U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Accomplishments Report

Water Power Technologies Office

2021-2022

Disclaimer

ACKNOWLEDGMENTS

The U.S. Department of Energy's Water Power Technologies Office 2021–2022 Accomplishments Report reflects the hard work and commitment of staff who supported projects across national laboratories, academic institutions, companies, and other organizations. This report highlights these efforts and how they help advance the hydropower and marine energy industries. The following individuals were instrumental in writing, reviewing, and verifying the impacts of these projects:

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Thank you to all.

LETTER FROM THE ACTING ASSISTANT SECRETARY

Dear colleagues,

Incredible work is underway across the U.S. Department of Energy to make progress toward the nation's goals of a carbon-free electricity sector by 2035 and a net-zero-emissions economy by 2050. Throughout Fiscal Year 2022, our Water Power Technologies Office (WPTO) and its partners at national laboratories, academic institutions, companies, and other organizations led efforts crucial to advancing the hydropower and marine energy technologies that have an important role in achieving these goals and our clean energy future.

For example, WPTO awarded $8 million across three projects for its first HydroWIRES-focused funding opportunity, which solicited projects to increase hydropower's flexibility and strengthen its ability to support an electric grid that increasingly relies on variable renewable energy sources. Also, as part of President Biden's Executive Order 14017, America's Supply Chains, WPTO and Oak Ridge National Laboratory researchers assessed the U.S. hydropower supply chain and found that while the existing supply chain currently supports the nation's large hydropower fleet, anticipated new construction and the need to refurbish, upgrade, and relicense facilities point to the need to scale up domestic supply chain activities.

Meanwhile, marine energy projects focused on deploying devices in the water, upgrading and constructing critical testing infrastructure, and engaging with stakeholders on materials and manufacturing research needs. For example, WPTO supported CalWave Power Technologies, Inc.'s 10-month deployment of its xWave wave energy pilot device, which represented the company's and California's first at-sea, long-duration wave energy project. These and other efforts advance the marine energy sector so it can contribute to energy needs, particularly in remote and island communities, and power applications such as ocean-observation technologies or desalination and water treatment devices.

These projects and many others featured in WPTO's 2021–2022 Accomplishments Report offer a snapshot of how the office and its partners are working to ensure hydropower and marine energy play an important role in the United States' clean energy system. Congratulations to everyone who contributed to this valuable work, and I look forward to communicating more progress in these areas to all of you in the years to come.

Sincerely,

Alejandro Moreno
Acting Assistant Secretary for Energy Efficiency and Renewable Energyw
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

LETTER FROM THE WATER POWER TECHNOLOGIES OFFICE DIRECTOR

Dear Stakeholders,

I am pleased to share the 2021–2022 Accomplishments Report from the U.S. Department of Energy's Water Power Technologies Office (WPTO). This report offers a glimpse into the important work happening across our Hydropower and Marine Energy programs with partners at national laboratories, academic institutions, companies, and other organizations.

At locations across the United States, researchers, developers, and other experts are assessing the potential of water power resources, developing and testing technologies to harness that power, and growing the existing and next-generation workforce needed to realize hydropower's and marine energy's full potential. These are just a few of the projects I am incredibly excited to share with you this year. These efforts can help transform our country's energy system—from bustling urban centers to remote and rural communities—and even how we power the technologies we rely on for weather monitoring at sea and water desalination.

A committed team focused on opportunities to deploy renewable energy today and tomorrow is behind each of these projects. I thank everyone working on WPTO-supported projects—those within these pages and the many more not included here—for their hard work and dedication. I hope you enjoy learning more about their crucial efforts. I also encourage you to learn more about our office's work in our recently released 2022 Peer Review report. This report describes the valuable input and feedback our external stakeholders shared with us during our virtual peer review in July 2022 that will inform our Hydropower and Marine Energy programs now and in the years to come.

You can stay up to date on all of WPTO's work, latest news, and events throughout the year by subscribing to our monthly Water Wire newsletter and bimonthly Hydro Headlines and Water Column newsletters. And please do not hesitate to reach out to us via email.

Sincerely,
Jennifer Garson
Director, Water Power Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

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ACRONYMS AND ABBREVIATIONS

Argonne	Argonne National Laboratory
CVF	Cybersecurity Value-at-Risk Framework
DOE	U.S. Department of Energy
ETIPP	Energy Transitions Initiative Partnership Project
H2Os	Hydropower Operations Optimization
HAWSEC	Hawaii Wave Surge Energy Converter
HCC	Hydropower Collegiate Competition
HERO WEC	Hydraulic and Electric Reverse Osmosis Wave Energy Converter
HydroWIRES	Hydropower and Water Innovation for a Resilient Electricity System
IEC	International Electrotechnical Commission
MECC	Marine Energy Collegiate Competition
NMRECs	National Marine Renewable Energy Centers
NPD	non-powered dam
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
ORPC	Ocean Renewable Power Company
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
RFTS	request for technical support
RHT	Restoration Hydro Turbine
Sandia	Sandia National Laboratories
TC 114	Technical Committee 114 for Marine Energy Systems
TEAMER	Testing Expertise and Access for Marine Energy Research
TENG	triboelectric nanogenerator
TFiT	Triton Initiative Field Trials
waterSHED	Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design
WPTO	Water Power Technologies Office

PROJECTS ACROSS THE WATER POWER TECHNOLOGIES OFFICE

WPTO Releases First Multi-Year Program Plan Outlining Research Priorities and Activities

Project Name: WPTO Multi-Year Program Plan

In 2022, the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) released its first Multi-Year Program Plan, a comprehensive report detailing the office's future research, development, demonstration, and commercial activities across both hydropower and marine energy and outlining how these efforts can help meet the nation's energy and sustainability goals.

The report details key performance goals for each of WPTO's activity areas until 2025 and includes long-term, follow-on objectives through 2030. This report serves as a strategic vision and operational guide to help WPTO manage and coordinate its activities and communicate its mission, goals, and plans. The Multi-Year Program Plan was an integral part of the 2022 Peer Review, providing reviewers insight and guidance on the office's strategy to which WPTO-funded projects must align.

WPTO released its first Multi-Year Program Plan, a comprehensive report outlining the office's future research, development, demonstration, and commercial activities. *Image from Jong Marshes, Unsplash*

Inclusive Energy Innovation Prize Selects Climate Justice Changemakers

Project Name: Inclusive Energy Innovation Prize

Project Team: National Renewable Energy Laboratory (lead) and the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and Office of Economic Impact and Diversity with additional support from the Office of Technology Transitions

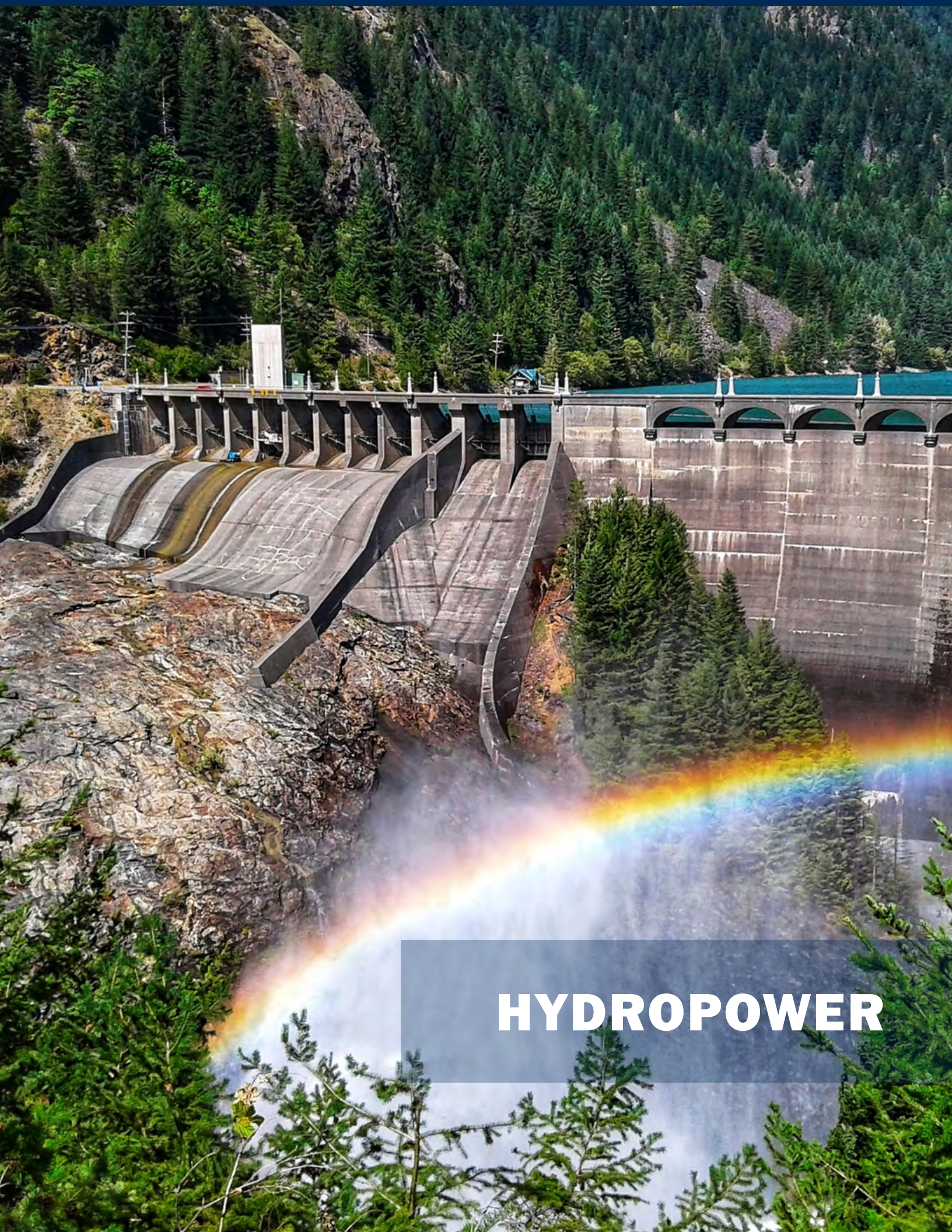
Prize Recipient Locations: Anchorage, Alaska; Atlanta, Georgia; Bethesda, Maryland; Chicago, Illinois; Detroit, Michigan; Edinburg, Texas; Fresno, California; Knoxville, Tennessee; Minneapolis, Minnesota; New Haven, Connecticut; New Orleans, Louisiana; New York, New York; Pine Ridge, South Dakota; Portland, Oregon; Richland, Washington; Tuscaloosa, Alabama; Utuado, Puerto Rico; Washington, D.C.

In May 2022, DOE awarded $3.6 million to 18 organizations in Phase One of the Inclusive Energy Innovation Prize. These organizations are working to enhance entrepreneurship and innovation in climate and clean energy technologies through programs for business and technology incubation and acceleration, workforce development, and community- and university-based leadership development activities.

The winning teams from Phase One, now in Phase Two, are from a wide range of geographic regions spanning from Puerto Rico to Alaska, and embedded in rural, urban, and indigenous communities. The teams' activities range from workforce and leadership training in the clean energy economy to restoring and fortifying community clean energy resilience based on local principles and resources. During Phase One, teams submitted impact plans detailing their experiences engaging and supporting disadvantaged communities. These plans also included activities teams would implement during Phase Two, resources and capabilities needed to successfully engage with communities, and finally, their vision and anticipated long-term impacts of their project.

With more than 200 applications, this prize attracted the most applicants of any Office of Energy Efficiency and Renewable Energy prize to date. Of those submissions, 85% identified themselves as first-time applicants, and 54% of applications were submitted by businesses owned by women, minorities, or disadvantaged persons. This prize is part of DOE's Justice40 efforts.

Launched by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and Office of Economic Impact and Diversity, the Inclusive Energy Innovation Prize centers on climate and environmental justice as part of the transition to a net-zero-carbon economy by 2050. *Image from National Renewable Energy Laboratory*



HYDROPOWER

HYDROPOWER PROGRAM

Hydropower is one of the oldest and largest sources of renewable energy and uses the flow of moving water to generate clean electricity that powers homes, businesses, and industries. In 2021, hydropower accounted for 31.5% of U.S. renewable electricity generation, while pumped storage hydropower (PSH) remains the largest contributor to U.S. energy storage, representing roughly 93% of all commercial storage capacity in the United States.

WPTO's Hydropower Program conducts research, development, demonstration, and commercial activities to advance transformative, cost-effective, reliable, and environmentally sustainable hydropower and PSH 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.

WPTO envisions 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. To achieve this vision, WPTO's Hydropower Program supports R&D projects across five activity areas. Success stories in the WPTO 2021–2022 Accomplishments Report are presented within these activity areas:

- Innovations for Low-Impact Hydropower Growth
- Grid Reliability, Resilience, and Integration (HydroWIRES Initiative)
- Fleet Modernization, Maintenance, and Cybersecurity
- Environmental and Hydrologic Systems Science
- Data Access, Analytics, and Workforce Development

Testing On New Turbine Demonstrates Safe Passage For Large And Small Fish

Project Name: Advanced Compact Generation Module with Fish Safe Runner Technology

Project Team: Natel Energy (lead) and Pacific Northwest National Laboratory

Lead Recipient Location: Alameda, California

Natel Energy developed a solution validated by Pacific Northwest National Laboratory (PNNL) to help fish move safely through hydropower facilities. Natel's Restoration Hydro Turbine (RHT) has a unique design with thicker blades, rounded leading edges, and a forward slant from the blade's hub to its tip. Natel and PNNL tested the passage of American eel and rainbow trout, ranging from 8-20 inches in length, through the RHT. Collectively, more than 99% of fish passed safely through the turbine. The RHT is the first turbine in the industry to enable safe passage for large and small fish while still meeting high performance metrics and matching standard installation configurations for multiple sizes and configurations of hydropower facilities. This innovation demonstrates significant progress in efforts to preserve biodiversity while advancing renewable energy production.

Natel Energy's Restoration Hydro Turbine is designed to make it easier for fish to navigate through hydropower facilities without getting hurt. *Image from Natel Energy*

New Composite Material Results in Lighter, More Durable Hydropower Runner Blades

Project Name: Design and Development of a Composite Hydropower Turbine Runner

Project Team: Composite Technology Development Inc. (lead), Penn State University Advanced Research Laboratories, Sandia National Laboratories, Tribologix, Inc., and Voith Hydro Inc.

Lead Recipient Location: Lafayette, Colorado

A team led by Composite Technology Development Inc. created and tested a composite hydropower turbine runner and found composite blades performed nearly identically to traditional blades made of stainless steel. This composite material aims to reduce the weight and extend the useful life of runner blades, which are attached to the rotating part of the turbine used to convert the energy of falling water into mechanical energy.

This lighter, more durable composite material could be a viable candidate for new and replacement runner blades. When the composite materials are applied to an existing runner blade or used to create a new one, the resulting blade has potential to be less expensive and easier to install than traditional blades and reduces maintenance by decreasing the effects of cavitation, the phenomenon that erodes hydropower turbines when vapor bubbles form and implode due to rapid pressure changes within the hydropower turbine.

The blades were tested at Penn State University Advanced Research Laboratories. Sandia National Laboratories (Sandia), Tribologix, Inc., and Voith Hydro Inc. provided support during the development and testing process.

New Assessment Finds Opportunities for Conduit Hydropower Development Across the United States

Project Name: National Conduit Resource Assessment

Project Team: Oak Ridge National Laboratory (lead), Upstream Tech, and U.S. Environmental Protection Agency

Lead Recipient Location: Oak Ridge, Tennessee

An Oak Ridge National Laboratory (ORNL) report found opportunities to develop hydropower on conduits in every state, which could add 1.41 gigawatts of new generating capacity. The report, which is the first to assess the potential for new hydropower development on conduits nationwide, conservatively estimates new hydropower potential across municipal (374 megawatts), agricultural (662 megawatts), and industrial (378 megawatts) sectors.

Conduit hydropower utilizes existing pipelines, irrigation canals, and other humanmade water conduit structures as the basis for electricity generating equipment. This eliminates the need for a dam or reservoir and allows for greatly reduced environmental impacts, a simplified permitting process, and the potential to generate new revenue for water system operators. Water conduit projects tend to be small but have high development feasibility, meaning many communities, including those in small and rural areas, could implement this type of renewable energy project and reduce their dependence on the local grid during periods of peak electricity demand.

According to the report, the United States has potential for more than double the currently installed conduit hydropower capacity, with the largest resource potential in the western United States, especially in California, Colorado, Washington, Nebraska, and Oregon. There are also sizable resource potential opportunities spread across the country, including in New York, Maryland, Texas, and much of the Midwest.

Conduit hydropower turbines can be installed in existing man-made water conduits, such as this drinking water distribution system in California.
Image from Canyon Hydro

To conduct the analysis, an expert team led by ORNL evaluated four categories of conduits: water supply pipelines, wastewater discharge conduits, agricultural irrigation conduits, and conduits for cooling water discharge from thermoelectric power plants. For each category, the team developed and implemented methods to estimate hydraulic head (the vertical distance that water falls or the pressure drops), annual water flows, and hydropower potential based on analyses of satellite imagery, topography, and existing datasets.

The assessment was conducted at the reconnaissance level, considering resources that could be available for development at the state and national levels using present-day assumptions about conduit hydropower technology. This approach offers a replicable evaluation methodology for conduit hydropower potential across the country.

New Research Informs Decision-Making on Powering Non-Powered Dams

Project Name: NPD Development Opportunities Assessment

Project Team: Oak Ridge National Laboratory

Lead Recipient Location: Oak Ridge, Tennessee

Researchers at ORNL developed two tools and published a report to aid developers' decisions when adding power-generating infrastructure to dams that currently do not generate power, referred to as non-powered dams (NPDs). There are more than 90,000 dams in the United States, but less than 3% generate hydropower. ORNL's NPD Retrofit Exemplary Design for Hydropower Applications report, NPD Explorer App, and NPD Custom Analysis and Taxonomy App will facilitate knowledge sharing across the industry and support decision-making on retrofitting NPDs with power-generating infrastructure.

The NPD Retrofit Exemplary Design for Hydropower Applications Report identified key NPD development challenges facing the industry, including aging infrastructure, dam design limitations, development costs and timelines, and environmental considerations. The report also outlined technology innovations—such as the use of advanced manufacturing techniques and standard modular hydropower, and combining the development of alternative energy systems to share equipment costs—to help address these challenges. The report identifies best practices to guide development activities, and identifies opportunities to achieve non-energy benefits, such as restoring river environments or improving infrastructure reliability, through an NPD project.

ORNL also released the NPD Explorer App, an interactive platform that allows researchers and developers to explore NPD development opportunities in the United States. The tool features filters that allow users to narrow down NPDs by a variety of characteristics, such as location and proximity to existing electricity transmission infrastructure. Meanwhile, the NPD Custom Analysis and Taxonomy App is a step-by-step tool that allows users to easily group and compare dams across the country, providing valuable insights into NPD development opportunities.

Oak Ridge National Laboratory released a report identifying key opportunities to add hydropower generation to non-powered dams in the United States. *Image from Andrea Walls, U.S. Department of Energy's Make a Splash Photo Contest*

Natel Energy Advances Modular Hydropower Technology that Supports Watershed Restoration

Project Name: Restoration Hydro: A Watershed Approach to Standard Modular New Hydropower

Project Team: Natel Energy (lead); McLaughlin Whitewater; Natural Systems Designs; Oak Ridge National Laboratory; Small Hydro Consulting; University of California, Berkeley's Environmental Systems Dynamics Laboratory; and Wells Engineering

Lead Recipient Location: Alameda, California

Natel Energy developed a modular hydropower concept called Restoration Hydro, which incorporates the company's RHT. This modular approach can help expand hydropower while supporting safe fish passage, river channel connectivity, and watershed restoration efforts.

The design process began with detailed site selection criteria that emphasized combining watershed restoration efforts with new hydropower development. Project partner Natural Systems Design led the initial site search, and the team narrowed options to alluvial pockets, which are wider stretches of a river where sediment-rich floodplains are bounded upstream and downstream by steeper, more confined river reaches. These pockets were found to be ideal targets for simultaneous hydropower development and watershed restoration activities such as floodplain reconnection with other river systems, elevated water tables, recharged aquifers, and increased overall wildlife habitat.

Project partners—including McLaughlin Whitewater; University of California, Berkeley's Environmental Systems Dynamics Laboratory; ORNL; Small Hydro Consulting, LLC; and Wells Engineering, LLC—also collaborated to create a facility design that supports downstream and upstream fish and sediment passage.

Through this project, Natel developed a framework to identify potential sites for modular hydropower development and a blueprint for future site and facility design using this concept.

Natel Energy's Restoration Hydro concept combines watershed restoration efforts with hydropower development. *Image from Jon Flobrant, Unsplash*

New Tool Helps Developers Evaluate Locations for Small Hydropower Projects

Project Name: Standard Modular Hydropower Technology Acceleration

Project Team: Oak Ridge National Laboratory (lead) and Natel Energy

Lead Recipient Location: Oak Ridge, Tennessee

Researchers at ORNL developed and launched the Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design (waterSHED) tool, which aims to reduce the time and money developers must spend evaluating the design, operation, and feasibility of new, small hydropower projects at streams and sites with existing water infrastructure like NPDs. By rapidly evaluating potential sites, developers can quickly determine how to best use existing water resources to provide power and support environmental services like fish and sediment passage. The expedited optimization process—which uses novel metrics for economic, environmental, and social performance to help quantify design tradeoffs and identify win-win scenarios—saves developers time and money during site evaluation.

Results from tests of the waterSHED tool, which is a Python application, were discussed in in several case studies. This includes one study by Natel Energy that evaluated the costs and potential benefits related to fish passage for the company's turbine design compared to conventional designs.

The tool currently exists as open-source code with multiple user-friendly functionalities. Future testing and industry case studies could make it even more user-friendly and prove the waterSHED tool could be an important part of small hydropower development.

The Water Allocation Tool Enabling Rapid Small Hydropower Environmental Design tool aims to reduce the time and money developers must spend evaluating the design, operation, and feasibility of new, small hydropower projects at streams and sites with existing water infrastructure. *Image from Jani Brumat, Unsplash*

WPTO Launches New Hydropower Prize Focused on Grid Resiliency and Selects Winners for Phases One and Two

Project Name: Hydropower Operations Optimization (H2Os) Prize

Project Team: National Renewable Energy Laboratory (lead) and RTI International

WPTO launched the Hydropower Operations Optimization (H2Os) Prize in April 2022. During the remainder of Fiscal Year 2022, competitors completed two prize phases, and WPTO awarded $25,000 to innovators developing new solutions that can help advance hydropower's contribution to the grid.

As the United States works to decarbonize the power grid by 2035, hydropower's evolving role will be crucial to improving the grid's reliability, resilience, and overall performance. Teams competing in the H2Os Prize are helping make hydropower more flexible by offering new ideas on how this resource can provide on-demand power for the grid, especially as more variable renewable energy resources begin to power the nation.

The H2Os Prize is funded by WPTO and administered by the National Renewable Energy Laboratory (NREL) in partnership with RTI International.

The H2Os Prize challenges innovators to develop cutting-edge solutions for hydropower systems to coordinate with existing grid scheduling practices and meet water management needs, such as water supply, environmental flow requirements, and flood management. *Graphic by the National Renewable Energy Laboratory*

Researchers Identify Opportunities to Expand Pumped Storage Hydropower

Project Names: A Review of Technology Innovations for Pumped Storage Hydropower, and Closed-Loop Pumped Storage Hydropower Resource Assessment for the United States

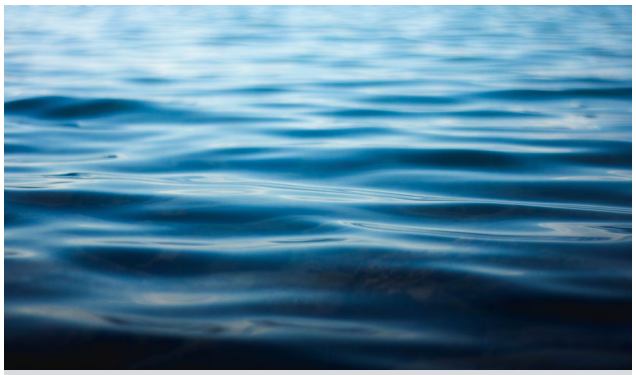
Project Teams: Argonne National Laboratory and National Renewable Energy Laboratory

Lead Recipient Locations: Lemont, Illinois, and Golden, Colorado

Researchers from two national laboratories conducted studies that found potential for future development of PSH technology and highlighted ways to significantly reduce cost, time, and risk for new PSH projects as the United States works to achieve a carbon-free electricity grid by 2035 and a net-zero-emissions economy by 2050.

In their study, A Review of Technology Innovations for PSH, Argonne National Laboratory (Argonne) researchers performed a landscape analysis of current PSH technology and reviewed a dozen promising new PSH concepts and innovations, including submersible pump-turbines and motor-generators, geomechanical PSH, open-pit mine PSH, and hybrid PSH technologies. They found that several of these new concepts have the potential to significantly reduce cost, time, and risk for the development of new PSH projects.

For the study, Closed-Loop PSH Resource Assessment for the United States, NREL researchers conducted a large-scale study of potential PSH sites across the United St ates that are separated from a naturally flowing body of water (like a river), also known as closed-loop PSH. Using mapping to track suitable locations and features such as reservoir volume, elevation, and paired upper and lower reservoirs, NREL identified nearly 15,000 possible sites where PSH technology could be deployed in the future.



Researchers at Argonne National Laboratory and the National Renewable Energy Laboratory conducted studies that found potential for future development of pumped storage hydropower technology and highlighted ways to significantly reduce cost, time, and risk for new projects. *Image from Borna Bevanda, Unsplash*

National Lab Analyses Help Hydropower Operators and Developers Understand How Facilities Can Integrate and Be Profitable on the Changing Electricity Grid

Project Name: HydroWIRES Reports on Pumped Storage Hydropower, Transmission, and Energy Markets

Project Team: Argonne National Laboratory and Pacific Northwest National Laboratory

Lead Recipient Locations: Lemont, Illinois, and Richland, Washington

Researchers at Argonne and PNNL conducted several analyses to help hydropower operators, developers, and grid planners better understand how hydropower facilities can integrate and be profitable on a changing electricity grid that increasingly relies on variable renewable resources like wind energy and solar power.

As a uniquely flexible and scalable asset, PSH can support the electric grid by balancing supply and demand, as well as providing other valued grid services. Two white papers—A Computational Framework for Energy Storage Participation in Transmission Planning with Electricity Market Participation from Argonne and Enabling Principles for Dual Participation by Energy Storage as a Transmission and Market Asset from PNNL—evaluated how to use energy storage technologies like PSH for both transmission benefits and competitive participation in the electricity market. Argonne researchers developed a framework to help PSH project operators determine how their plant can best be a transmission solution, which is a critical input for participating in the transmission planning process.

Meanwhile, the PNNL paper reviewed the current technical barriers that prevent the realization of dual-use energy storage projects that provide both regulated transmission and competitive market services. The paper described principles that dual-use energy storage projects must satisfy to support transmission and market services and identified considerations for regional market operators, utilities, developers, regulators, policymakers, and other stakeholders.

Argonne and PNNL also released two white papers examining ways hydropower can operate in future energy markets with increased solar power and wind energy resources. Price Formation in Zero-Carbon Electricity Markets: The Role of Hydropower, authored by Argonne researchers, looked at how generators could be compensated when the energy they produce is relatively

Recent studies from Argonne National Laboratory and Pacific Northwest National Laboratory are helping hydropower operators and developers better understand how to integrate hydropower into a changing energy grid.
Image from Shutterstock

low-cost and how hydropower can respond to the subsequent electricity market challenges and opportunities. It found that hydropower—especially reservoir hydro and PSH—is likely to benefit from market conditions in a zero-carbon system because it can provide flexibility and energy storage in systems with large shares of variable renewable resources.

Meanwhile, Compensation Mechanisms for Long-Duration Energy Storage, written by PNNL researchers, reviewed compensation and business models from around the world including plant ownership structures such as multiple owners and renters, third-party ownership, and subscription lease models. It found that these alternate compensation and ownership models may be needed to incentivize new PSH development in the current regulatory environment. these alternate compensation and ownership models may be needed to incentivize new PSH development in the current regulatory environment.

Predicting Grid and Market Trends to Maximize Pumped Storage Hydropower Flexibility

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

Project Team: Missouri University of Science and Technology (lead), Midcontinent Independent System Operator, Stevens Institute of Technology, Ross Baldick Educational and Consulting Services, DTE Energy, Consumers Energy, and Ameren Missouri

Lead Recipient Location: Rolla, Missouri

A team led by the Missouri University of Science and Technology built an optimization model to help grid operators decide how to distribute a PSH facility's time between generating power and pumping water to store energy. The model has enormous potential to increase electricity market efficiency and profit for PSH owners while reducing costs for energy consumers.

The model leverages real data and operational experiences from industry partners to ensure it is accurate and can provide results quickly. The team estimated that using the PSH optimization model could result in up to a 97% increase in PSH operator profit and reduce total system costs by up to 0.67%. Annually, this could result in tens of millions of dollars saved for large grids that stretch across multiple states and potentially lower the cost consumers pay for energy. This model could help further support the clean energy transition by helping to integrate more renewable energy onto the electricity grid. By maximizing PSH facilities' flexibility, grid operators will be able to balance the fluctuations of other renewable energy sources.

A new optimization model for pumped storage hydropower can help grid operators decide how to distribute a facility's time between generating power and pumping water to store energy. *Image from Consumers Energy*

Study Examines Sustainability of New Closed-Loop Pumped Storage Hydropower

Project Name: Life Cycle Assessment of Pumped Hydropower Storage

Project Team: National Renewable Energy Laboratory (lead), Argonne National Laboratory, and representatives from industry and academia

Lead Recipient Location: Golden, Colorado

Published in August 2022, the Life Cycle Assessment for Closed-Loop Pumped Hydropower Energy Storage in the United States study explores the potential environmental impacts of new closed-loop PSH projects in the United States compared to other energy storage technologies. The authors, who are from NREL, compared data on PSH and alternative energy storage options and found that across many future energy scenarios and grid mixes, PSH plants contribute the least to global warming potential.

This study is the first to examine the full life cycle of new closed-loop PSH projects—from resource extraction through operation and on to end-of-life material recovery (or disposal)—focusing on greenhouse gas emissions. Such data can help industry build investor confidence by demonstrating that PSH can be a valuable and sustainable addition to tomorrow's clean energy grid. Before this study, relatively little was known about the environmental impacts of constructing new, closed-loop PSH plants. Now, the team's findings could help stakeholders strategize how to sustainably grow the industry.

Pumped storage hydropower could be a promising solution for grid-scale energy storage. Now, a new study evaluates how sustainable the technology is compared to other energy storage options. *Image from National Hydropower Association*

For example, though the team based its research on a plant with an 80- to 100-year lifespan, the results represent a range of potential plant specifications and geographic locations. And larger plants, according to the study, could have lower overall lifetime carbon emissions. Developers can use this data to accurately assess their proposed plant's emissions, and the results could help inform decision making about future investments in new closed-loop PSH projects versus other energy storage technologies. A Technical Review Committee, which included nine representatives from industry and academia, as well as Argonne, provided valuable guidance to the report's authors and contributed advice on data sources, assumptions, modeling approach, and dissemination to stakeholders.

Researchers Demonstrate How to Design and Operate Francis Turbines to Increase Hydropower Facilities' Operational Flexibility

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

Project Team: General Electric Research (lead), Eagle Creek Renewable Energy, and General Electric Renewable Energy

Lead Recipient Location: Niskayuna, New York

The General Electric Research-led team demonstrated a new hydropower turbine design and operating approach that allows plant operators to adjust power output in a few seconds to meet energy demand without needing to start or stop units, which can take up to 90 seconds. Historically, hydropower units are mainly operated close to their nominal power output and, when power demand changes, plant operators must start or stop units.

The team's approach to design and subsequently operate Francis hydropower turbines at low-head sites increases facility flexibility (or its ability to quickly respond to changes in power demand), as well as oxygen levels in water. Francis turbines are the most commonly used in the world for hydropower generation, and for this project, low-head hydropower facilities are defined as those with 80 meters or less of height differential between the water intake and discharge.

The team's solution relies on a new turbine hydraulic design and a monitoring methodology to unlock new hydropower plant operation strategies. This methodology leverages detailed measurements onsite and on the test bench along with numerical simulations to assess the exact behavior of the turbine and its capability to operate in a fully flexible way, far from its nominal output.

The increased flexibility gained by implementing the new methodology, combined with design changes made when manufacturing new Francis turbines, will enable facilities to generate power over a wider operating range, as demonstrated during a test at High Rock powerplant, operated by Eagle Creek. The operating range at hydropower plants that utilize Francis turbines is determined by the amount of water discharged, which correlates to output power. Being able to handle a wide range of water discharge volume means the facility is able to quickly adjust the amount of power it can provide to the grid.

The team developed a methodology that can be applied to any low-head facility using Francis hydropower turbines. If adopted broadly, hydropower operators can not only increase their facility's flexibility but also fish survival because the new turbine design and monitoring methodology help to increase oxygen levels in water. Moving forward, the project team will continue to improve the methodology so it can be widely deployed.

A General Electric Research-led team demonstrated a new hydropower turbine design and monitoring methodology that allows plant operators to adjust power output in a few seconds to meet energy demand without needing to start or stop units. *Image from American Public Power Association, Unsplash*

National Laboratory Team Develops First Model for Hydropower Digital Twin

Project Name: Digital Twin for Hydropower Systems Open Platform Framework

Project Team: Oak Ridge National Laboratory and Pacific Northwest National Laboratory

Lead Recipient Locations: Oak Ridge, Tennessee, and Richland, Washington

Building on hydropower R&D cooperation between the United States and Norway, a collaborative project between ORNL and PNNL developed a one-dimensional model of a hydropower digital twin, which is a virtual representation of a test hydropower unit in Norway that provides equipment manufacturers, end users, and utilities with insights into the real system. This newly developed model is the first step in developing a three-dimensional, open-source model that will support in-depth analyses of hydropower plants.

To create the one-dimensional twin, the project team developed mathematical models to represent the physics of a hydropower system. These models allow the one-dimensional twin to provide information on a system's major components, such as torques, speeds, and hydrodynamic forces on turbines, generators, and control devices.

Equipment manufacturers, owners, operators, and other interested stakeholders can use insights from the one-dimensional (and, eventually, the three-dimensional) twin of a hydropower facility to predict and inform future decisions related to hydropower maintenance, modernization and asset management.

The digital twin is a virtual platform that represents and can mimic the operation of a real hydropower plant, allowing developers to gain insights from existing plants more efficiently. *Image from Cedric Dhaehens, Unsplash*

New Tool Helps Hydropower Plants Assess Cybersecurity Risk

Project Name: Cybersecurity Value At-Risk Framework

Project Team: National Renewable Energy Laboratory (lead) and Argonne National Laboratory

Lead Recipient Location: Golden, Colorado

The hydropower industry can now access a new, free, and publicly available tool, called the Cybersecurity Value-at-Risk Framework (CVF), which offers a self-guided, automated way to make sound cybersecurity investment decisions for individual facilities. As more hydropower facilities transition to modern systems that are interconnected with the broader power grid, the risk of cyberattacks can increase. Simply assessing cybersecurity risk can be costly, and it is not easy to decide which cybersecurity investments are necessary. That's why researchers at NREL and Argonne built a free tool that will enable hydropower owners and operators to understand their individual plant's cybersecurity risk and how to best conserve resources while mitigating those risks.

In 2022, the multi-lab team published the first iteration of the CVF tool along with an instructional guide. The team also assessed the tool's performance in partnership with Berkshire Hathaway Energy's PacifiCorp hydropower facilities. Based on positive feedback during WPTO's peer review, the research team also plans to work with more industry partners to learn whether the CVF can help hydropower facilities save time, money, and effort while achieving the security they need. In coming years, the CVF is expected to contribute to enhanced cybersecurity for dam infrastructure, reduce operation and maintenance costs, and increase the resilience of natural ecosystems.

Anuj Sanghvi (left) helped design a new tool for hydropower industry owners and operators to make well-informed cybersecurity investments. *Image from Dennis Schroeder, National Renewable Energy Laboratory*

Researchers Find U.S. Hydropower Supply Chain Effectively Supports Existing Fleet but Must Scale Up to Meet Future Demand

Project Name: Hydropower Supply Chain Deep Dive Assessment

Project Team: Oak Ridge National Laboratory

Lead Recipient Location: Oak Ridge, Tennessee

As part of a series of supply chain assessments, ORNL researchers assessed the U.S. hydropower supply chain and found that while the existing supply chain is mature and effectively supports the nation's large hydropower fleet, anticipated new construction and the need to refurbish, upgrade, and relicense facilities point to the need to scale up domestic supply chain activities.

The Hydropower Supply Chain Deep Dive Assessment, published in response to President Biden's Executive Order 14017, America's Supply Chains, examined the U.S. hydropower supply chain to identify potential bottlenecks, challenges, and opportunities related to domestic capabilities. ORNL researchers analyzed hydropower workforce data and conducted interviews with equipment manufacturers, plant owners, operators, and consultants to understand the hydropower supply chain. The team identified common themes and trends from the interviews.

The report found that while the current supply chain effectively supports the existing fleet, it will need to scale up activities to meet anticipated industry growth due to a combination of increased refurbishments and upgrades—partly connected to the wave of relicensing expected to take place during the 2020s—and construction of the new hydropower and pump storage hydropower capacity needed to achieve clean energy goals. The report outlined a few key challenges the supply chain faces, including vulnerabilities related to securing large components with long lead times, managing global disruptions, and maintaining a well-trained workforce.

The report detailed concrete ways to bolster the supply chain. New construction and modernization of the existing fleet could drive expansion of domestic manufacturing, reshoring, and foreign direct investment in the U.S. hydropower supply chain. Reshoring manufacturing of critical components should also be a high priority to improve supply chain resilience and meet increased U.S. demand for domestically produced hydropower components.

The Hydropower Supply Chain Deep Dive Assessment provides an in-depth analysis of the current and future needs of the hydropower supply chain. *Image from Karl Specht, U.S. Department of Energy's Make a Splash Photo Contest*

New Machine Learning Technology Helps Hydropower Facilities Detect Migrating Eels

Project Name: Deep Learning for Fish Identification from Sonar Data

Project Team: Electric Power Research Institute and Pacific Northwest National Laboratory

Lead Recipient Location: Palo Alto, California, with testing completed in Richland, Washington

An Electric Power Research Institute and PNNL team optimized advanced machine learning technology that uses sonar data to identify migrating eels near hydropower facilities. The resulting object detection software uses images and videos to identify multiple fish species and distinguish them in near-real time from other objects in the water.

Existing technology at hydropower facilities cannot automatically detect migrating eels, so many operators curtail turbine operation during migration season to ensure safe eel passage. This new technology will help operators better identify these migrating eels, decreasing injuries to these fish populations and reducing the need to cut back turbine operation when fish are not present.

The team—which included machine learning experts, data scientists, biologists, and engineers—experimented with and optimized data and information (such as neural networks, algorithms, training datasets, and thresholding specifications) to ensure computers could identify the correct fish shapes from field data collected by the Electric Power Research Institute's Eel Research Centre. The team further tested the detection software at PNNL's Aquatic Research Laboratory with fish to validate and improve the program's performance.

A team of researchers optimized deep learning software and created software that can automatically detect migrating fish near hydropower facilities.
Image from Josh Newhard, U.S. Fish and Wildlife Service

Multi-Regional Study Shows Hydropower Is Reliable Even During Severe Drought

Project Name: Retrospective Analysis of Drought Impacts on Hydropower in Western United States

Project Team: Pacific Northwest National Laboratory

Lead Recipient Location: Richland, Washington

Researchers at PNNL completed the most comprehensive study into the effects of drought on hydropower generation in the western United States this century. The study found that while drought raises concern for hydropower generation, the overall western hydropower fleet sustained 80% of its average expected generation—even during the most severe droughts over the past two decades. Furthermore, hydropower could still be relied upon to supply flexible power during periods of high energy demand.

To conduct the study, researchers gathered data from eight climate sub-regions across 11 western states: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. That data indicated 2021 to be the second worst year for drought this century, with overall hydropower generation 16% lower than the average since 2001. However, the large sizes of western states and the wide range of weather across the West means drought rarely impairs hydroelectric power across all climate sub-regions simultaneously. Consequently, the overall hydropower fleet remains reliable even if certain plants or sub-regions produce less power.

A study from Pacific Northwest National Laboratory found that while drought raises concern for hydropower generation, the overall western hydropower fleet sustained 80% of its average expected generation, even during the most severe droughts over the past two decades. *Image from Tara Kothari, U.S. Department of Energy's Make a Splash Photo Contest*

New Collegiate Competition to Support Hydropower Workforce Growth

Project Name: Hydropower STEM and Workforce Development

Project Team: National Renewable Energy Laboratory (lead) and the Hydropower Foundation

Competitors: Columbia University; Cornell University; Endicott College; Northern Arizona University; Pennsylvania State University; Texas Tech University; University of California, Riverside; University of Houston; University of Virginia; Virginia Polytechnic Institute and State University; and Yale University

In 2022, WPTO launched the inaugural Hydropower Collegiate Competition (HCC) to pave the way for a new generation of diverse, highly skilled workers to modernize the U.S. hydropower fleet and chart their careers in clean energy. The hydropower industry is critical to achieving the Biden administration's goal of a carbon-free power sector by 2035, but more than a quarter of the hydropower workforce over the age of 55 is expected to retire in the next decade. The industry needs a new generation to fill these jobs and support the country's clean energy transition.

HCC participants will gain direct hydropower industry experience, valuable exposure to potential career pathways, and greater understanding of hydropower's role in a clean energy future. Eleven schools, including three minority-serving institutions, are participating in the inaugural competition.

The HCC is intended to inspire and guide students to join the hydropower workforce. At the same time, the competition aims to incentivize academic leaders to include hydropower in their institution's curricula, help align industry needs with workforce development programs, and get people excited about growth in new or modern hydropower technologies, like low-impact hydropower, PSH, and adding power to NPDs.

Through this competition, WPTO and its partners are working to address several barriers that could slow hydropower workforce growth. HCC organizers are performing outreach to underrepresented students to help increase diversity in the hydropower industry. The competition also aims to spread awareness and skills to better prepare students for careers in hydropower.

WPTO funds the HCC, while NREL and the Hydropower Foundation administer the competition.

Students eager for more hydropower professional development activities, like the ones seen here competing in the Hydro Think Tank™, can compete in the new Hydropower Collegiate Competition, which offers participants direct hydropower industry experience, valuable exposure to potential career pathways, and greater understanding of hydropower's role in a clean energy future. *Image from Bree Mendlin, Hydropower Foundation*

WPTO Investments Advance Hydropower's Contributions to Grid Resilience

Project Names: HydroWIRES Laboratory Call and Technology Innovation to Increase Hydropower Flexibility Funding Opportunity

Selectees: *Laboratory Call:* Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory; *Funding Opportunity:* General Electric Research, Littoral Power Systems, Inc., and Oregon State University

Selectee Locations: *Laboratory Call:* Lemont, Illinois; Idaho Falls, Idaho; Golden, Colorado; Oak Ridge, Tennessee; and Richland, Washington; *Funding Opportunity:* Niskayuna, New York; New Bedford, Massachusetts; Corvallis, Oregon

In Fiscal Year 2022, WPTO made investments through its HydroWIRES Initiative focused on advancing hydropower's contributions to grid resilience. In November 2021, WPTO announced $16 million in projects across five national laboratories. These projects will create tools and products to support the industry's decision-making abilities. For example, these projects will enable the U.S. hydropower community to more accurately model future water availability, evaluate opportunities for adding hydropower to NPDs, and understand how to operate hydropower to mitigate wildfires' impacts to the power grid.

In May 2022, WPTO awarded $8 million across three projects for its first HydroWIRES-focused funding opportunity, which solicited projects to increase hydropower flexibility. By increasing hydropower's flexibility, these projects will strengthen hydropower's ability to support an electric grid that increasingly relies on variable renewable energy sources.

Hydroelectric Production Incentive Program Distributes $13.5 Million to a Record Number of Facilities

Project Name: Section 242: Hydroelectric Production Incentive Program

Locations: Payments distributed to 55 hydroelectric facilities across the country

DOE's Hydroelectric Production Incentive Program distributed $13.5 million in incentive payments to 55 hydroelectric facilities, a record number. This program supports hydropower development by providing funding for electricity generated and sold from dams and other water infrastructure throughout the United States that add or expand hydroelectric power-generating capabilities.

For the first time since the program was initially funded in 2014, all hydroelectric facilities that applied were fully funded at the amount for which they were eligible. This was all the first year the program's eligibility criteria were expanded to include facilities located in communities with inadequate electric service. As a result, five newly eligible hydroelectric facilities received incentive payments.

The U.S. Department of Energy's Hydroelectric Production Incentive Program distributed $13.5 million in incentive payments across a record 55 hydroelectric facilities. *Image from Pablo McLoud, U.S. Department of Energy's Make a Splash Photo Contest*


MARINE ENERGY

MARINE ENERGY PROGRAM

Marine energy technologies transform the incredible amount of energy in the natural flow of oceans and rivers—like currents, tides, and waves—into clean electricity. The U.S. has tremendous marine energy resources. The total available marine energy resource in the United States is equivalent to approximately 57% of all U.S. power generation in 2019. Even if only a small portion of this technical resource potential is captured, marine energy technologies would make significant contributions to U.S. energy needs.

WPTO's Marine Energy Program conducts research, development, demonstration, and commercial activities that advance the development of reliable, cost-competitive marine energy technologies and reduce barriers to deployment.

The program's vision is for 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 achieve this vision, WPTO's Marine Energy Program supports R&D projects across four activity areas and one initiative. Success stories in the WPTO 2021–2022 Accomplishments Report are presented within these areas:

- Foundational R&D
- Technology-Specific System Design and Validation
- Reducing Barriers to Testing
- Data Access, Analytics, and Workforce Development
- Powering the Blue Economy™ Initiative

Analysis Tool Improves Turbine Foil Designs, Increasing Energy Capture by 24%

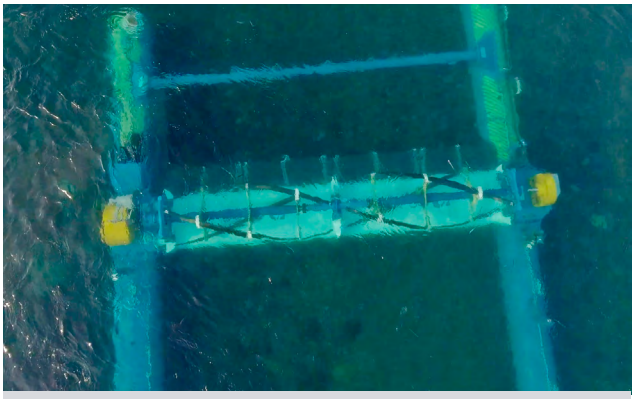
Project Name: Design of High-Deflection Foils for Marine Energy Applications

Project Team: Ocean Renewable Power Company (lead), Sandia National Laboratories, and University of New Hampshire

Lead Recipient Location: Portland, Maine

Ocean Renewable Power Company (ORPC) developed new marine energy hydrofoil (or blade) designs that use composite materials to reduce costs and increase energy capture by up to 24%. ORPC worked with the University of New Hampshire to collect data on the hydrofoil designs' performance that could help the water power industry improve reliability of marine energy systems with more advanced blade designs.

ORPC also developed a new computational data toolset for modeling and simulating foils for crossflow turbines, which are vertical-axis water power turbines with spinning blades oriented perpendicular to the direction of water flow. The toolset analyzes how turbine blades bend (or deflect) as a result of water currents, which can impact foil performance. This enables turbine designers to select foil materials that provide a desired amount of deflection and achieve a higher level of confidence that the turbine will perform as designed.



Ocean Renewable Power Company developed a set of analytical tools for crossflow turbines like the RivGen® Power System (shown here). The three-year project resulted in new marine energy turbine foil (or blade) designs that use composite materials to reduce costs, improve reliability, and increase system performance.
Image from Igiugig Village Council

The University of New Hampshire collected data from a scale model of the hydrofoil to compare with results from the toolset, and the dataset will be available for use by the water power industry. Additionally, Sandia provided guidance on the selection and installation of fiber optic sensors and supplied devices that transfer data from the rotating turbine to a stationary data acquisition system.

Ocean Motion Technologies Demonstrates Wave Energy Converter Capable of Generating Power from Boat Wakes

Project Name: Leveraging Co-Development for the Energy Capture Subsystem of a Small-Scale Adaptive Wave Energy Converter

Project Team: Ocean Motion Technologies, Inc.

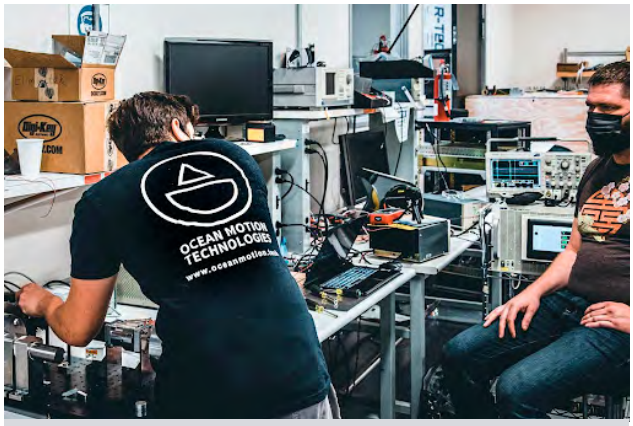
Lead Recipient Location: San Diego, California

A project team led by Ocean Motion Technologies deployed a prototype wave energy converter that can generate power from passing waves created by boat wakes. This test, which took place off the coast of San Diego, California, successfully demonstrated that power can be harnessed from waves as small as those created by boats. By generating power from waves of this size, this test showed greater versatility and environments in which marine energy devices could be used to harness power.

Ocean Motion Technologies worked with several commercial and strategic partners throughout this effort. The commercial end users provided regular feedback to ensure product-market fit (primarily focused on ocean-observing applications), while NREL provided guidance and technical support.

Ocean Motion Technologies also partnered with the Technology Career Institute at MiraCosta College to provide mentorship and hands-on experience to trade school students.

This project was funded through the Small Business Innovation Research and Small Business Technology Transfer Programs.



The team at Ocean Motion Technologies conducted a mechanical bench-top test in preparation for the sea trial. *Image from Ocean Motion Technologies, Inc.*

New, Comprehensive Data Now Available on U.S. Marine Energy Resources

Project Name: Model Validation and Site Characterization for Early Deployment MHK Sites and Establishment of Wave Classification Scheme

Project Team: National Renewable Energy Laboratory (lead), Pacific Northwest National Laboratory, Sandia National Laboratories, University of Hawaii, North Carolina State University, TerraSond Limited, Ocean Renewable Power Company, and Integral Consulting

Location: Cook Inlet, Alaska, with information on additional marine energy resources located across the country

Between 2021 and 2022, a multi-lab research team created a new tool for marine energy developers to estimate how much energy their device could produce in specific ocean and river sites, expanded the most comprehensive data available on marine energy resources across the United States (specifically in Alaska's energetic Cook Inlet), and published the data in the free, publicly available Marine Energy Atlas. This is part of an effort led by a team of researchers from NREL, PNNL, and Sandia to gather information on wave, tidal, and current resources available in U.S. waters and to provide data on wave heights, extreme wave events, turbulence, velocity, sediment, and other conditions. Developers need this information to build technologies that are well-suited to survive in these environments and produce high amounts of energy.

The project team—which included partners from several universities and companies—enhanced the Marine Energy Atlas and, as a result, helped to advance the marine energy sector. To help the industry identify promising sites for specific wave technology designs, NREL researchers added a new tool to the Marine Energy Atlas. With the new Capacity Factor Tool, users can upload information on their wave energy device to estimate how much electricity it would produce. The tool also generates a map of the most promising sites for that device.

In Alaska, NREL researchers continued to collect data in the Cook Inlet, which contains one of the largest tidal energy resources in the world. In 2022, the team focused on the Inlet's East Foreland site, an especially promising location for tidal energy. To advance tidal energy technologies, developers need demonstration sites that share similar environmental characteristics—like sediment, ice, velocity, turbulence, and the presence of fish and marine mammals—to where these devices may actually be deployed. The NREL team's data on the East Foreland site provides technology developers with at least some of the information they need to plan their demonstration projects. Such data are critical to improve the

Technology developers need reliable data on marine energy resources to understand how to build their devices and where to deploy them. That's why a multi-lab team recently combined its massive computing power to create the most comprehensive, high-resolution data on marine energy resources across the United States. *Image from Levi Kilcher, National Renewable Energy Laboratory*

cost, reliability, and performance of devices. The project team also collected data beyond Cook Inlet. Researchers at PNNL and Sandia expanded their comprehensive, high-resolution wave hindcast dataset (which captures historical data on wave climates) for sites across the United States and its territories to include an additional decade of wave data, now covering information from 1979 to 2020. This data allows researchers to create a more accurate estimate of conditions at specific sites. During 2022, PNNL also expanded its coastal ocean model of Washington's Salish Sea.

Now, all that data is freely available in the Marine Energy Atlas to provide technology developers with a clear understanding of the resource they will encounter in U.S. waters. Developers can also use the tool to identify sites that hold the greatest promise for marine energy projects, while energy planners can better understand the contribution marine energy could make to the grid. Even ocean engineers, like offshore wind energy developers, could tap into the atlas' data to learn how to optimize their builds for specific wave climates and ocean sites. Next, this multi-lab team will use its comprehensive data to help inform international marine energy standards, so the marine energy industry can continue to advance toward commercial success.

Workshop Helps Guide Investments in Marine Energy Materials and Manufacturing

Project Name: Workshop on Materials and Manufacturing for Marine Energy Technologies

Project Team: Sandia National Laboratories (lead), Montana State University, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory

In October 2021, Sandia and WPTO hosted a virtual workshop on the marine energy industry's current and future materials and manufacturing research needs. More than 100 participants from academia, industry, and DOE national laboratories shared ideas on research needs and funding gaps that may need to be addressed to advance marine energy and help build longer lasting and more affordable and efficient marine energy technologies. This feedback will help WPTO strategize future research and development investments in materials and manufacturing, specifically for wave and current energy technologies.

New materials and manufacturing processes could help the marine energy industry advance and achieve the United States' clean energy goals. For example, new materials that are more flexible, resilient, recyclable, effective at harnessing energy, or environmentally friendly are potential solutions to help advance marine energy. Further, new manufacturing processes, like additive manufacturing, could help minimize development costs for industries beyond marine energy. The workshop's partners helped organize the event, prepared content for breakout sessions, and took notes for a summary report, which provides major insights from workshop discussions, along with synopses of nine case studies presented by marine energy experts.

In a 2021 workshop, members from industry, academia, and the U.S. Department of Energy's national laboratories discussed how new materials and manufacturing processes could help the marine energy industry advance and achieve cost and durability goals. *Image from Dennis Schroeder, National Renewable Energy Laboratory*

CalWave Successfully Completes Open-Water Pilot Project

Project Name: CalWave Open-Water Demonstration

Project Team: CalWave Power Technologies, Inc. (lead); DNV-GL; Integral Consulting, Inc.; MarineLabs; National Renewable Energy Laboratory; Sandia National Laboratories; University of California, Berkeley; and the University of California San Diego Scripps Institution of Oceanography

Lead Recipient Location: Oakland, California, with testing off the coast of San Diego, California

In July 2022, CalWave Power Technologies, Inc. retrieved its xWave wave energy pilot device after a successful 10-month deployment off the coast of San Diego, California. Located near the University of California San Diego's Scripps Institution of Oceanography research pier, this deployment represented the company's (and California's)) first at-sea, long-duration wave energy project. The device survived two extreme storms, required no interventions, and remained operational for 99% of its time deployed. This deployment's success demonstrates that a wave energy device can efficiently generate clean electricity from ocean waves, a critical step in proving the industry's commercial viability.

CalWave installed its xWave pilot unit during fall 2021. During the open ocean trial, a 14-foot by 14-foot prototype of the xWave was anchored at the test site and deployed in water about 75 feet deep, but the device can be smaller or larger to suit a customer's needs and can work in a variety of depths and distances from shore. CalWave also used the trial to collect data on how the xWave performed at sea. The device not only achieved high performance—remaining operational 99% of the time—but it also safely survived major storms and demonstrated high reliability. Working with MarineLabs, CalWave also ensured the xWave did not interfere with other nearby ocean activities.

CalWave Power Technologies, Inc. successfully completed the company's and California's first at-sea, long-duration wave energy project with its xWave wave energy device. *Image from CalWave Power Technologies, Inc.*

In partnership with Integral Consulting, Inc. and PNNL, CalWave collected data to understand how marine energy devices could cohabit with their ocean environment. Because harnessing wave energy is still so new, it is important that scientists collect data on device-ecosystem interactions. The environmental interaction data collected during the xWave deployment showed no significant concerns to the local marine wildlife or ecosystem and will be made available in a public report.

The xWave design uses a promising architecture that could help marine energy technologies overcome key challenges in performance, reliability, survivability, and cost. For example, while some wave energy developers address device survivability using heavy steel for protection, the xWave design is manufactured with a far lighter and less expensive material to protect against extreme waves. Additionally, instead of weathering potentially destructive waves, the xWave autonomously dives farther below the water's surface to avoid them. The system can also operate while submerged at different depths, rather than floating on the ocean's surface, and will autonomously shut down to protect itself during storms. To hone its design, CalWave received key operational and research support from experts at NREL, Sandia, and the University of California, Berkeley.

Next, CalWave will use its device performance test data to inform design and installation procedures for its larger x100 device, which could generate more than 500 megawatts of power. CalWave has received guidance from DNV-GL on how to prepare both the xWave and x100 for certification. The x100 device will be validated in a two-year, grid-connected deployment at PacWave South off the coast of Newport, Oregon. That trial could eventually lead to multimegawatt wave energy farms delivering clean electricity to U.S. coastal communities or power grids.

Hawaii Wave Surge Energy Converter Moves to Build and Test Phase

Project Name: Hawaii Wave Surge Energy Converter

Project Team: University of Hawaii (lead), Gerard Nihous Consulting, National Renewable Energy Laboratory, and Oregon State University

Lead Recipient Location: Honolulu, Hawaii, with testing in Waimanalo, Oregon

Researchers at the University of Hawaii, with help from experts at Gerard Nihous Consulting, completed initial design and modeling for a small-scale version of their Hawaii Wave Surge Energy Converter (HAWSEC) and built and began testing a prototype. The HAWSEC uses off-the-shelf or readily fabricated turbine components, which could make the design more cost-effective than other types of wave energy converters. The data collected on the device's performance (which will be freely available to the public) could help guide the marine energy industry to create more cost-effective devices, a critical step to achieving commercial success.

A form of oscillating wave surge energy converter, the HAWSEC project contributes valuable data on how these devices perform, so other technology developers can learn from its efforts. The HAWSEC is intended to be fixed to the seabed in shallow, near-shore waters. Positioned there, the device's large, rectangular flap moves back and forth with ocean waves surging in and out; that motion then drives hydraulic cylinders to pump water through a turbine to generate electricity.

Prototype testing will allow the HAWSEC team to determine which of its two power take-off designs (which convert ocean motions into electricity) might produce the most energy. The team performed lab bench testing before heading to Oregon State University's wave basin to validate the prototype in real waves and gather extensive data on the hydrodynamics of their flap. For both lab bench and wave tank testing, the HAWSEC team received data collection support from experts at NREL. The HAWSEC team also collected motion data during a few hours of testing in the shallow waters off Makai Pier in Hawaii. These tests verified that the device and its data acquisition system (the Modular Ocean Data Acquisition systems developed by NREL) could perform as intended in a real-world ocean environment. Next, the team will complete testing of its smaller prototype, validate its numerical models, and build a larger prototype.

University of Hawaii researchers took their oscillating wave surge energy converter prototype for a trial run in the shallow waters off Hawaii's Makai Pier. *Image from Patrick Cross, University of Hawaii*

Researchers Demonstrate Prototypes for Harvesting Wave Energy to Power Sensors on Ocean Observation Systems

Project Name: Triboelectric Nanogenerator for Harvesting Wave Energy and Powering Marine Sensors

Project Team: Pacific Northwest National Laboratory

Lead Recipient Location: Richland, Washington

PNNL researchers developed and demonstrated prototypes of triboelectric nanogenerator (TENG) systems. These emerging technologies are aimed at harvesting energy from low frequency, randomly directed waves. TENGs can be used to power instruments aboard hurricane and tsunami detection or water quality monitoring systems, particularly low-power instrumentation such as temperature or pressure sensors. Currently, TENG prototypes can produce a few milliwatts of power.

Researchers integrated cylinder-shaped TENG prototypes with power management circuits, sensors, and communications systems, and demonstrated the feasibility of using TENG technology to power sensing equipment. The team also designed a new disk-shaped TENG device integrated with a mechanical transmission system for efficiently extracting energy from random low-frequency waves. The input of the gearbox takes the back-and-forth (i.e., clockwise and counterclockwise) motion of a pendulum, but spins the disk-shaped TENG device in only one direction, meaning the disk does not need to come to a stop and switch directions.

Triboelectric nanogenerators are an emerging and cost-effective technology for harvesting energy from low-frequency, randomly directed waves. *Image from Pacific Northwest National Laboratory*

These TENGs can be easily fabricated using low-cost and versatile materials when compared to conventional electromagnetic generators. In addition, TENGs can float freely and do not have to be moored to the seafloor, which is suitable for powering ocean observation systems and other relevant blue economy applications. While these prototypes currently harness enough energy to power small sensors and transmitters, researchers aim to develop TENGs that produce a few watts of power in the coming years.

New International Report Outlines Opportunities to Integrate Marine Energy with Offshore Aquaculture

Project Name: Offshore Aquaculture: A Market for Ocean Renewable Energy

Project Team: Pacific Northwest National Laboratory (lead), Blue Economy Cooperative Research Center, Commonwealth Science and Industrial Research Center, Ocean Pixel Pte. Ltd., and International Energy Agency Ocean Energy Systems Technology Collaboration Program

Lead Recipient Location: Seattle, Washington

A team led by PNNL developed a report for the International Energy Agency Ocean Energy Systems Technology Collaboration Program that explored and made recommendations for how offshore aquaculture could use marine energy resources for power. This report is one of the first to consolidate hard-to-find information pertaining to the integration of marine energy with offshore aquaculture. The report reviewed various renewable energy technologies' potential applications for aquaculture, quantified aquaculture power needs, and shared lessons learned from case studies around the world.

The report outlined how marine energy technologies could help adequately fuel offshore aquaculture systems to meet operational energy demands. Taking a deep dive into 12 case studies, the authors reviewed lessons learned from offshore aquaculture projects that have demonstrated the potential for integrating renewable energy solutions with their operations. These case studies could help highlight research priorities and solve some of the challenges outlined in the report related to specific operational energy needs of different aquaculture industries, economic considerations, regulatory processes, and technical issues.

The report showcased how stakeholders across the offshore aquaculture industry could learn from one another to become more sustainable within their operations. For example, replacing diesel fuel (the current method of fueling for most offshore aquaculture operations) with marine or other renewable energy technologies could help make aquaculture and its development sustainable for the surrounding marine ecosystems. Further, co-locating aquaculture and marine energy infrastructure could reduce the need to transport fuel to ocean farms.

The Blue Economy Cooperative Research Centre (Australia), Commonwealth Scientific and Industrial Research Organisation (Australia), and OceanPixel Pte. Ltd. (Singapore) assisted with literature reviews, compiled information, and helped envision what aquaculture would look like not just from a national, but a global, perspective.

Following the report's release in April 2022, the PNNL-led team held a webinar to detail the report's findings and recommendations. The project team also presented the report at several other events around the world, including the Australian Ocean Energy Group Market Summit, Pan American Energy Conference, and the International Conference of Ocean Energy.

A new report discusses how stakeholders across the offshore aquaculture industry could learn from one another to become more sustainable within their operations. *Image from Sebastian Pena Lambarri, Unsplash*

International Marine Energy Standards Buoy a Growing Industry's Success

Project Name: Standards Development

Project Team: National Renewable Energy Laboratory (lead); British Standards Institute; BlueWater Network LLC; Cardinal Engineering; Pacific Northwest National Laboratory; PB Mechanical Consulting Service, LLC; Sandia National Laboratories; and Streamwise Development

Lead Recipient Location: Golden, Colorado

In Fiscal Year 2022, NREL published a reference document for the International Electrotechnical Commission (IEC) Technical Committee 114 for Marine Energy Systems (TC 114) standards called the IEC/TC 114 cheat sheet. This reference contains summaries, status reports, and links to all TC 114 technical specifications and will help government agencies incorporate these relevant standards into funding opportunities. The suite of marine energy standards will help facilitate the certification of marine energy technologies, which builds investor trust and supports the growing marine energy industry's success, which builds trust and supports the growing marine energy industry's success.

Also in Fiscal Year 2022, the technical committee developed a new, internationally approved TC 114 strategic business plan, which outlines the next generation of marine energy standards that could help the industry achieve commercial success. In addition, the strategic business plan ties marine energy to 10 of the United Nations' 17 sustainable development goals for the first time, demonstrating the committee's contribution to global sustainability and responsible, equitable development.

Verdant Power's deployment of its tidal power turbine represents an application of the TC 114 62600-200: Electricity producing tidal energy converters – Power performance assessment. *Image from Drone Altitude*

Also during Fiscal Year 2022, WPTO participated in the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications, which updated seven Marine Energy Certification Scheme operations documents related to test reporting, including measurement of loads, power performance assessments, and conformity assessment requirements. These documents help certification bodies and test centers comply with the TC 114 marine energy standards.

NREL experts serve on TC 114 and, as part of the TC 114's efforts to develop standards and conformity assessment systems for marine energy devices and projects, NREL manages the United States' contributions to standards and certification. NREL also provides subject-matter experts from the marine energy industry, academia, and other national labs to help write and publish standards and certification schemes.

Triton Initiative Publishes First Large-Scale Environmental Monitoring Recommendations for the Marine Energy Industry

Project Name: The Triton Initiative: Triton Field Trials (TFiT)

Project Team: Pacific Northwest National Laboratories (lead), CalWave Power Technologies, Pacific Marine Energy Center, Scripps Institution of Oceanography, Solid State Lighting Systems, University of Alaska Fairbanks, University of New Hampshire, and University of Washington

Lead Recipient Location: Sequim, Washington

The Triton Initiative Field Trials (TFiT) team completed and published the first large-scale environmental monitoring methodology recommendations for the marine energy industry produced from field tests in the United States. The results, which were published in a special issue of the Journal of Marine Science and Engineering, explored environmental stressors associated with marine energy devices and effective methods to monitor them with commercially available technologies.

In practice, these results could be used to help speed regulatory and permitting decisions, supporting developers' efforts to deploy marine energy devices. The TFiT team's work will help developers understand the environmental effects of devices going into the water and characterize related stressors.

As of October 2022, the 10-paper special issue had received nearly 11,000 views and was cited 18 times. According to Altmetric, a data company that measures how scholarly articles and academic publications are discussed and referenced, the TFiT team's papers were among the top 25% of most referenced research in academic publications since the team published them. Two papers published by the TFiT team are in the top 5% of most referenced research since publication.

The PNNL-led Triton Initiative also launched the Triton Talks webinar series to further disseminate TFiT's results and recommendations. The TFiT team discussed its field work, expertise, methods, results, and recommendations directly with key marine energy stakeholders. Topics included underwater noise, electromagnetic fields, collision risk, and habitat change, among others.

The University of Washington, University of New Hampshire, University of Alaska Fairbanks, Pacific Marine Energy Center, and Scripps Institution of Oceanography supported the journal articles and field tests. CalWave Power Technologies worked with the team to collect underwater sound measurements around a wave energy converter it deployed near San Diego, and Solid State Lighting Systems led the writing of a paper that focused on ecological lighting around marine energy devices.

The Triton Initiative Field Trials team deploys an environmental monitoring device into the water for testing. *Image from Pacific Northwest National Laboratory*

PacWave Construction Continues, Projects Selected for Open-Water Testing

Project Name: Enabling Cost-Effective Electricity from Ocean Waves: PacWave

Project Team: Oregon State University (lead), National Renewable Energy Lab, European Marine Energy Centre, Bonneville Power Association, Central Lincoln People's Utility District, Williwaw Engineering, HDR, HT Harvey & Associates, 3U Technologies, Stoel Rives, David Evans Associates, HGE Architects, Jacobs Engineering, The HDD Co., and RT Casey

Lead Recipient Location: Newport, Oregon

Construction continued in 2022 on PacWave South, a grid-connected and pre-permitted wave energy testing facility in the United States. The project team, led by Oregon State University, provided engineering, testing, accreditation, consulting, design, conduit drilling and installation, and cable procurement. The team completed the horizontal directional drilling for the conduit, with bores running up to 120 feet below the seafloor. A total of 6.2 miles of undersea and onshore conduit was installed, which will carry cables transmitting power from ocean devices to the local utility. At Driftwood Beach State Recreation Site, the project team installed a vault that will provide access to both subsea and terrestrial cables, resurfaced the parking lot above the vault, and made other improvements to return the site to its original condition.

In addition, WPTO selected $25 million in projects that will represent the first round of open-water testing at PacWave South. These projects focus on testing wave energy converter technologies, improving wave energy converter designs, and performing research and development to advance the marine energy industry as a whole.

At the Driftwood Beach State Recreation Site near Newport, Oregon, the PacWave project team installed a 74-by-17-by-10-foot underground cable vault, where subsea cables will transition to terrestrial cables.
Image from PacWave

The PacWave underground cable vault is nearly completed with an opening showing where workers will be able to access subsea and terrestrial cables.
Image from PacWave

TEAMER Testing Network Grows and Initiates 35 New Technical Support Activities

Project Name: Testing Expertise and Access for Marine Energy Research Program

Project Team: Pacific Ocean Energy Trust (lead) and more than 30 institutions offering more than 100 capabilities throughout TEAMER's facility network

Lead Recipient Location: Portland, Oregon, with TEAMER-supported activities taking place nationwide

During Fiscal Year 2022, the Testing Expertise and Access for Marine Energy Research (TEAMER) program selected a total of 35 technical support recipients through four requests for technical support (RFTS), which accelerate the idea-to-market process by providing support for technology developers seeking access to the nation's best marine energy testing facilities and leading marine energy experts. Through these requests, TEAMER helps technology developers and researchers advance their devices, while also building knowledge, fostering innovation, and driving commercialization of marine energy technologies.

The Fiscal Year 2022 RFTSs included:

- RFTS 4: Nine projects, for a total funding amount of more than $1.1 million.
- RFTS 5: Nine projects, for a total funding amount of nearly $900,000.
- RFTS 6: 10 projects, for a total funding amount of more than $1 million.
- RFTS 7: Seven projects, for a total funding amount of more than $750,000.

These technical support awards granted these projects access to numerical modeling, lab testing, and tank/flume testing within TEAMER's expanded facility network.

In addition to the projects listed above, the TEAMER program selected three recipients through ongoing open-water RFTSs. These technical support awards, which enable field testing in at-sea environments, totaled $215,000.

TEAMER is sponsored by WPTO and executed by the Pacific Ocean Energy Trust.

The Testing Expertise and Access for Marine Energy Research program gives technology developers and researchers access to world-class testing infrastructure and expertise, helping them advance their devices, build knowledge, foster innovation, and drive commercialization of marine energy technologies. *Image from Devan Kochersperger, Pacific Ocean Energy Trust*

Infrastructure Upgrades at the National Marine Renewable Energy Centers Will Help Accelerate Marine Energy Technology Advancements

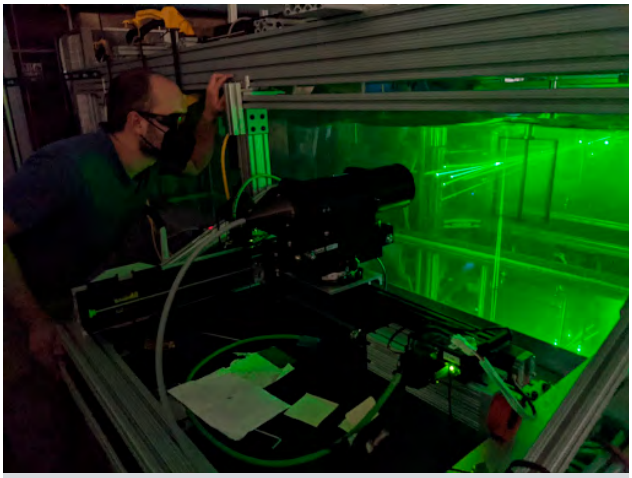
Project Name: National Marine Energy Center Infrastructure Upgrades

Project Team: University of Washington, Oregon State University, University of Alaska Fairbanks, University of Hawai'i, Florida Atlantic University

Infrastructure Upgrade Locations: Near Nenana, Alaska; Corvallis, Oregon; Seattle, Washington; Honolulu, Hawaii; and Boca Raton, Florida

The National Marine Renewable Energy Centers (NMRECs), which comprise multiple universities across the country, are undertaking infrastructure upgrades to support increased marine energy testing and development with the goal of accelerating the wide-scale commercialization of marine energy technologies. Tailored to align with the existing test infrastructure and capabilities of each NMREC, these upgrades offer marine energy developers more options for testing their devices in laboratory and open-water settings.

- Pacific Marine Energy Center: The team completed upgrades at the University of Alaska Fairbanks, Oregon State University, and University of Washington. At the University of Alaska Fairbanks' Tanana River Test Site, the team commissioned new data acquisition systems and sensors that more accurately characterize turbine efficiency. Bladerunner Inc. used these systems to test its turbine that harnesses energy from river currents. Meanwhile, Oregon State University installed a new surface and sub-surface motion-tracking system in its wave basin that developers can use to track devices' movements through water to optimize wave converter control. This system can also monitor autonomous underwater vehicles, ensuring they correctly dock with wave converters that recharge the vehicle's batteries. Finally, the University of Washington commissioned a new sensor system in its flume (which is like a water tunnel) that can accurately measure water speeds close to turbine blades in laboratory-scale tests. This new system will provide developers with new information about how currents interact with blades, leading to more efficient and cost-effective turbine designs.



A laser doppler velocimeter was commissioned at the University of Washington. This sensor allows researchers to measure extremely close to the turbine blade, which can provide insight into power generation and other variables. *Image from University of Washington*

- Hawai'i National Marine Renewable Energy Center: Hawai'i National Marine Renewable Energy Center: The University of Hawaii completed several upgrades to support marine energy testing at the Kilo Nalu Observatory on the south shore of Oahu. This location is easier to access and has more weather windows during which marine energy devices can be deployed than the neighboring Wave Energy Test Site. The facility installed a new marine radar with accompanying measurement buoys, which will help developers to more accurately measure wave energy potential during tests.

Future upgrade plans include a docking station for autonomous underwater vehicles, which could be powered by wave energy converters in the future.

- Southeast National Marine Renewable Energy Center: Florida Atlantic University began upgrading its offshore and onshore tow testing capabilities to include a stronger deck winch and cables, which allow for testing of larger devices. Tow testing refers to pulling a turbine through water to simulate a current moving past an anchored turbine, providing another way to test marine energy technologies. The project team is also upgrading the facility's dynamometer, a device that measures generator efficiency. These upgrades will allow the Southeast National Marine Renewable Energy Center to support developers with larger turbines and generators.

By bolstering current testing infrastructure, along with the addition of the Atlantic Marine Energy Center (established in 2021), the NMRECs are making significant contributions to the future landscape of marine energy. These upgrades will allow marine energy technology developers to test their devices in laboratory and open-water environments, providing insights that will help these technologies advance along the path to commercialization.

Bladerunner Inc.'s river energy converter was deployed in summer 2022 at the University of Alaska Fairbanks' Tanana River Test site in support of a project funded by the U.S. Department of Energy's Advanced Research Projects Agency–Energy. *Image from University of Alaska Fairbanks*

National Laboratories Upgrade Marine Energy Testing Infrastructure

Project Name: Long-Term, Laboratory-Wide Facilities and Infrastructure Upgrades Strategy for Marine Energy

Project Team: National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories

Lead Recipient Locations: Golden, Colorado; Sequim, Washington; Albuquerque, New Mexico

As part of a $7.1 million investment in marine energy testing infrastructure, NREL, PNNL, and Sandia designed, upgraded, or installed new world-class testing infrastructure to advance marine energy technologies.

NREL's new wave tank will enable early-stage, proof-of-concept testing for wave energy devices. This tank, combined with NREL's manufacturing capabilities, will enable a rapid design and test cycle to verify the viability of marine energy devices at a small scale. In 2022, the team installed and began operating the tank. Next, NREL researchers will undertake a demonstration project that involves designing, manufacturing, and testing a model wave energy device in the tank.

PNNL's plug-in hybrid research vessel, the R/V Resilience, will enable future research and testing to support harvesting renewable power from the ocean and advance long-term opportunities for energy innovation and decarbonization of marine transportation. Vessel construction is 35% complete. The vessel is equipped with a diesel engine and a parallel hybrid-electric 374 kW propulsion system. When operating in battery-electric mode, the vessel will be nearly silent and less intrusive for studying fish and other wildlife.

Sandia designed a line testing facility that could be used to validate the performance and test the long-term durability of power take-off mooring lines, belts, and umbilical cables for marine energy devices. Fifteen industry representatives provided input—including feedback on types of testing, the forces required, and materials needed—which informed the final test stand design.

The National Renewable Energy Laboratory's new wave tank will enable early-stage, proof-of-concept testing for wave energy devices. *Image from Joe DelNero, National Renewable Energy Laboratory*

Study Helps Clarify Marine Energy's Potential Value to the Grid

Project Name: Grid Value Proposition of Marine Energy: A Preliminary Analysis

Project Team: Pacific Northwest National Laboratory (lead), National Renewable Energy Laboratory, Oregon State University, and Pacific Ocean Energy Trust

Lead Recipient Location: Richland, Washington

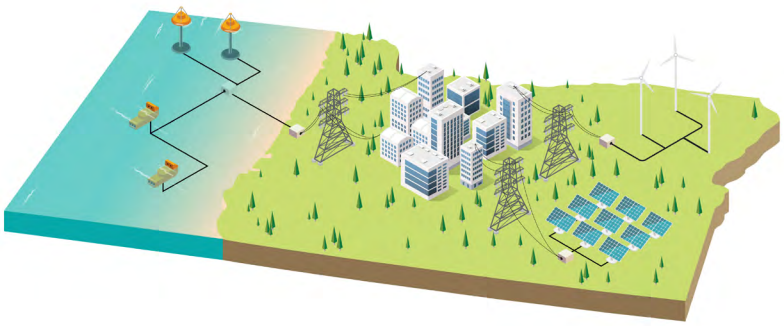
A new report, Grid Value Proposition of Marine Energy: A Preliminary Analysis, provided a framework to assess marine energy's potential grid benefits, like supporting local resiliency and complementing other renewable energy resources. To achieve commercial success, the marine energy industry must explain the unique benefits it can provide beyond decarbonization, and this value had not previously been well quantified. This framework helps quantify these benefits to support future grid planning and investment decisions.

Because marine energy is still in the early stages of development, the industry has only deployed a handful of devices. That lack of real-world deployment, along with current high costs relative to wind energy and solar power, make it challenging to accurately evaluate marine energy's value with traditional metrics, like cost of energy produced. Without these metrics, developers and utilities will likely be hesitant to deploy marine energy devices.

To begin to clarify marine energy's value, PNNL, working with colleagues from NREL, Oregon State University, and the Pacific Ocean Energy Trust, conducted several types of analyses to illustrate and quantify marine energy's benefits.

The authors found many potential opportunities for the deployment of marine energy technologies both in the near term and within typical utility planning timeframes (up to 20 years). From a resource and technology perspective, marine energy can deliver distinct and valuable benefits to different configurations of the grid, including large, interconnected electrical systems like the U.S. national grid, as well as smaller, isolated systems that provide power to remote communities and islands, and microgrids. For example, marine energy can:

- Help increase the diversity of energy-generating technologies that serve a specific community, which helps increase a grid's resiliency. (If one source needs repairs, for example, others can fill the gaps.)



To build a 100% clean energy future, the country's power grid is evolving to incorporate more renewable energy resources, including marine energy. The Grid Value Proposition of Marine Energy: A Preliminary Analysis report helps clarify the many ways marine energy could add value to this future grid. *Image from Pacific Northwest National Laboratory*

- Provide energy where it is otherwise difficult to come by, like in remote Alaskan towns or islands, which often depend on expensive shipments of liquid fuels.
- Complement other resources, like wind energy and solar power; marine energy can often generate more electricity at times when other sources tend to generate less (like in the winter months and at night).
- Be deployed in water to avoid land constraints, which is especially critical for island systems or developed coasts where the footprint of existing renewable energy technologies could limit ambitious decarbonization goals.

An enhanced understanding of marine energy benefits, the authors argue, will help ensure utilities and systems operators consider marine energy technologies in energy planning. Greater awareness of marine energy's value will also help manufacturers and developers tailor their device designs to optimize the benefits they could deliver to the grid.

Fourteen Student Teams Build and Test Marine Energy Devices Through DOE Competition

Project Name: Marine Energy STEM and Workforce Development

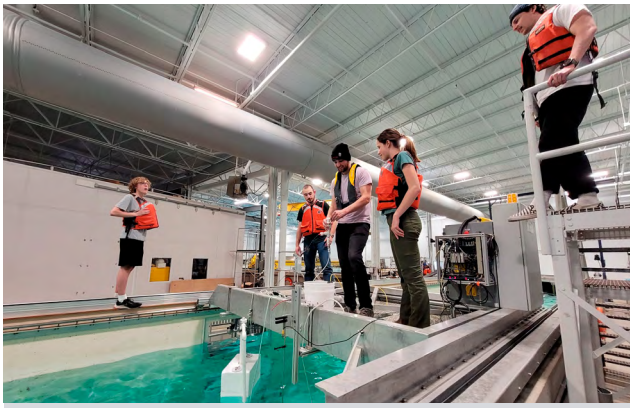
Competitors (2022): Boise State University; California State University, San Marcos (partnering with New Mexico State University); Federal University of Rio de Janeiro; Michigan Technological University; North Carolina A&T State University (partnering with University of North Carolina Wilmington); Oregon State University; Purdue University; Texas A&M University at Galveston (partnering with Sam Houston State University, University of Rochester, University of Sao Paulo, Qatar University, and University of Engineering and Technology, Taxila); University of California, Riverside; University of Houston; University of Massachusetts Dartmouth; University of New Hampshire; University of North Florida; University of Washington; Virginia Tech (partnering with Stevens Institute of Technology); Virginia Tech (partnering with University of Maine, Pennsylvania State University, and Queen's University Belfast); Webb Institute

Competitors (2023): California Polytechnic State University; California State University Fresno; California State University San Marcos; Cornell University; Instituto Superior Tecnico; Manhattan College; Michigan Technological University; North Carolina Agricultural & Technical State University; Oakland University; Oregon State University; Purdue University; Stevens Institute of Technology; Texas A&M University; University of California Merced; University of California Riverside; University of Houston; University of Massachusetts Dartmouth; University of Michigan; University of New Hampshire; University of North Carolina; Virginia Polytechnic Institute & State University; Webb Institute

In June 2022, WPTO announced the winners of the third annual Marine Energy Collegiate Competition (MECC) and the 19 teams selected for the fourth annual competition. MECC provides undergraduate and graduate students with real-world experience and industry connections to help them prepare for future careers in the marine energy sector and the blue economy. The competition challenges multidisciplinary student teams to advance the marine energy industry by proposing ideas for how to capture the power of the ocean.

In 2022, MECC hosted 17 teams, each of which developed designs and business plans to power blue economy activities, like marine research and offshore seafood farming, using a diverse range of marine energy technologies. Of those, 13 built and tested their designs in wave tanks, and the Virginia Tech team tested its prototype in a lake by creating waves with a boat. The competition also held a virtual poster session, which brought students together with industry representatives. Webb Institute emerged from the competition as the overall win ner, followed by Oregon State University and the University of New Hampshire.

MECC is funded by WPTO and administered by NREL.



In the Marine Energy Collegiate Competition, students, like the 2022 third-place winners pictured here, design and test out marine energy devices, gaining real-world experience while forming connections with industry.
Image from University of New Hampshire

WPTO Selects Three New Marine Energy Research Fellows and Opens the Program to All Graduate-Level Students

Project Name: Marine Energy Graduate Student Research Program

Participants' Academic Institutions: University of California, Santa Barbara; Rensselaer Polytechnic Institute in Troy, New York; and Lehigh University in Bethlehem, Pennsylvania

In March 2022, WPTO announced the three latest fellows selected under the Marine Energy Graduate Student Research Program. This program funds graduate students to pursue marine energy research at a host institution, such as a federal agency, national laboratory, industry technology developer, or another approved organization.

The 2022 cohort of fellows includes:

- Claire Gonzales, who is a student at University of California, Santa Barbara, and working with the Bureau of Ocean Energy Management to advance research into the co-location of marine renewable energy with offshore aquaculture development.
- Habilou Ouro-Koura, who is a student at Rensselaer Polytechnic Institute and working with PNNL on a reliable and clean energy source to power the uncrewed underwater vehicles used in ocean research and other sectors.
- Christopher Ruhl, who is a student at Lehigh University and working with Sandia to understand how turbulence might impact tidal energy devices at potential sites around the world.

Starting with the 2023 program, WPTO expanded eligibility to include both doctoral and master's students with the goal of improving program accessibility and reaching more students pursuing marine energy.

Enabling students to partner with host institutions helps bridge the gap between marine energy research in academia and real-world marine energy research. According to a survey conducted by WPTO and NREL in 2018, 83% of marine energy organizations surveyed say recent graduate hires have limited to no knowledge of marine energy, while 63% say recent graduate hires have limited to no hands-on experience. Through its Marine Energy Graduate Student Research Program, WPTO is aiming to change that and prepare students for clean energy careers.

Claire Gonzales, a fellow in the Marine Energy Graduate Student Research Program, poses with her scuba gear. Gonazles' love for scuba diving led her to a career in marine science. *Image from Claire Gonzales*

Waves to Water Prize Concludes with DRINK Finale and Selection of Grand Prize Winner

Project Name: Waves to Water Prize

Project Team: National Renewable Energy Laboratory (lead) and Coastal Studies Institute

Final Test Location: Nags Head, North Carolina

In Fiscal Year 2022, WPTO celebrated the finale of the the Waves to Water Prize—a competition designed to accelerate the development of small, modular, wave energy-powered desalination systems—and awarded Oneka Technologies the $500,000 grand prize for its Oneka Snowflake, the Wave-Powered Watermaker device. Prize competitors produced some of the first wave-powered desalination prototypes to ever be deployed and illustrated opportunities for future marine energy desalination research, like adaptable and resilient mooring systems to anchor devices in place.

The Waves to Water Prize enabled teams to design and build systems that have the potential to address coastal resiliency challenges, like providing clean water in disaster and recovery scenarios, as well as in water-scarce coastal and island locations. The prize awarded a total of $1 million to the four teams that competed in the DRINK Stage and represents the first time WPTO and NREL supported a competition to develop and test devices that can turn ocean water into drinking water using the power of ocean waves.

During the DRINK Finale event, the competitors' wave-powered desalination devices were safely and successfully deployed in the waters surrounding Jennette's Pier, which sits on the shores of Nags Head, North Carolina. Each of the following devices produced desalinated water while harnessing wave power from the Atlantic Ocean:

- MarkZero Prototypes' rapidly deployable MZSP Freshwater Production System features pivoting arms, inflatable pontoons, an onboard, reverse-osmosis system (which turns salt water into fresh water), and a constant-pressure, variable-moment pump, all designed to meet the changing demands of diverse ocean conditions.
- Oneka Technologies' Oneka Snowflake, the Wave-Powered Watermaker, is a raft-like device that can be assembled without tools. Easy to install and adaptable to most ocean conditions, the Snowflake has the potential to produce up to 7,000 liters of clean water per week, which is especially important for disaster and recovery situations.

Team Oneka prepares to deploy its wave-powered desalination prototype in the water surrounding Jennette's Pier in Nags Head, North Carolina during the Waves to Water Prize DRINK Finale. *Image from Werner Slocum, National Renewable Energy Laboratory*

- Project 816's Ballast, Buoys, and Borrowing from Archimedes device can be deployed in a variety of site conditions by just two people with common equipment and basic tools. The inflatable, raft-based wave energy converter—built with commercial, off-the-shelf components—powers a land-based desalination system.
- WATER BROS' Wave Actuated, Tethered, Emergency Response, Buoyant Reverse Osmosis System is a wave-powered device that has a unidirectional, rotational wave-energy conversion mechanism. Optimized for emergency response, the device is rapidly deployable, low cost, and highly resilient, and uses near-shore waves to generate clean drinking water in even the harshest conditions.

In addition to the $500,000 grand prize and $229,000 in category prizes awarded to Oneka Technologies, the following teams were also awarded for their devices' accomplishments:

- Team WATER BROS received $178,000.
- Mark Zero Prototypes LLC received $58,000.
- Project 816 received $35,000.

The DRINK Finale was the result of a partnership between WPTO, NREL, and the Coastal Studies Institute, which hosted the prize finalists at Jennette's Pier. These organizations also worked closely to help ensure a fair and safe competition—successfully installing and retrieving competitors' wave-energy desalination systems.

Team MarkZero's Freshwater Production System (front) and Project 816's Ballast, Buoys, and Borrowing from Archimedes (back) wave-powered desalination prototypes float in the water surrounding Jennette's Pier in Nags Head, North Carolina, during the Waves to Water Prize DRINK Finale. *Image from Werner Slocum, National Renewable Energy Laboratory*

Ocean Observing Prize Awards BUILD Contest Innovators Investigating Rechargeable Underwater Vehicles

Project Name: Ocean Observing Prize

Project Team: Pacific Northwest National Laboratory, National Renewable Energy Laboratory, National Oceanic and Atmospheric Administration's Integrated Ocean Observing System Office, and Naval Surface Warfare Center Carderock

Test Location: Carderock, Maryland

In August 2022, DOE and the National Oceanic and Atmospheric Administration announced three winners of a $500,000 prize pool in the BUILD Contest, the second phase in the Powering the Blue Economy™: Ocean Observing Prize DEVELOP Competition. The prize challenges competitors to develop new ocean observing technologies powered by marine renewable energy.

For the BUILD Contest, competing teams tested their marine energy-powered ocean observing prototypes in a state-of-the-art wave tank at the Naval Surface Warfare Center in Carderock, Maryland. Each prototype was tested in the Maneuvering and Seakeeping Basin (also known as the U.S. Navy's indoor ocean) and weathered a variety of wave conditions to demonstrate its capabilities through a data-collecting maneuvering mission and a wave-powered recharging session. Such devices have the potential to lengthen the amount of time ocean observing technologies can remain at sea to provide more coverage and collect higher-resolution data. Weather forecasters can use this information to more accurately predict hurricane intensities and paths.

The Ocean Observing Prize is administered by NREL and PNNL on behalf of WPTO and the National Oceanic and Atmospheric Administration's U.S. Integrated Ocean Observing System Office.

The Wave Powered Oceanographic Gliders team tests its early-stage prototype at the Naval Surface Warfare Center's wave tank facility in Carderock, Maryland.

Image from Josh Baurer, National Renewable Energy Laboratory

Community-Driven Program Selects 12 Remote and Island Communities to Accelerate Their Transition to Resilient, Clean Energy

Project Name: Energy Transitions Initiative Partnership Project

Project Team: National Renewable Energy Laboratory (lead for program administration), Alaska Center for Energy and Power, Coastal Studies Institute, Hawaii Natural Energy Institute, Island Institute, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratories, Spark Northwest, and Renewable Energy Alaska Project

Participating Communities: Aquinnah and Chilmark, Massachusetts; Bainbridge Island, Washington; Beaver Island, Michigan; Guam Power Authority, Guam; Hui o Hau'ula, Hawaii; Igiugig, Alaska; Makah Tribe, Washington; McGrath, Alaska; Microgrid of the Mountain, Puerto Rico; Mount Desert Island, Maine; Nikolski and St. George, Alaska; University of Hawaii, Hawaii

In June 2022, DOE announced 12 competitively selected remote and island communities for the second Energy Transitions Initiative Partnership Project cohort. ETIPP connects remote and island communities with regional organizations and national laboratories to develop strategies to improve their energy resilience, or the ability to anticipate and adapt to changing conditions and recover rapidly from energy disruptions. Projects in selected communities focus on efforts to reduce reliance on fossil fuels, increase energy efficiency and resilience, and optimize renewable resources and battery or storage technologies.

Energy resilience is a particularly complex and costly challenge for remote and island communities. Many of these communities face risks associated with natural disasters and climate change impacts, on top of high energy costs, vulnerable fuel supply chains, and unreliable energy infrastructure prone to outages or damage. ETIPP provides technical assistance—in the form of strategic energy analysis and planning—for communities to make informed decisions regarding their energy transition choices. ETIPP's community-driven approach keeps communities involved in the decision-making process, with regional organizations providing contextual knowledge of local culture and challenges to national lab experts, who use these insights to help identify the technical solutions that best meet community needs.

ETIPP is supported by WPTO, along with the Office of Energy Efficiency and Renewable Energy's Energy Transitions Initiative, Geothermal Technologies Office, Solar Energy Technologies Office, and Wind Energy Technologies Office.

The Energy Transitions Initiative Partnership Project provides strategic energy analysis and planning to remote and island communities that aim to build greater energy resilience. *Image from Aaron Gonzalez, Unsplash*

National Laboratory Researchers Deploy Their First Wave-Powered Desalination Device

Project Name: National Renewable Energy Laboratory's Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC)

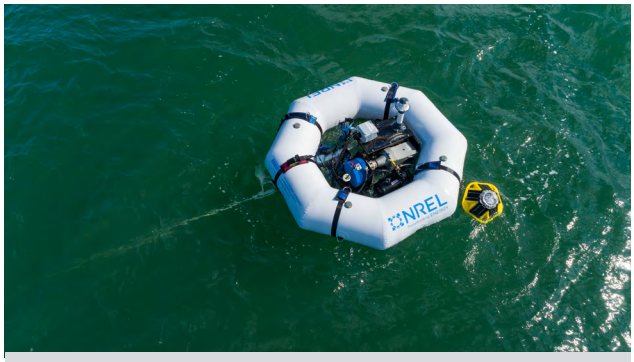
Project Team: National Renewable Energy Laboratory (lead) and Coastal Studies Institute

Lead Recipient Location: Boulder, Colorado, with in-water testing in Nags Head, North Carolina

NREL deployed its first wave-powered desalination test device in North Carolina's Outer Banks. Researchers and crews tested the Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC) twice over the year, successfully demonstrating a wave energy converter deployment and producing desalinated water. Demonstrations like this provide critical lessons learned related to deployment, installation, operations, and wave energy converter design reliability.

With help from the Coastal Studies Institute, NREL deployed the HERO WEC for the first time in February 2022 from Jennette's Pier—the same location where Waves to Water Prize finalists tested their wave-powered desalination prototypes. This first deployment prepared the crew to safely install and deploy each of the prize finalists' prototypes during the DRINK Finale in April 2022. NREL created the HERO WEC alongside teams competing in the prize, and while the NREL researchers were not competitors, they did abide by the prize guidelines to better understand what was required of competitors.

NREL researchers then deployed the HERO WEC a second time in August 2022. During this test, the



As the National Renewable Energy Laboratory's first marine-powered desalination device to weather real ocean waters, the Hydraulic and Electric Reverse Osmosis Wave Energy Converter signals significant advancements for marine renewable energy and desalination technologies. *Photo from Coastal Studies Institute*

HERO WEC spent more time in the water, collecting data to advance NREL's research on small-scale wave energy converters. The team also had the opportunity to test the electrical power take-off system (which converts wave energy into electricity to pump water through a reverse osmosis system) in the ocean for the first time, and the device ultimately produced desalinated water.

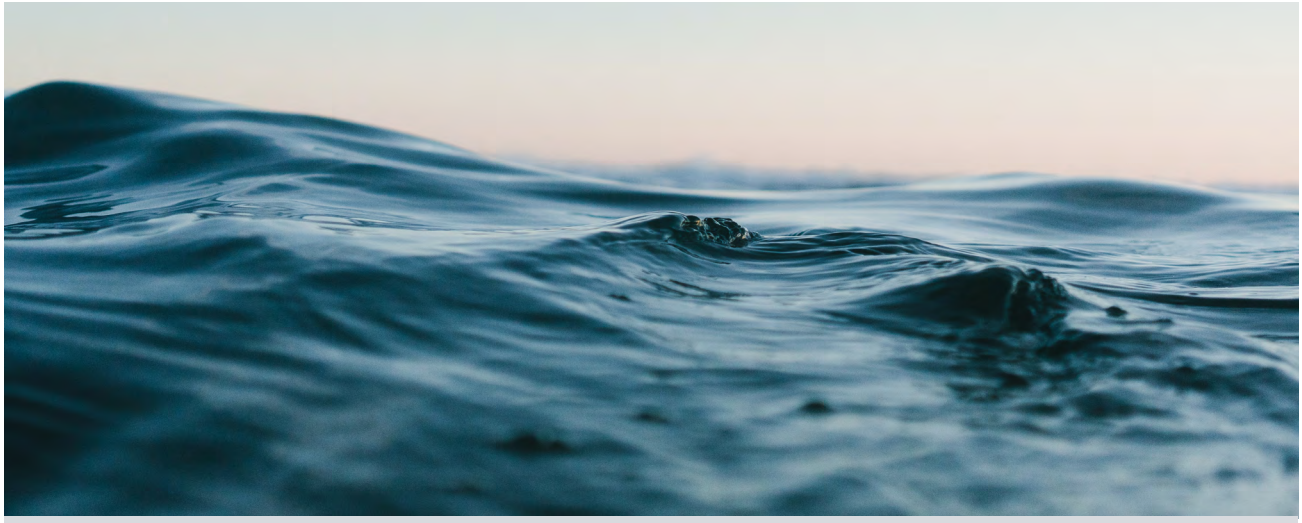
NREL anticipates more in-water tests for the HERO WEC and will continue refining the device's design. The HERO WEC is helping advance marine renewable energy and desalination technologies through device documentation (like drawings, parts, and data), which will be publicly available in Fiscal Year 2023.

DOE Releases First Significant Funding Opportunity Investing in Blue Economy Market

Project Name: Marine Energy Systems Innovation at Sea Funding Opportunity

In September 2022, WPTO issued a $10.3 million funding opportunity to accelerate the development and testing of marine energy technologies with a focus on wave and ocean current resources. This represented the first significant funding opportunity announcement by DOE focused on a blue economy market and was designed to encourage faster and smaller-scale designing, building, and testing of marine energy technologies.

The funding opportunity supported wave-powered systems innovation for seawater desalination, research and development for blue economy markets, and a feasibility assessment for an ocean current test facility. This opportunity built on the success of WPTO's Waves to Water Prize, which helped accelerate the development of small, modular, wave-powered desalination systems capable of providing clean water in disaster and recovery scenarios, as well as in water-scarce coastal and island locations.



In Fiscal Year 2022, WPTO released a funding opportunity representing the first significant funding the U.S. Department of Energy is investing in a blue economy market. *Image from Matt Hardy, Unsplash*

REFLECTING ON WATER POWER SUCCESSES

In 2021 and 2022, WPTO supported projects across the country at national laboratories, academic institutions, companies, and other organizations. Researchers, scientists, engineers, students, and many others behind these projects are committed to realizing water power's full potential to help reach the Biden administration's goals of a carbon-free electricity sector by 2035 and a net-zero-emissions economy by 2050.

Projects supported through WPTO's Hydropower Program focused on 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. Partners developed new, low-impact hydropower technologies to protect wildlife and river ecosystems, created tools to help developers assess how to increase hydropower's contributions to the electricity grid, and launched efforts to grow and diversify the industry's workforce.

As part of WPTO's Marine Energy Program, projects focused on research, development, demonstration, and commercial activities that advance the development of reliable, cost-competitive marine energy technologies and reduce barriers to technology deployment. Partners advanced novel materials and marine energy technologies, performed in-water or lab-based tests of promising prototypes, compiled more detailed data on U.S. marine energy resources, standards, and market value, and created resources for the next generation of marine energy workers.

Along with projects supported through the Hydropower and Marine Energy programs, WPTO also championed important efforts across DOE, like the Inclusive Energy Innovation Prize, which aims to fund organizations for ongoing and/or proposed activities related to climate and clean energy that support, build trust, and strengthen relationships and partnerships with disadvantaged communities in support of the Justice40 Initiative.

Water power technologies have a crucial role to play today and in the future as the United States works to achieve its clean energy and climate goals. The projects featured in WPTO's 2021–2022 Accomplishments Report, along with many more, are helping to advance the hydropower and marine energy technologies that can help transform the country's energy system.

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DOE/EE-2689 • March 2023