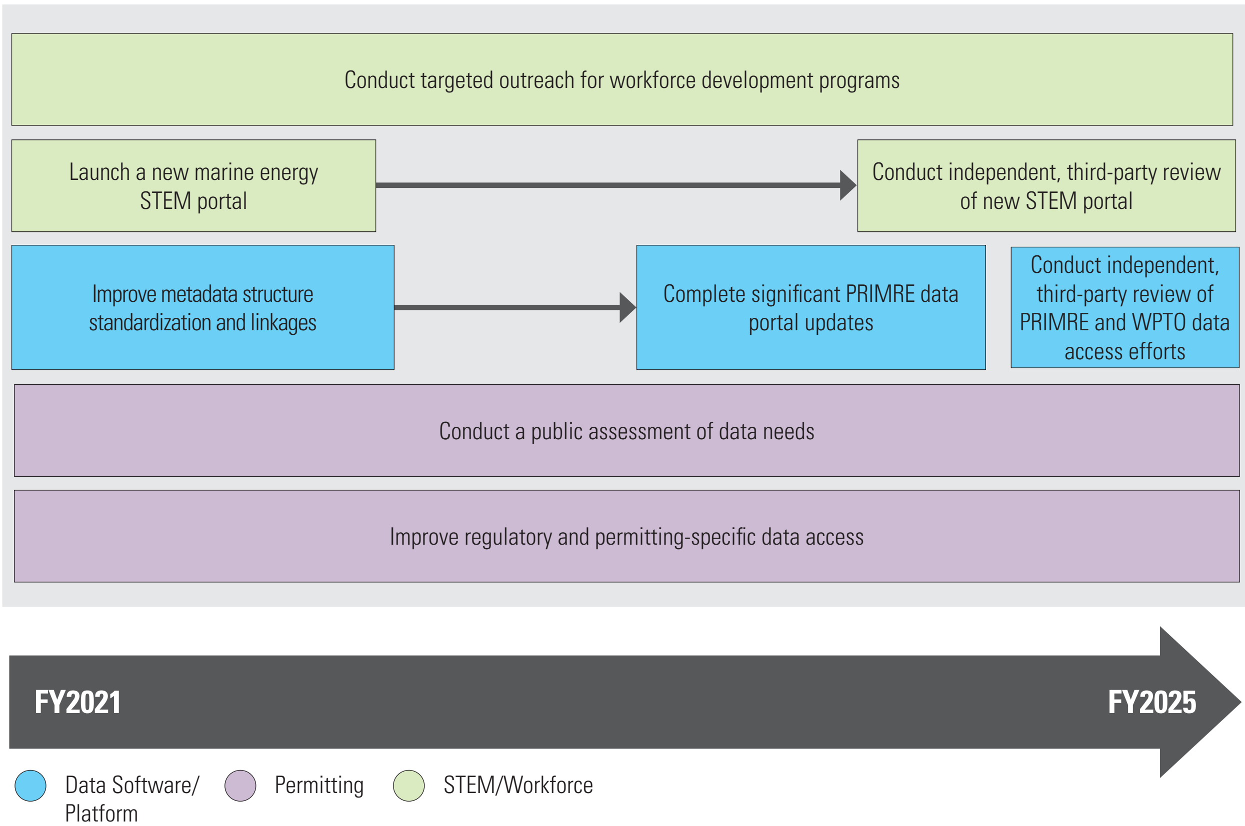
The following are the research priorities that will be emphasized within the Sub-Activity 4.1 – Data Access and Workforce Development:

- **Conduct targeted outreach for workforce development programs**: Target outreach to universities, student associations, and professional societies across the nation to improve awareness of workforce development opportunities such as the graduate student research fellowship and Marine Energy Collegiate Competition.
- **Launch a new marine energy STEM portal**: Launch new portal within the Portal and Repository for Information on Marine Renewable Energy (PRIMRE) consisting of educator and student resources and curricula. Add new curricula resources to the portal as they are developed.
- **Conduct independent, third-party review of new STEM portal**: Gather feedback from students, educators, and marine energy employers on portal's ease of use, as well as the quality of the content, and incorporate recommendations in portal.
- **Improve metadata structure standardization and linkages**: Improve connectivity between existing WPTO-funded marine energy databases by implementing consistent metadata, enabling a search function across multiple databases, and providing linkages to non-WPTO resources domestically and internationally.
- **Complete significant PRIMRE data portal updates**: Update PRIMRE data to support highest-priority industry and stakeholder use-cases identified through a data needs reassessment.
- **Conduct independent, third-party review of PRIMRE and WPTO data access efforts**: Assess the usability and usefulness of data portals, as well as gaps in our data access portfolio. Seek feedback and incorporate into longer-term direction.
- **Conduct a public assessment of data needs**: Conduct and publish results of a reassessment of marine energy industry and researcher data needs, not limited to but including access to data produced via DOE-funded projects.
- **Improve regulatory and permitting-specific data access**: Launch a new permitting and regulatory toolkit to improve marine energy data access for regulators and other stakeholders involved in the permitting of marine energy.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 39.

Figure 39. Sub-Activity 4.1 – Data Access and Workforce Development Research Priorities



Additional Details

Currently, WPTO supports several data portals and works to improve their accessibility and interconnectivity through PRIMRE.[70] PRIMRE provides a central access point to existing marine energy databases and other informational resources. PRIMRE also provides standardization, community building, and integration of federally funded marine energy data in order to reduce barriers to access information and data on technology, research, design, and testing. There are a number of databases and tools funded under data access, which are already integrated into PRIMRE or are working towards integration, including:

1. **The Marine Hydrokinetic Data Repository (MHKDR)** which contains data collected during WPTO-funded projects, including data on marine energy devices, testing, resource and environmental impact assessments, cost analyses, and more.
2. **Tethys** which facilitates the exchange of information and data on the environmental effects of wind and marine renewable energy technologies.
3. **Tethys Engineering** which stores documents from around the world about the technical and engineering aspects of marine renewable energy.
4. **The MRE Technology Database** which provides information on existing marine energy technologies, companies active in the field, and development of projects in the water.

[70] For more information, visit https://openei.org/wiki/PRIMRE.

5. The **MHK Instrumentation & Sensor Database** which shares information on instrumentation and lessons learned from laboratory testing and field deployments.
6. A collection of open-source **marine energy relevant software**, including a code hub and code catalog.
7. The **Marine Hydrokinetic (MHK) Environmental Toolkit for Licensing and Permitting** which seeks to increase regulators' understanding of marine energy projects and their potential environmental effects.
8. The **STEM for Marine Energy portal**, an information-sharing portal designed to support workforce development by connecting educators and students with educational and training resources.
9. **Marine Energy Atlas**, an interactive mapping tool which displays the potential for marine and hydrokinetic resources.

Given the existing number of WPTO projects focused on marine energy data access, the Marine Energy Program considers it imperative to conduct a thorough assessment of stakeholder data needs with respect to current investments. As part of this assessment, the Marine Energy Program will consider: (1) more efficient and effective means to collect, organize, and analyze high-quality data and the storage needs/implications for such data; (2) whether the current form of PRIMRE has helped address marine energy data challenges; and (3) metrics to quantify the impact of this work that are more meaningful than the number of downloads of datasets or visits to a site. The Marine Energy Program acknowledges that this could be a multiyear effort and that our existing approach to data access—through a number of different inter-connected databases—may or may not prove to be the most desirable long-term approach.

Sub-Activity 4.2 – Data Analytics

Overview

Marine energy technologies are evolving rapidly, both in the United States and around the world. In addition to the need to aggregate otherwise disparate marine energy data, there is also a significant need to leverage these data to produce lessons learned and useful analysis across a range of topics. These lessons learned and analyses will help improve performance, cost, and reliability of new marine energy systems, location and characteristics of available resources, new market applications and business development pathways, and research and monitoring of any potential environmental impacts of technologies. There are many technical and operational challenges in developing new marine energy systems and increasing opportunities to analyze and glean insights from completed research can aid in increasing the speed of future design cycles. Improved abilities to access, compare, and analyze many types of information will focus new research efforts on priority needs; allow technology developers to keep pace with changes across the industry; convey the state of various technologies to financers, insurers, and policymakers; and provide relevant information to regulators for timely and well-informed decision-making. As a technology-neutral, national research entity with significant core capabilities in data management and analysis, DOE is also in a unique position to help serve as an objective and unbiased aggregator for relevant non-DOE-generated data. DOE also interacts with similarly interested international parties through engagements with the IEA's OES Implementing Agreement. Some business-sensitive cost and performance information for new technologies is also collected for internal analytical purposes to inform WPTO's long-term research strategies and compare the performance of ongoing awards to industry trends.

FY 2021–25 Research Priorities

The following are the research priorities that will be emphasized within the Sub-Activity 4.2 – Data Analytics:

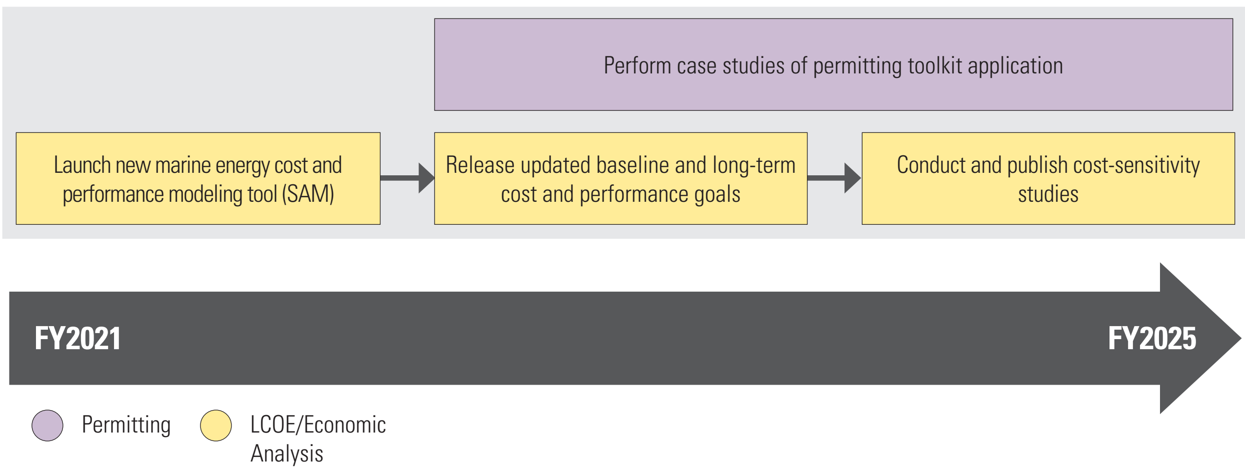
- **Perform case studies of permitting toolkit application** to inform further improvements or new analytical capabilities.
- **Launch new marine energy cost and performance analysis tool (SAM)** to underpin WPTO, awardee and researcher-led studies.

- **Release updated baseline and long-term cost and performance goals** in line with DOE and GPRA requirements.
- **Conduct and publish grid-scale marine energy cost-sensitivity studies** specifically investigating cost relationships for manufacturing, transportation, deployment, operations, and maintenance for large-scale potential future deployments.

Timing and Sequencing of Research Priorities

The timing and sequencing of FY 2021–2025 research priorities are summarized in Figure 40.

Figure 40. Sub-Activity 4.2 – Data Analytics Research Priorities



Additional Details

In contrast to other renewable energy industries, such as wind and solar, the marine energy industry has not yet converged on a specific device archetype or archetypes. Given the limited public and private resource available to develop marine energy technologies, it is critical to identify and direct R&D efforts towards design innovations that have the greatest techno-economic potential. The Marine Energy Program will continue to update its long-term cost and performance related goals and underlying analysis informing year-to-year research strategies. The Marine Energy Program will also continue work to collaboratively develop and apply quantitative metrics to identify and advance technologies with high ultimate techno-economic potential for their market applications. The Marine Energy Program is working with industry stakeholders and international collaborators to develop transparent and publicly disseminated performance metrics that can be used to identify promising technology improvements most effectively.

Powering the Blue Economy

Introduction

The PBE Initiative formally launched out of WPTO in 2019. Built out of an analytically driven process that focuses on the need to understand the potential for using marine energy within the blue economy, the program is strategically growing a portfolio of investments to accelerate development and deployment of marine energy technologies. Investments in the portfolio include supporting foundational research, access, and upgrades to testing assets, entrepreneurial ecosystem development, and fostering the partnerships with government and private sector stakeholders needed for successful development and adoption of marine energy systems that power the blue economy.

Importance of the Blue Economy and Energy Needs

The oceans are critical to the global ecosystem and are important to both human health and productivity. The oceans present myriad opportunities, including new sustainable sources of protein, production of freshwater, new medicines, enhanced security, data, and systems to protect against and detect catastrophic weather events, carbon mitigation strategies, and energy. To fully realize these opportunities, there is a need for new technologies, partnerships, and enhanced government coordination.

The expanding demand for ocean-derived food, materials, energy—and a more thorough knowledge about the ocean—is driving rapid growth in the emerging blue economy. This expansive view of how oceans can serve fundamental human needs and drive economic growth include everything from harnessing the power of oceans to generate energy, to sustainable aquaculture, to enabling observations that expand the understanding of the ocean by mapping and observing the more than 90% of the ocean that remains unobserved.

From a purely economic perspective, the blue economy is a rapidly growing sector of the world economy. The Organization for Economic Cooperation and Development predicts the global economic value attributable to ocean-related activities will double from $1.5 trillion in 2015 to $3 trillion by 2030, growing at twice the rate of the rest of the global economy.[71] And from a domestic policy perspective, developing and advancing the blue economy is a federal government priority.[72] There is a growing recognition of the importance of technologies to support the blue economy. Some sectors and opportunities, such as aquaculture, ocean observing, and mineral extraction, are expanding further offshore, but moving further from shore requires systems that allow for access to consistent, reliable power that are untethered to land-based power grids. And these opportunities are not limited to the offshore environment. Coastal communities are also looking to the ocean to develop resilient energy, food, and water systems.

However, growth in many blue economy sectors is constrained by the lack of available energy and energy sources that require frequent refueling or battery changes, limiting the growth potential. There are many opportunities to innovate and improve on existing energy solutions that are often unfit for purpose, limited in capacity, damaging to the environment, and expensive. There is significant potential to develop technologies to serve both deep offshore and nearshore energy solutions. And while these technology breakthroughs in the blue economy are possible, they will require new thinking about energy development, multidisciplinary approaches, co-development of energy solutions embedded within or tied to blue economy platforms, and innovation across multiple technology domains.

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71 Organisation for Economic Co-operation and Development, 2016. "The Ocean Economy in 2030." https://www.oecd.org/environment/the-ocean-economy-in-2030-9789264251724-en.htm.

72 Federal Register, 2020. "National Ocean Month, 2020." https://www.federalregister.gov/documents/2020/06/05/2020-12428/national-ocean-month-2020.

Marine Energy and the Potential to Power the Blue Economy

Energy is foundational to nearly all blue economy sectors. Removing and addressing energy constraints in the blue economy could accelerate economic growth by strengthening existing—and creating or enabling new markets and applications for sustainable economic development. Because there are myriad federal partners and organizations committed to the sustainable growth of the blue economy, DOE serves an especially critical role as a research organization and nexus point among other federal agencies. DOE is a primary funder of energy technologies and solutions that could serve the blue economy and already works with a diverse set of federal and other stakeholders with equities in the blue economy. DOE is poised to convene diverse stakeholders to achieve common goals to address energy barriers, constraints, and opportunities in the blue economy. Offices within DOE that will play an increasing role in enabling the blue economy include the EERE, Office of Science, the Advanced Research Projects Agency—Energy, the Office of Fossil Energy, and the Office of Electricity, among others.

EERE has a critical role in the development and advancement of solutions to address energy needs in the oceans. There are two main areas that EERE has within its mission space to support the blue economy: (1) grid-scale electricity solutions to power energy needs for coastal, grid-tied communities; and (2) power for the expanding blue economy, like solutions that can increase the resilience of remote and coastal communities and provide energy for offshore applications. R&D supported by EERE for grid-scale electricity includes wave energy, tidal energy, thermal ocean gradients, offshore wind, and floating solar. In addition to powering the electricity grid, R&D of these technologies could also address remote and island communities' access to energy and water; development of energy-enabled systems to understand, observe, protect and clean oceans; harnessing the potential energy from the ocean to power markets of the future like aquaculture and seawater mineral mining; directly desalinating water through the power of the ocean; and the advancement of technologies to advance the maritime sector, including maritime transport.

Marine energy resources, such as wave, tidal and ocean currents, could be particularly well poised to address these power constraints in the blue economy, as they are abundant, geographically co-located, geographically diverse, energy dense, predictable, and complementary to other energy sources. Over the last decade, WPTO has made progress in both R&D focused on marine energy technology development as well as in understanding how these resources could and should serve grid-scale electricity needs. But to better understand the opportunities specific to marine energy's role in the blue economy, WPTO, with the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory investigated the potential opportunities for marine energy in blue economy sectors. From 2017 through early 2019, WPTO, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory conducted extensive analysis and stakeholder engagement as part of this effort.

Powering the Blue Economy Initiative: Overview

This foundational discovery analysis to understand marine energy's role in the blue economy resulted in the release of a report in April 2019, entitled Powering the *Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets*.[73] The report was a landscape analysis of the different ways marine energy could be used in the blue economy aside from powering the regional electrical grid. It demonstrated that WPTO's marine energy program has an important role to play in enabling innovation and growth in the blue economy by engaging directly with the relevant communities and public and private sector organizations.

The report identifies potential opportunities and challenges for marine energy in eight different ocean applications and markets, including those far out at sea—like ocean observation and seawater and mineral mining—and those nearshore, like desalination and coastal resilience. The eight identified markets are outlined in Figure 41.

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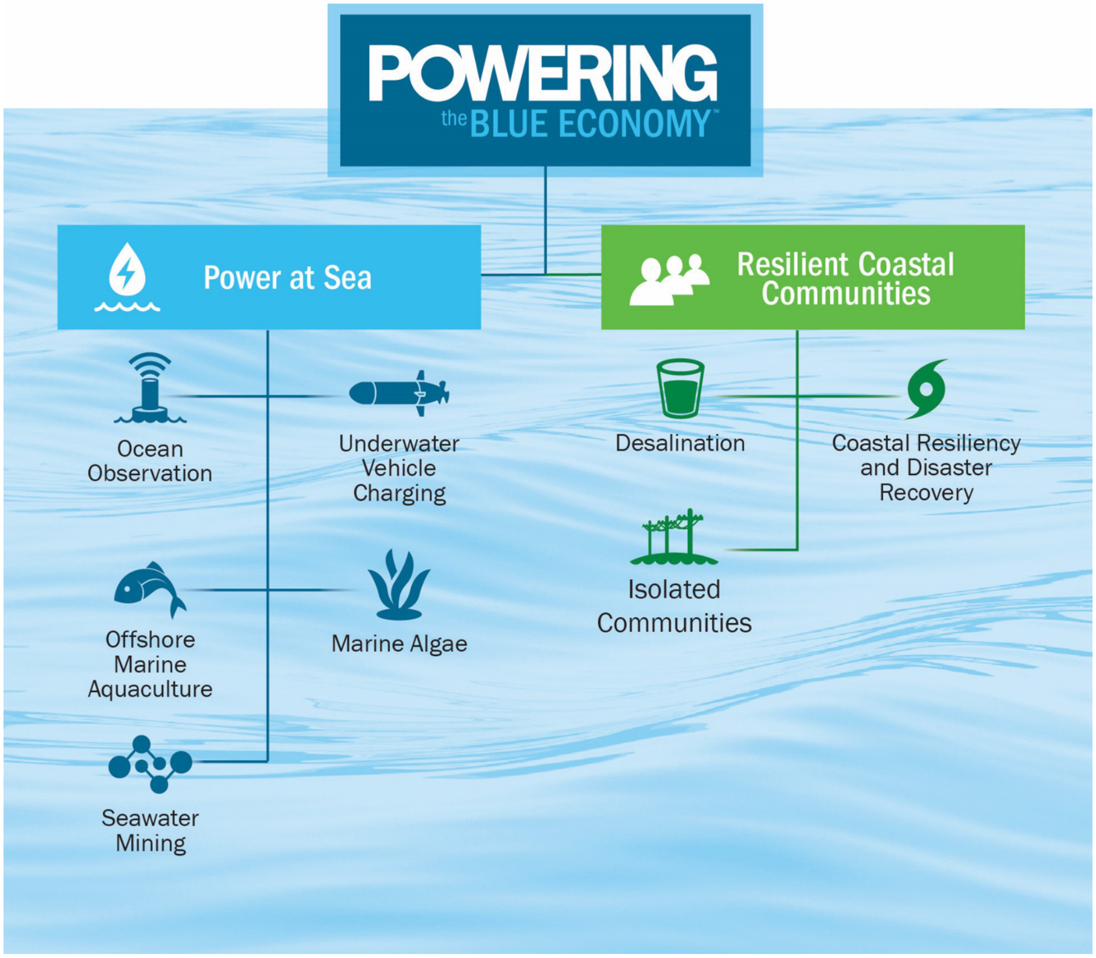
[73] U.S. Department of Energy, 2019, "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets." https://www.energy.gov/eere/water/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets#pbereport.

Figure 41. Blue Economy Market Applications



Additional markets, like powering offshore data centers or small consumer goods are also included in an additional Other Applications chapter. Building on this report, WPTO is exploring partnerships between the marine renewable energy industry, coastal stakeholders, and blue economy sectors to address two thematic challenges: Power at Sea and RCCs.

- **Power at Sea**: From ocean exploration and navigation to aquaculture, many marine-based applications and markets are located far from shore—sometimes in deep water. Delivering power to these systems can be expensive and difficult. Powering systems that use energy derived from the ocean offers a cost-effective alternative. Markets considered within the report include ocean observation, underwater vehicle charging, marine aquaculture, marine algae, and seawater mining.
- **RCCs**: Marine energy can help support coastal communities, making them more resilient to address their long-term energy and water needs, and in the face of extreme events such as tsunamis, hurricanes, floods, or droughts. Many marine energy applications are ideally suited to coastal development by offering relatively easy access for installation and operation and maintenance activities, providing a predictable and uninterrupted energy supply, and potentially reducing land requirements needed by many land-based energy solutions. Markets considered within this theme include seawater desalination, coastal resilience and disaster recovery, and isolated communities.

Since the release of the report, WPTO has established the PBE Initiative. This initiative seeks to understand the power requirements within the thematic challenges, and to advance technologies that integrate marine renewable energy to relieve power constraints and promote economic growth. As part of this initiative, understanding and realizing marine energy's value requires an end-user centric, cross-sector, and systems-focused approach. Through the PBE initiative, WPTO has been building a portfolio of R&D to better understand energy constraints and requirements in the blue economy, established partnerships to advance marine energy solutions in the blue economy, and launched activities to support the R&D of prototypes to realize the potential of an ocean energy-enabled blue economy.

PBE Initiative Goals and Principles

The PBE initiative expands WPTO's strategic vision to more fully encompass an ocean-centric view of marine energy innovation in close partnership with other offices within DOE, other federal agencies, and the diverse set of industries and sectors that make up the blue economy. This creates opportunities to understand and obtain new value from marine energy to address the energy needs of the blue economy, and where those needs intersect with the unique attributes and advantages of wave, tidal, ocean current, ocean thermal, and river current energy.

WPTO has set out three interwoven goals for PBE to quantify the value of marine energy in the blue economy, support individuals and companies in the development of prototypes and solutions to provide power in these markets, and partner with the end-users who need these solutions and ultimately can make them successful. The PBE initiative goals are:

- Goal 1: Understand end-user needs and **quantify the value of marine energy** in emerging ocean markets uniquely suited to marine renewable energy technology attributes.
- Goal 2: **Accelerate marine energy technology readiness** through near-term opportunities, supporting WPTO marine renewable energy strategy and mission.
- Goal 3: Enable broader blue economy goals by **developing solutions to meet energy challenges facing private and public sector blue economy partners**, including unlocking the potential of new ocean-enabled technologies, enhancing scientific capabilities in the ocean, and the development of more resilient coastal and island communities.

To accomplish the goals of PBE, WPTO has identified five key principles that drive decision making and the establishment of a portfolio of research, analysis, development, and partnership.

1. ***Analytically driven opportunity identification***: Analytical efforts will focus on understanding which applications and markets are best suited to marine energy and quantifying the full value of marine energy within the blue economy.
2. ***Start with near-term opportunities; learn by doing***: Starting with such near-term opportunities provides the best pathway towards meeting PBE goals through early wins and rapid learning within the marine energy industry. Additionally, by pursuing multiple lower-cost opportunities through investing in smaller scale PBE opportunities, the program has a higher likelihood of successfully development commercial-ready devices in the long-term.
3. ***Exploring and using all available financing mechanisms to accelerate growth***: Funding decisions for PBE projects are driven by evaluating all of the financing mechanisms at WPTO's disposal and correlating them with the appropriate outcomes sought. All funding opportunities will require evidence of market demand and end-user need.

4. ***Emphasis on partnerships***: Stakeholder and industry outreach processes have been and will be designed to understand blue economy end-user needs and to create connections and collaboration opportunities between end-users and energy innovators. Additionally, within the government, intra- and interagency outreach mechanisms are aimed at coordinating missions and pooling resources supporting federal policy, R&D, and energy innovation within the blue economy.
5. ***Marine energy as part of the broader set of solutions***: PBE opportunities present multi-disciplinary challenges; no one sector, institution, or laboratory has the capacity or capability to solve these problems in isolation. Therefore, there is a need for establishing an enduring cross-disciplinary and cross-sector foundation for innovation in the blue economy that leverages the unique strengths of WPTO's core partners (the marine energy industry, the national laboratories, NMRECs, and existing university partners), as well as a new set of blue economy partners and stakeholders working to address technology challenges.

How PBE Fits Within the Marine Energy Program

The PBE portfolio within WPTO consists of activities to support R&D, engagement, and innovation that encompass the marine energy program. PBE portfolio investments leverage traditional and emerging innovation tools available to DOE and are actively coordinated across activities to maximize impacts. As described in the marine energy section of this strategy document, there are several key activities within the PBE sub-activity of the marine energy program.

PBE market success will deliver benefits to marine energy technologies that will ultimately target large-scale grid applications, including critical near-term revenue, design and operational experience in water, supply chain development, and a skilled workforce, as well as the opportunity to increase public familiarity and real near-term understanding of how harnessing ocean energy can provide benefits. The foundational research and accelerated development of systems that are part of PBE can inform and support the maturation and cost reduction of grid-scale marine energy systems. Specifically, innovation at smaller scales provides cost-effective, accelerated pathways and learning for grid-scale markets; challenges like the integration of marine energy with storage or advanced microgrid systems could directly influence grid-scale power markets. Conversely, WPTO-supported advancements over the last 10 years in grid-scale markets benefit PBE markets and applications, including the development of systems to power off-grid markets, like tidal and current applications for remote communities.

Implementing the PBE initiative and fully realizing the potential for marine energy in the blue economy involves aligning the following activities with the three primary PBE goals:

- **Goal 1**: Understand end-user needs and quantify the value of marine energy in emerging ocean markets uniquely suited to marine energy technology attributes.
    - Develop and release a PBE R&D strategy and execution plan.
    - Develop analytical products to quantify market and application opportunities; use these products to assess impacts of and value propositions for individual applications and develop engineering-based use case studies to understand critical R&D and adoption challenges within applications.
    - Understand end-user needs through focused outreach activities (surveys, interviews, conferences). Use this information for R&D planning and to ensure alignment of funded opportunities with end-user needs to encourage and increase the likelihood of successful technology commercialization and adoption.
- **Goal 2**: Accelerate marine energy technology readiness through near-term opportunities, supporting WPTO marine energy strategy and mission.
    - Support a robust portfolio of R&D through the national laboratories to develop a deeper understanding of research challenges critical to unlocking near-term opportunities for industry to address through prototype development.

- Fund research, development, and training at universities nationwide to address both crosscutting research and prototype development to advance technologies in the blue economy.
- Launch prizes that attract a diverse set of problem solvers and identify new ways to solve challenging problems in near term markets. Prizes highlight near term opportunities, expand the problem-solving community, and galvanize innovation towards meeting initial technology development goals.
- Leverage opportunities through the SBIR/STTR programs to support development of prototypes and commercial-ready solutions. SBIR projects, if successful, can quickly and effectively move from design, to prototype, to commercial solution.
  - Maximize use of SBIR/STTR Phase 1 to identify promising industry partners and concepts on marine energy/blue economy system integration.
  - Use SBIR/STTR Phase 2 to advance early-stage, component-scale R&D and initial prototype development.
  - Implementing a multi-year commitment to the maturation of solutions through SBIR can help to ensure commercial adoption. SBIR provides commercialization services beyond the Phase 1 and 2 grants, which can help to increase the likelihood of adoption of solutions post period of performance.
- Include PBE markets, applications, challenges, data, and information in WPTO's marine energy FOAs.
- Leverage existing testing investments and identify new assets uniquely suited to PBE markets. This includes incorporating PBE themes within the TEAMER program and in large investments such as PacWave.
- Develop, promulgate, and facilitate access to existing knowledge repositories to the extent that they are suited to PBE markets, including Tethys, Tethys Engineering, PRIMRE, MHKDR, Marine and Hydrokinetic Toolkit (MHKit), etc.

- **Goal 3**: Work directly across EERE, with other DOE offices, and with public sector partners to address blue economy energy system needs and contribute to national goals set by the federal government; align activities with private and public sector needs to attract investment and interest to support development of solutions to tackle energy challenges.
  - Develop interagency partnerships that jointly support blue economy energy innovation. This includes representing DOE and energy system expertise within national ocean policy frameworks such as the National Oceanographic Partnership Program (NOPP) and the White House Ocean Policy Council. This also includes the development of interagency funding mechanisms to achieve shared blue economy goals.
  - Cultivate intra-agency partnerships that support cross-sector technology innovation to address the complex set of energy opportunities and challenges in the blue economy.
  - Develop a sustainable, early-stage, cross-market R&D, testing, and demonstration ecosystem within laboratories and university partners that supports industry activities in near-term and future markets and applications.
  - Leverage and invest in emerging and existing blue economy regional clusters, accelerators, and incubators to connect R&D and demonstration projects to investors, capital providers, and market opportunities.
  - Develop effective engagement strategies with potential funders and adopters of solutions and communicate opportunities in energy innovation in the blue economy, including specifically innovation emerging from PBE.

Marine Energy Strategic Partnerships and Crosscutting Activities

Coordination and collaboration with other DOE offices and government agencies is essential to optimize federal investments, leverage limited resources, avoid duplication, ensure a consistent message to stakeholders, and meet national energy goals.

WPTO coordinates and collaborates with other DOE offices and federal agencies as shown in Table 24.

Table 24. Summary of Collaborations with Other DOE Offices and Federal Agencies

DOE Office	Description
Fossil Energy and Carbon Management (FECM)	WPTO coordinates with FECM on issues of subsea instrumentation development and inspection/observational equipment and related needs for offshore/subsea power.[74]
EERE Office	**Description**
AMO	WPTO coordinates with AMO to better understand the opportunities for advanced manufacturing and materials for marine energy, and WPTO supports the office's respective desalination research.
Bioenergy Technologies Office (BETO)	WPTO coordinates with BETO to meet the goals of EERE's Plastics Innovation Challenge.
ETI	ETI works to advance self-reliant island and remote communities through the development of resilient energy systems. In collaboration with SETO, WPTO is working to establish a public-private partnership to provide technical assistance and expertise to remote coastal and island communities.
Hydrogen and Fuel Cell Technologies Office (HFTO)	WPTO works with the Hydrogen and Fuel Cells Technologies Office to examine the potential for marine-powered systems for hydrogen production.
SETO	In addition to supporting technical assistance in partnership with ETI, WPTO works closely with SETO on its various prizes, including its desalination prize.
WETO	WPTO coordinates with WETO to support examination of environmental monitoring technologies, resource assessment, and joint opportunities to support coastal energy workforce opportunities.
Federal Agencies	**Description**
U.S. Department of the Interior (DOI), Bureau of Ocean Energy Management (BOEM)	WPTO has historically coordinated and worked with BOEM via the National Oceanographic Partnership Program (NOPP) and continues to engage via projects developing new environmental monitoring technologies and studies to monitor potential effects.

74 National Energy Technology Laboratory, 2019, "Energy Department Invests $9 Million in Offshore Projects in Support of Enhanced Oil Recovery." https://www.netl.doe.gov/node/9170.

Federal Agencies	Description
U.S. Department of the Navy	WPTO has several ongoing projects with the U.S. Navy, including Naval Facilities Engineering Command and Office of Naval Research. Specifically, WPTO leverages Navy facilities, like WETS in Hawaii and the Carderock Wave Basin in Maryland to conduct marine energy R&D. Both DOE and the Navy also sponsor university-led research at universities including the University of Washington and the University of Hawaii at Manoa) via the NMREC and University-Affiliated Research Center (UARC) initiatives, respectively.
NOAA	WPTO has launched a joint prize on ocean observing technologies, but is also coordinating with NOAA on marine debris, resource assessment, and is exploring opportunities to work closely with NOAA Sea Grant.
U.S. Economic Development Administration (EDA)	The U.S. Department of Commerce's EDA and WPTO released a joint solicitation[75] in 2020 to fund organizations supporting entrepreneurship in the blue economy.
U.S. Maritime Administration (MARAD)	With the Department of Transportation's Maritime Administration, WPTO has convened R&D organizations government-wide to better understand and address R&D challenges in the maritime sector.

Oceans for Climate

The oceans are critical to the global ecosystem and are important to human health and productivity. The oceans present opportunities for new sources of energy, protein, freshwater and medicines, with significant implications for global and environmental security. Ocean policy and managing associated economic and environmental equities presents a challenge and an enormous and timely opportunity to reimagine oceans as an asset in the fight against climate change. Oceans already support millions of jobs, underpin our food system and contribute $304 billion to our national GDP, with the potential to grow. The Organization for Economic Cooperation and Development predicts the global economic value attributable to ocean-related activities will double from $1.5 trillion in 2015 to $3 trillion by 2030, growing at twice the rate of the rest of the global economy. They also have the potential to be one of our strongest tools in the fight against climate change. in fact, a recent analysis commissioned by the *UN High Level Panel for a Sustainable Ocean Economy* found that ocean-based climate mitigation and carbon storage options could contribute 21% of the emissions gap to achieve 2050 net-zero emissions targets.[76]

Developing the technologies and approaches of the future that can serve to protect, understand, and leverage the natural assets of the ocean is a critical challenge in the coming decade. And there is a need to focus on coastal communities as they adapt to climate impacts, and as partners in an equitable energy transition. To fully realize these opportunities, there is a need for new technologies, partnerships, and enhanced government coordination. A new, bold federal initiative is needed to convene relevant agencies, develop a strategy to understand and maximize the potential to have the planet's oceans serve as an asset in the fight against climate change, and deploy the technologies and solutions needed.

[75] U.S. Economic Development Administration, 2020. "Build to Scale Industry Challenge." https://www.eda.gov/oie/buildtoscale/industry/.

[76] High Level Panel for Sustainable Ocean Economy, 2019. "The Ocean as a Solution to Climate Change." https://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf.

The oceans are key to enable a net-zero emissions economy that benefits the environment and communities that rely on them. The ocean's contribution to emissions reductions, and a more equitable climate future, derive from four primary sectors:

- **Ocean energy**: Cross-technology and community-focused approaches are needed to accelerate offshore renewable energy—including offshore wind, marine energy, floating solar, and integrated storage. These technologies range in maturity but can all serve critical roles in the pursuit of a 100% clean energy future for terrestrial power consumption. Additionally, harnessing power out in the ocean can serve as energy resources for markets of the present and future, like enhanced ocean observations in extreme environments necessary to underpin both environmental and security policies.
- **Maritime decarbonization**: Decarbonization is critical for maritime transportation, which includes both ships and port infrastructure. This could include electrification and new replacement fuels like hydrogen, ammonia or biofuels, to replace existing fuels—as global shipping contributes approximately 3% of annual CO_2 emissions, equivalent to three times the annual emissions of France.
- **Low-emission sustainable food**: The ocean can serve as a source of low emission food production to reduce agricultural emissions. Sustainable fisheries, "regenerative" aquaculture, and seaweed cultivation all present opportunities for coastal communities to expand their economies and serve a growing population. Some of these solutions also have additional benefits, like cleaning the water of the local environment and serving as a carbon sink.
- **Ocean and coastal habitats, blue carbon, and carbon dioxide removal/storage**: There is a need to protect the critical function the ocean plays as the world's largest sink of atmospheric CO_2, and to pursue strategies that enhance this function and store carbon long term, which could include both natural and technology-focused solutions.

Plastics Innovation Challenge

In November 2019, DOE launched the Plastics Innovation Challenge, which aims to accelerate innovations in energy-efficient plastics recycling and collection technologies.[77] Led by DOE's EERE, the Plastics Innovation Challenge is a multi-pronged R&D initiative that focuses on:

- Collection technologies to prevent plastics from entering the ocean.
- Deconstructing plastic waste, including from rivers and oceans, through biological and chemical methods.
- Upcycling waste streams into higher-value products.
- Developing new plastics that are recyclable-by-design.
- Supporting a plastics upcycling supply chain in domestic and global markets.

With 90% of global marine debris attributed to just ten rivers, inland waterways such as rivers and canals are key to remediation efforts. Marine and hydrokinetic energy is uniquely positioned to help power promising technologies for remediation of marine debris. As part of the Plastics Innovation Challenge, WPTO conducts R&D to develop marine energy-powered systems to remove trash from waterways before it has a chance to enter the ocean.

In addition, WPTO is collaborating with BETO to characterize the plastic and marine debris 'resources' available in order to inform collection, deconstruction, and upcycling activities. Collection, deconstruction, and upcycling of plastic waste depends on an understanding of the geographic distribution and prevalence of plastic waste in order to deploy solutions in the most impactful locations.

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[77] U.S. Department of Energy, 2019, "Department of Energy Launches Plastics Innovation Challenge." energy.gov/articles/department-energy-launches-plastics-innovation-challenge.

There are many challenges associated with converting plastics collected from oceans and waterways into useful products, such as contamination and a lack of collection infrastructure. By working to understand how to handle contaminated ocean plastics and their impacts on collection, recycling, and upcycling processes, we can find cost-effective ways to collect and process ocean plastic. This helps to close the recycling loop and ensure that recycled plastics are reused for other consumer products, resulting in less virgin plastic used in production. Ultimately, this collaboration between WPTO and BETO could inform potential deployment locations of marine energy-powered collection systems and provide a valuable waste stream for deconstruction and upcycling.

Water Security Grand Challenge

Launched in 2018 by the White House, the Water Security Grand Challenge is a framework to advance transformational technology and innovation to meet the global need for safe, secure, and affordable water. Led by DOE, the Grand Challenge is a coordinated suite of prizes, competitions, early-stage R&D, and other programs supporting five specific goals for the United States to reach by 2030.

As part of the Water Security Grand Challenge, WPTO's Marine Energy Program launched the Waves to Water Prize in 2019. Waves to Water is a five-stage, $3.3 million project to accelerate technology innovation through a series of contests to design, develop, and demonstrate desalination systems that use the power of the ocean to provide potable drinking water to remote coastal and island communities. Waves to Water was the first prize released to support the Secretary's Water Security Grand Challenge and specifically aligns with two of the challenge's 2030 goals: to launch desalination technologies that deliver cost-competitive clean water and to develop small, modular energy-water systems for urban, rural, tribal, national security, and disaster response settings. In addition to the prize, WPTO is developing a national lab-designed test system to understand some of the novel challenges of wave powered desalination, as well as conducting customer discovery, researching the sizing and optimization of systems, and conducting research to better understand the ability to scale systems for small-scale applications such as remote communities. WPTO expects a number of lessons learned via these activities will have broad and transferable knowledge under the Secretary's Water Security Grand Challenge.

In the future, the program seeks to support opportunities focused on critical field test conditions over longer duration test periods (2 week – 6 months), collecting specific device performance data across a number of deployment scenarios, advancing the testing of modular and novel mooring designs, and advancing the sizing and optimization of integrated wave desalination systems. These outcomes are critically important for establishing the reliability and robustness of designs as industry looks to find investment off-ramps and specific customers focused on disaster relief, military operations, and remote community energy/water services.

Science and Technology for America's Oceans: A Decadal Vision

Ensuring responsible ocean stewardship with science and technology (S&T) breakthroughs relies on a strategic federal portfolio supported by foundational basic research. *Science and Technology for America's Oceans: A Decadal Vision*[78] identifies pressing research needs and areas of opportunity within the ocean S&T enterprise for the decade 2018-2028. The Vision was published by the Subcommittee on Ocean Science and Technology (SOST), under the Committee on Environment, which is part of the National Science and Technology Council[79] (NSTC), a cabinet-level council chaired by the President.

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[78] Federal Register, 2018. "Science and Technology for America's Oceans: A Decadal Vision." https://www.federalregister.gov/documents/2018/06/28/2018-13926/science-and-technology-for-americas-oceans-a-decadal-vision.

[79] For more information, visit whitehouse.gov/ostp/nstc/.

The Vision outlines a need for research into new potential energy sources, including waves and currents, that are necessary for achieving American leadership in energy generation and innovation. Outcomes from new energy resource capture include economic development in coastal communities. Pairing marine renewable energy with growing and emerging markets can benefit other industries including aquaculture, ocean mineral mining, and oceanographic research, which are highlighted in the PBE Report.[80] The development of these technologies can improve technology transfer and increase U.S. competitiveness in the global market, which is a priority across all federal agencies.

Ongoing coordination with high-level ocean policy activities has facilitated the integration of WPTO equities into the Vision. WPTO representation in NSTC, SOST, and the Ocean Policy Committee, a White House level committee responsible for coordinating ocean-related agency work, continues to help foster high-level, interagency support for marine renewable energy and its applications. Agencies represented across these high-level committees also coordinate through the NOPP.[81] This interagency initiative facilitates partnerships between federal agencies, academia, and industry to advance ocean science research and education by leveraging funding from multiple agencies. WPTO is also an active participant in NOPP.

[80] U.S. Department of Energy, 2019, "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets." https://www.energy.gov/eere/water/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets#pbereport.

[81] For more information, visit www.nopp.org.

APPENDIX A: MARINE ENERGY MODELING TOOLS

WPTO has invested in or leveraged over a dozen numerical models. These models include design and analysis models to improve marine energy analysis and evaluate and compare different device designs, models to evaluate the performance and environmental effects of device arrays, models for turbulent inflow conditions or extreme sea states to evaluate structural load response, and economic benefits models.

- CACTUS (Code for Axial and Cross-flow TUrbine Simulation) - turbine performance simulation code, based on a free wake vortex method, to study wind turbines and marine energy devices.
- HARP_Opt (Horizontal Axis Rotor Performance Optimization) - utilizes MATLAB's optimization algorithms and the National Renewable Energy Laboratory's WT-Perf blade element momentum (BEM) code to design axial-flow wind and water (i.e. hydrokinetic) turbine rotors.
- Wave Energy Converter SIMulator (WEC-Sim) - open-source code for simulating wave energy converters.
- Mooring Analysis Program (MAP) - used to simulate performance of different mooring designs for marine energy devices.
- SNL-SWAN (Sandia National Laboratories – Simulating WAves Nearshore) - evaluate the performance and environmental effects of device arrays.
- SNL-Delft3D-CEC - evaluate the performance and environmental effects of device arrays.
- TurbSim - turbulent inflow conditions or extreme sea states to evaluate structural load response.
- WEC Design Response Toolbox (WDRT) – extreme response and fatigue analysis tools, specifically for design analysis of ocean structures such as wave energy converters (WECs).
- DOLfYN (Doppler Oceanography Library for pYthoN) - turbulent inflow conditions or extreme sea states to evaluate structural load response.
- JEDI (Jobs and Economic Development Impacts Marine and Hydrokinetic Power Model) - economic benefits and market penetration models.
- SAM (System Advisor Model) Tool – techno-economic benefits model to estimate the LCOE.
- AeroDyn - simulation code to predict the aerodynamics of horizontal axis turbines.
- FVCOM_MHK – SNL tidal current energy converter model coupled with the coastal model.
- MHKit – modeling tool that includes modules for ingesting, quality controlling, processing, visualizing, and managing data.

APPENDIX B: LCOE METRICS

Over the next several years, it is critical that a robust suite of additional metrics beyond modeled LCOE are developed and utilized to evaluate the effect of the Marine Energy Program's efforts. There are a number of demonstrated drawbacks in the sole use of LCOE for evaluating marine energy technology improvements, most notably that LCOE methodologies are geared toward utility-scale power generation and incorporate an increasing number of widely-varying assumptions for early-stage technologies.

The use of marine energy technologies to solve energy challenges in other Blue Economy markets will have very different technical and performance requirements and cost limitations. In addition, the standardized marine energy LCOE calculation requires detailed understanding and cost estimates of each capital cost component, learning rates, and maintenance schedules, as well as the need for many different variables related to full-scale array deployment and operation. Variations of the LCOE methodology may be considered to allow for it to be applied to evaluate technologies designed for different market opportunities, but there will also be a focus on developing and utilizing additional metrics for tracking subsystem performance improvements and techno-economic potential at early technology readiness level stages when the uncertainty of LCOE estimates is high. For example, metrics that have been used to track performance improvements in subsystem-focused projects (such as advanced controls, structure optimization, and power-take-off research) have utilized power-to-weight ratios, overall availability or uptime of the system, absorbed power, load reduction, component rating per unit cost, and reduction in failure rates. Other examples of performance metrics are capture width per characteristic device dimension ("capture width ratio"), ratios of absorbed energy to surface area, power-take-off force, and characteristic mass. LCOE proxies, intended for low technology readiness level system evaluation, include the average climate capture width per characteristic capital expenditure metric, which was utilized in the 2015-2016 Wave Energy Prize[82] along with the hydrodynamic performance quality metric. In addition, a methodology to evaluate the ultimate long-term techno-economic potential for cost reductions of different technologies/archetypes, the technology performance level evaluation, is newly under development with the hope that it can be applied where appropriate (Sandia National Laboratories 2015; Weber et al. 2017). The development and refinement of new and more nuanced metrics are immensely important to effectively evaluate progress.

The United States is also making a concerted effort to track global progress related to the development and use of metrics to align with the international community in the evaluation of technologies, as appropriate. A long-term activity the United States is participating in is the International Energy Agency's Ocean Energy Systems technology collaboration program. An ongoing multinational task within that group is centered on comparing and evaluating performance metrics to track progress, evaluate techno-economic potential, and make stage-gate decisions in R&D programs. The United States is a co-lead of this task and will continue to stay actively involved in such international efforts.

82 U.S. Department of Energy, 2016. "2016 Wave Energy Prize." https://www.energy.gov/eere/water/wave-energy-prize-home.

APPENDIX C: GLOSSARY

Array: A group of multiple devices collecting energy and converting power to an electric or nonelectric product.

Commercial viability: The state of a technology having proven both a high readiness and technology performance level such that an array-scale project is deemed investment worthy; being safe, reliable, and cost competitive.

Device: An individual unit capable of absorbing power and converting power to electricity (or other energy form for delivery in case of non-electric applications); the device is just one sub-system included in a number of others making up an entire system.

Levelized cost of energy (LCOE): The lifetime project costs divided by lifetime energy production, resulting in the total present value cost of operating a power plant. LCOE characterizes the average price in $/kilowatt-hour that a power plant must receive to break even over its operational lifetime.

Life cycle: The implementation of a project across all of its stages: engineering (includes permitting), procurement, construction, installation, operations, maintenance, decommissioning, and disposal. Usually used in the context of LCOE.

Performance: In most cases, as in the clause "performance and reliability," performance generally refers to the energy capture and conversion efficiency, but in the case of technology performance level, performance refers to all attributes of the array and any necessary supporting infrastructure that impact the techno-economic viability of the technology.

Project: Captures all aspects of a demonstration or deployment, including (if applicable depending on scale and product produced from project) permitting, training/securing workforce, arranging power purchaser or nonelectric product buyer, and so on that may not be captured by the "system." Projects can be pilot or commercial and at a device or array scale. A commercial project sells electricity to a grid (utility or micro), or a nonelectric product. A utility project is a specific commercial project delivering electricity as its product, at higher capacities serving a grid of significant size.

Readiness: The degree to which technology has progressed from an early stage of development (i.e., from conceptualization to commercialization, wherein the technology and its application in an array and supporting infrastructure have been derisked to a degree that the technology is certifiable/insurable at reasonable rates commensurate with other similar energy projects.

Reliability: Broad term intended to include all system aspects that effect the availability (percentage of time the energy conversion system is not in operation and thus available to convert energy from the resource and deliver the product—electricity—to the end user). For instance, downtime of the system regardless of the degree of severity—from an unreliable component that breaks but can be fixed to the failure of the system to survive—are all covered under the "reliability" term for the purpose of this report.

System: Refers to the device, mooring, grid connection (or energy delivery in nonelectric applications) subsystems as well as the effort and infrastructure for installation, operation, and maintenance, and recovery over the project's life cycle.

Technology performance level (TPL): Metric that rates a technology on a scale of 1–9 for having the necessary attributes to be techno-economically viable in a target market of high energy intensity and low cost of energy.

Technology readiness level (TRL): Metric that ranks a technology on a scale of 1–9, from the beginning of exploration and planning to the commercial application of the technology. See Open EI (2013) for more information.

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