



Alaska Energy Authority

Emerging Energy Technology Fund



In-Stream Testing of Three Hydrokinetic Turbine Designs in Alaskan Rivers



Emerging Energy Technology Fund Overview

New technology passes through a variety of phases as it proceeds from development and testing in the laboratory to commercialization in the real world. Emergence is a critical middle phase in the development process of energy technology, linking research and development to the commercialization of energy solutions. Although the Arctic possesses bountiful energy resources, the Arctic also faces unique conditions in terms of climate, environment, population density, energy costs, logistics, and the isolated nature of electrical generation and transmission systems. These conditions, challenging under the best of circumstances, make the Arctic an ideal test bed for energy technology. Emerging energy technology provides a unique opportunity to meet Arctic energy needs, develop energy resources, and create global expertise.

Building on the success of the Emerging Energy Technology Grant, funded by the Denali Commission in 2009, the Alaska State Legislature created the Emerging Energy Technology Fund (EETF) in 2010 to promote the expansion of energy sources available to Alaskans. These grants are for demonstration projects of technologies that have a reasonable expectation of becoming commercially viable within five years. Projects can:

- test emerging energy technologies or methods of conserving energy;
- improve an existing technology; or
- deploy an existing technology that has not previously been demonstrated in the state.

The funded projects for Round 1 of the EETF include the following:

Alaska Division of Forestry, Biomass Reforestation of Boreal Forests
Altaeros Energies, Inc., High Altitude Airborne Wind Turbine
Alaska Applied Sciences, Inc., Solid State Ammonia Synthesis Pilot Plant Demonstration System
Arctic Sun, LLC, Arctic Thermal Shutter & Door Development
Boschma Research, Inc., Cyclo-Hydrokinetic Turbine Energy Production
Cold Climate Housing Research Center, Cold Climate Ground Source Heat Pump Demonstration
Genesis Machining and Fabrication, Ultra-Efficient Generators and Diesel-Electric Propulsion
Hatch, Application of Flywheels for the Integration of Wind-Diesel Hybrid Systems
Intelligent Energy Systems, Small Community Self Regulating Grid
Intelligent Energy Systems, Wind Diesel Battery Hybrid System
Marsh Creek LLC, High Efficiency Diesel Electric Generator for Energy Projects in Alaska
Oceana Energy Company, In-Stream Hydrokinetic Device Evaluation
Ocean Renewable Power Corporation, RivGen™ Power System Commercialization Project
University of Alaska Fairbanks, Safe and Efficient Exhaust Thimble
University of Alaska Fairbanks, Enhanced Condensation for Organic Rankine Cycle

Award recipients for EETF grants are selected through a competitive application process. Project selection for the EETF program uses a two-stage application process and has a volunteer advisory committee appointed by the governor.

Data Collection

Data collection is a central component of all EETF awards. The recording and careful analysis of high-quality performance data are critical parts of testing new energy technology, to understand how the technology performed and make future refinements. Using this information to support data-driven decisions will continue to prove the value of Alaska as an energy laboratory and ensure that new energy systems are applied appropriately.

Under an agreement with the University of Alaska, performance data generated by projects are independently verified and analyzed by the Alaska Center for Energy and Power (if a potential conflict of interest arises for any technology, another independent third party is identified). As projects conclude, summary reports and non-sensitive data are made available to the public.¹



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The Alaska Center for Energy and Power (ACEP) is an applied energy research group housed under the Institute of Northern Engineering at the University of Alaska Fairbanks. ACEP is serving as the program manager of the EETG program on behalf of the Denali Commission.

A key deliverable for each EETG project is a lessons learned report by ACEP. As the projects deal with emerging energy technology, providing lessons learned and recommendations is critical for understanding the future of the technology in Alaska, and the next steps needed in developing energy solutions for Alaska.

ACEP's technical knowledge and objective academic management of the projects, specifically for data collection, analysis, and reporting, are vital components to the intent of the solicitation.

In-Stream Testing of Three Hydrokinetic Turbine Designs in Alaskan Rivers

An Emerging Energy Technology Project

EETG Funding:
\$3,673,276
Total Project Funding:
\$4,814,535
Project Timeline:
July 20xx-March 20xx

Report Overview

Company	EETF Grant Funds	Match Funds
Boschma Research Inc. (BRI)	\$728,630	\$141,360
Ocean Renewable Power Company, LLC (ORPC)	\$1,491,750	\$379,899
Oceana Energy Company (Oceana)	\$1,452,896	\$620,000

In this report, we discuss three hydrokinetic power generation systems designed to harness energy from the natural flow of Alaska rivers, without the construction of dams. The three systems undergoing pre-commercial development were built by Boschma Research, Inc. (BRI), Ocean Renewable Power Company (ORPC), and Oceana Energy Company (Oceana). All three systems were selected for Emerging Energy Technology Fund support to advance the state of hydrokinetic technologies for implementation in Alaska.

This report is an analysis of data collected during testing of the BRI and ORPC systems in the Kvichak River near Igiugig, Alaska, and of the Oceana system at the ACEP AHERC Tanana River test site near Nenana, Alaska. These systems were evaluated for total demonstrated output and characteristic performance as a function of river velocity and turbine blade tip speeds, as demonstrated in their power curves.

Challenges were experienced with all three systems, as expected for pre-commercial technologies, and the ability of the manufacturers to overcome these challenges will be discussed. Lessons learned from these challenges will serve to improve hydrokinetic technologies through better deployment and retrieval techniques, robustness of data collection, resilience of devices to river debris and sediments, connection to and integration with local electrical grids, and evaluation of environmental impacts.

In August 2014, the BRI system successfully generated 7 kWh (kilowatt-hours) during 36 hours of instrumented testing on the Kvichak River. Peak power output was 4.6 kW. River current was reported at 2.5 m/s (meters per second) during this output, although this flow velocity was not verified by ACEP (Jim Boschma, personal communication, October 10, 2014). Peak demonstrated efficiency was 9%. The instrumented in-river electrical generation took place during August 30–31, 2014, at the end of the 2014 testing season.

The ORPC RivGen® system operated in the Kvichak River for 80 hours in 2014. In 2015, an updated turbine recorded 310 hours of testing at the same location, generating 1855 kWh. Peak power output in 2015 was 17.8 kW from a river velocity of 2.1 m/s. Peak system efficiency was 33%.

The Oceana turbine was tested at the ACEP AHERC Tanana River test site in the summers of 2014 and 2015. In 12.4 hours of testing, during which high-quality river velocity data were collected, the system generated 36 kWh. Peak power output was 3.43 kW from a river velocity of 2.1 m/s. The system demonstrated a peak efficiency of 28%.

Project Introduction

Alaska is home to an abundance of hydrological energy resources, including 40% of the nation's total river energy (Johnson and Pride, 2010). Traditional hydropower systems use dams to create large water reservoirs with significant heights to generate reliable power (and control flooding) at the expense of environmental disruption to upstream regions. Run-of-the-river (ROR) systems use low-head dams with little to no reservoir storage, though they still disrupt the river's natural flow. Hydrokinetic systems differ from traditional hydropower and ROR systems by harnessing energy from the natural river flow without construction of a dam. These systems can be installed in regions where flowing water is sufficient, including rivers, ocean currents, and tidal regions. Hydrokinetic technology offers the ability to extract a much lower amount of energy from a river without the capital costs of dam building and the ecological impacts of disrupting the continuous flow of the river. In particular, for remote Alaska communities situated on suitable rivers, hydrokinetic electricity generation offers the potential to harvest a local renewable energy source in lieu of expensive imported fossil fuels.

Harnessing river energy entails submersing an electrical generation system in a turbulent, fast moving river environment that subjects the system to fine abrasive sediments and to massive debris such as dead trees. In Alaska, winter freeze-up and spring break-up of river surface ice have so far required seasonal installation and removal of generation systems. Hydrokinetic technology is frequently said to be at the commercial readiness state that wind energy technology was 20 or 30 years ago (Johnson and Pride, 2010).

The Alaska Energy Authority selected three proposals for Emerging Energy Technology Fund grants to advance the state of hydrokinetics and demonstrate its potential in remote Alaska rivers. These proposals were generated by Oceana Energy Company, Ocean Renewable Power Company, and Boschma Research, Inc..

The projects discussed in this report were also used as opportunities for academic studies by researchers at the University of Alaska Fairbanks, University of Alaska Anchorage, and University of Washington to conduct river characterization and ecologic impact studies. These efforts contributed to the understanding of the nature of water flow at the selected testing sites and identified the potential effects of hydrokinetic generation on fish and river ecosystems. The following organizations were involved in this project:

University of Alaska Fairbanks

Researchers in the Department of Mechanical Engineering at the University of Alaska Fairbanks (UAF) Institute of Northern Engineering worked with BRI to provide technical and logistical support during the project and initial data analysis. A UAF student intern worked in Igiugig with BRI during summer 2014.

University of Alaska Anchorage

University of Alaska Anchorage (UAA) researchers performed data collection, river modeling, and barge and supporting structure design and fabrication at the Tanana River test site for Oceana testing. They assisted in testing site coordination, planning and development of testing protocol, hydrodynamics and sediment monitoring and modeling, and design and development of instrumentation and controls for test parameters monitoring and data acquisition.

Alaska Energy Authority

The Alaska Energy Authority (AEA) is an independent corporation of the State of Alaska and the state's energy office; its programs place Alaska at the forefront of innovative ways to address high energy costs.

Oceana Energy Company

The Oceana Energy Company (Oceana), which is based in Washington, D.C., has developed a novel turbine designed specifically for marine hydrokinetic applications. Oceana's system uses an open center axial flow turbine with a ring of magnetic bearings to eliminate problematic shaft sealing that occurs in other hydrokinetic devices. The Oceana turbine underwent laboratory testing at the Naval Surface Warfare Center, Carderock Division in Bethesda, Maryland, before shipment to ACEP's Tanana River test site in Alaska.

Ocean Renewable Power Company Alaska, LLC

ORPC Alaska, LLC is a wholly owned subsidiary of Ocean Renewable Power Company, LLC (collectively, ORPC), based in Portland, Maine. The ORPC RivGen® (hereafter referred to as RivGen) and TidGen® Power Systems are submersible hydrokinetic systems designed for river and shallow tidal applications. Testing and demonstration of ORPC's horizontal cross-flow RivGen system in Igiugig, Alaska, in 2014–2015 was the company's first river energy project.

Boschma Research, Inc.

Boschma Research, Inc. (BRI), based in Brownsboro, Alabama, is developing affordable tools to harness hydropower from small rivers. BRI's cycloidal turbine, originally researched for U.S. Navy aviation, has been adapted for use in renewable energy generation. BRI tested its ducted cycloidal turbine in the southeast United State before shipping it to Igiugig, Alaska.

Naval Surface Warfare Center, Carderock Division

The David Taylor Model Basin at the Naval Surface Warfare Center, Carderock Division in Bethesda, Maryland, provides a controlled environment for hydrodynamic testing. Oceana used this facility for baseline system testing. At the Carderock testing facility, a carriage can move systems through a nearly 3000-foot-long test basin at speeds up to 18 knots. The facility allows laboratory evaluation of systems without the variability and remoteness inherent in real-world scenarios.

Alaska Hydrokinetic Energy Research Center

The Alaska Hydrokinetic Research Center (AHERC), housed within ACEP, focuses on applied research and engineering to help address the economic, technical, and environmental challenges of developing hydrokinetic technologies. AHERC

conducts environmental and technical studies, evaluating available hydrokinetic energy resources, turbulent flows and their effects on device power output and longevity, fisheries and marine mammal studies, habitat studies, approaches to anchoring hydrokinetic infrastructure and debris mitigation, and other issues pertinent to developing an Alaska hydrokinetic power industry. The AHERC Tanana River Hydrokinetic Test Site is used to test hydrokinetic power-generating devices and related technologies, and to characterize the river environment under realistic Alaska river conditions for both research and commercial projects.

Power Systems Integration Laboratory

The Power Systems Integration Laboratory (PSIL), housed within ACEP, operates on the same scale as a village power system, and has the ability to be modified for individual test scenarios. The lab transforms a potentially chaotic field-testing environment into a continuously improving process for optimizing efficiencies. In the PSIL, a wide range of islanded microgrid and distributed generation scenarios, as well as the performance of individual components, can be tested.

The developers of the hydrokinetic systems detailed in this report had initially intended to test their generators in the PSIL to verify each unit's ability to effectively connect and interact with a small islanded grid. Due to a variety of issues, including scheduling and funding, none of the systems described have been tested in the PSIL, although Oceana is currently in discussions to move forward with PSIL testing.

Alaska Center for Energy and Power

The Alaska Center for Energy and Power (ACEP), an applied energy research program based at UAF, provided technical support for data collection. In addition, ACEP provided independent project and performance analysis and reporting through an agreement with the Alaska Energy Authority. This report is the final product of that effort.

Technology Overview

Hydrokinetic technologies aim to harness the kinetic energy of naturally moving waters for electricity generation, in many ways analogous to how wind turbines are used to harness energy from wind. Hydrokinetic turbines are designed for use in rivers, oceans, or tidal currents. With a density more than 800 times greater than air, a water stream with a velocity of

2 m/s has power density equivalent to a 16 m/s air stream (Yuce and Muratoglu, 2015). Optimum currents for most hydrokinetic systems are in the 5–7 knot (1.5–3.5 m/s) range, although electricity can be generated from currents as slow as 2 knots (1 m/s) (Ortega-Achury et al., 2010). The United States has 250 TWh/yr (terawatt-hours per year) of technically recoverable tidal resources and 120 TWh/yr of technically recoverable river resources (Yuce and Muratoglu, 2015). Alaska contains roughly 40% of the nation's river energy potential and 90% of the nation's tidal energy potential, positioning the state as a key location for the development of hydrokinetic technologies (Ortega-Achury et al., 2010).

In-river hydrokinetic technology is of potential interest to any community located on a river, as many rural Alaska communities are. The high cost of traditional diesel power generation in off-grid communities makes locally sourced renewable power generation especially advantageous. In 2010, ACEP published a report on the status and future opportunities of hydrokinetic energy technologies in Alaska (Johnson and Pride, 2010). This work elaborated on existing studies and detailed the status of hydrokinetic power generation technology. The report discussed the expected trajectory of development, and highlighted achieving reliability in the face of debris, sediment, and seasonal changes as a critical objective. Finally, the report recommended continued study in both technology and site modeling and characterization to accelerate development in the hydrokinetic technology field.

Hydrokinetic turbines of several different designs are under development by commercial companies in the United States and around the world. A review paper written in 2015 reports that industry has more than 100 conceptual system designs in various stages of pre-commercial development worldwide (Yuce and Muratoglu, 2015). The U.S. Department of Energy's Water Power Program supports the development of advanced water power devices, including hydrokinetics, through its Technology Development and Market Acceleration initiatives.

Various hydrokinetic system designs can be distinguished by the orientation of turbine rotation to the flow direction of water and by anchoring method. The axis of rotation of axial flow turbines is parallel to the direction of flow, similar to airplane propellers and large wind turbines. Cross-flow turbines may be oriented horizontally or vertically, with the axis of rotation perpendicular to the flow of water. A schematic of turbine orientations is shown in Figure 1.

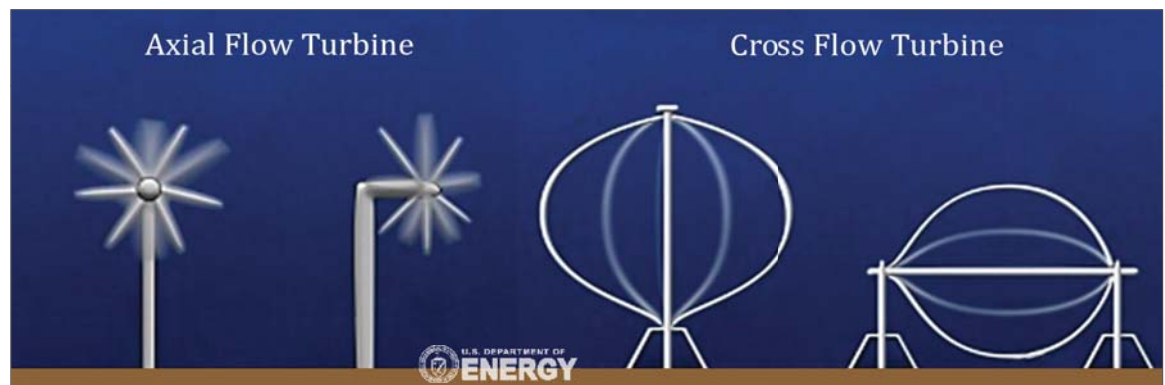


Figure 1. Turbine type schematic.



Figure 2. Map of Alaska showing site locations (left). Turbine testing locations near Nenana (top) and Igiugig (bottom, Alaska).

To generate power, the turbine must be held stationary while the water flows past. Hydrokinetic systems under development are either fully submerged and anchored to the river bottom, or lowered into the river from a surface barge moored to an upstream anchor. These various designs strive to produce electricity efficiently while withstanding the challenges of turbulence, debris, and abrasive sediments.

Developing standardized methodologies to analyze turbine performance is an ongoing challenge. The International Electrotechnical Commission (IEC) has been developing standards in IEC 114 (ITC 114) for marine hydrokinetic (MHK) technologies. As part of this effort, the IEC has formed working groups in several countries to work on IEC 62600-300 (Marine energy – Wave, tidal and other water current converters – Part 300: Electricity producing river energy converters – Power performance assessment). This standard, which is still in draft form, is intended to establish a methodology for evaluating the power performance of river current energy converters. However, considerable work is still needed to understand how to standardize the development of a power curve for a given technology. In particular, blockage ratio, current velocity shear, and turbulence are still poorly understood in terms of their quantitative impact on performance measurement. The uncertainty that this leads to in power performance reporting is an issue the industry continues to grapple with and understand as in-river hydrokinetic technologies steadily progress toward commercialization (Monty Worthington, personal communication, October 6, 2016).

Project Summaries

The Alaska Energy Authority selected the proposals of three companies for grants from the Emerging Energy Technology Fund (EETF) to advance the state of hydrokinetic technology and demonstrate its potential in remote Alaska rivers: Oceana Energy Company, Ocean Renewable Power Company, and Boschma Research, Inc.

The projects of these three companies take significantly different approaches to harvesting riverine energy. All three systems were designed to achieve robust, economical operation in challenging river environments at remote locations of Alaska (Figure 2). The following is a discussion of the design and development of each technology, the testing and results and the lessons learned.



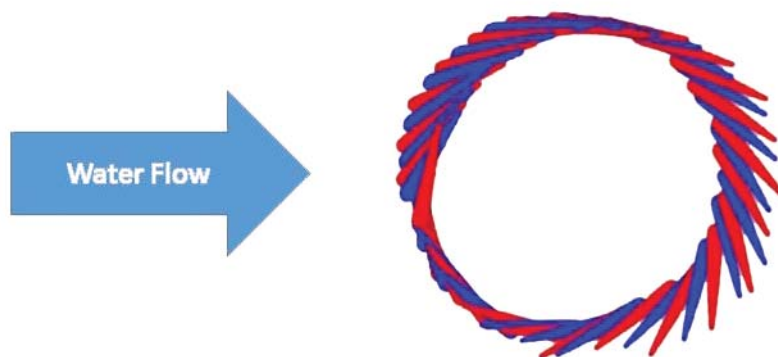
Boschma Research, Inc.

Boschma Research, Inc. (BRI) designed, built, and tested a horizontal cross-flow cycloidal turbine, shown in Figure 3. The turbine is housed in the Venturi section of a large duct. This ducting collects an area of water flow larger than the turbine, and the water flow accelerates as it travels through the smaller Venturi section. The hydrofoil blades on the turbine are connected to two parallel rotating discs that mechanically change the angle of the hydrofoils throughout rotation to improve their angle of attack relative to the water movement, as illustrated in Figure 4. This design increases efficiency compared with fixed-angle blades. BRI attempted to incorporate an active debris guard that features a rotating drum at the leading edge, as well as articulated fouling-resistant UHMW (ultra-high-molecular-weight polyethylene) wires across all intake paths. The system is designed to operate on the river bottom while tethered to an upstream anchor. The designed output for the system is 5 kW. The BRI hydrokinetic system was designed and built at BRI in Alabama. Initial testing was completed in the Tennessee River. The system was driven from Alabama to Anchorage, but missed the barge out of Homer due to late arrival, so was flown airfreight to Igiugig.



Figure 3. BRI's ducted cross-flow horizontal axis hydrokinetic testing on the Kvichak River near Igiugig, Alaska (Photo by Chris Pike/ ACEP).

Figure 4. BRI turbine blade angle throughout rotation (source – BRI website).



Ocean Renewable Power Company Alaska, LLC

Ocean Renewable Power Company, LLC (ORPC) designed the RivGen. ORPC, Alaska, LLC, a wholly owned subsidiary of ORPC, is the company presence in Alaska; it is developing projects for Alaska river and Cook Inlet tidal power generation. The work described here builds on ORPC's testing in 2010, funded by a Denali Commission Emerging Energy Technology Fund grant (ACEP, 2012).

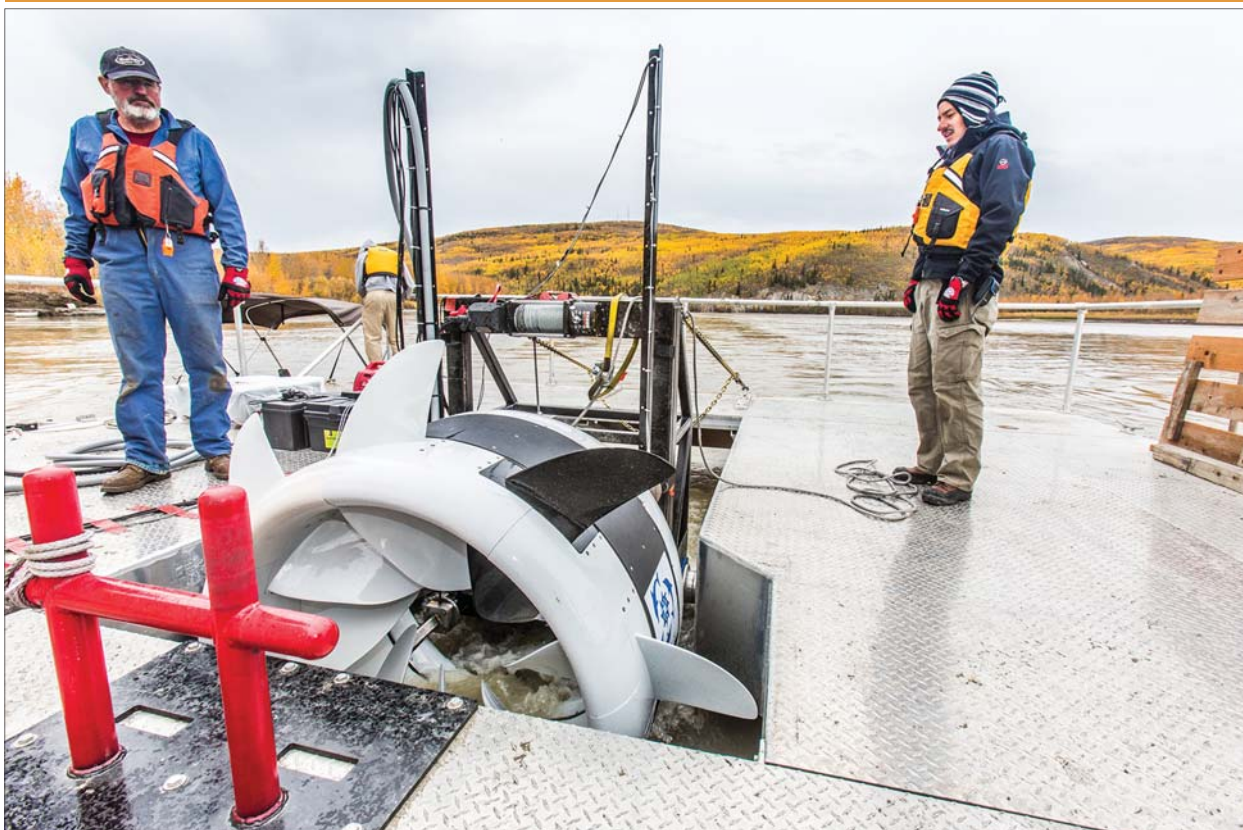
The ORPC RivGen system is composed of two horizontal cross-flow turbines coupled to a central electric generator. The turbines use hydrofoils in a helical arrangement. The system is mounted to two large pontoons that support it during

transport and are flooded to sink the turbine to the river bottom. The ORPC system is moored to two upstream anchors through an equalizing chain block. The submersible three-phase permanent magnet AC generator is rated for 50 kW shaft input power, while expected output is dependent on water velocity. The system tested in 2014 was rated to produce 17 kW in a 2.3 m/s current. The ORPC hydrokinetic device tested in 2014 is shown in Figure 5. After the test in 2014, the RivGen system structure was modified, and a fairing was added to reduce drag and improve performance. The cross-sectional area of the turbine remained unchanged, with a turbine length of 4.1 m and height of 0.7 m.



Figure 5. ORPC's cross-flow horizontal axis RivGen system prior to submersion for testing on the Kvichak River near Igiugig, Alaska.(Photo courtesy of ORPC.).

Figure 6. Oceana's open-center axial flow hydrokinetic turbine testing on the Tanana River near Nenana, Alaska (Photo courtesy of T. Paris/ UAF)



Oceana

Oceana Energy Company (Oceana) has developed and tested an open-center axial flow hydrokinetic turbine with hydrofoils both internal and external to the rotating ring. The rotating ring is supported by a patented permanent magnet-bearing system that supports the axial loads of the turbine without mechanical contact. Mechanical bearing surfaces are known

to be prone to failure due to abrasive sediment loads, which are particularly prevalent in many Alaska rivers. Radial loading in the Oceana turbine is carried by wear-resistant ceramic bearings. Another innovation in the Oceana turbine is the custom 9-pole permanent magnet generator design, which allows the system to operate completely sealed or flooded. The Oceana hydrokinetic device is shown during testing in Figure 6.



Figure 7. Oceana barge and debris diverter on the Tanana River.

Figure 8. Oceana turbine prior to being lowered into the river.



The Oceana turbine underwent initial testing at the Naval Sea Systems Command (NAVSEA) test basin at Naval Special Warfare Center, Carderock Division, in 2014, and was tested during the summers of 2014 and 2015 at AHERC's Tanana River hydrokinetic test site near Nenana, Alaska (Figure 7 and Figure 8). The Tanana River testing exposed the turbine to high sediment concentrations and surface debris that were quantified by AHERC research and data collection.

River Characterization

Hydrokinetic power generation in Alaska must be further developed to operate reliably in the state's demanding riverine environments. To be viable, a system must endure swift, turbulent currents laden with large debris and abrasive sediments. A successful hydrokinetic system must not have an unacceptable effect on the river ecosystem. River characterization serves to further the understanding of the hydrodynamic behavior of the river water, the specific qualities of the sediment carried by the river, the prevalence of and hazards posed by river debris, and the characteristics



Figure 9. Research debris diversion platform (RDDP) is shown upstream of the Oceana testing barge.

of ecosystems harbored by the river. This information is then used to inform the design of hydrokinetic systems and understand failures when they occur.

The devices described in this report were tested in one of two rivers in Alaska, each with very different characteristics. The Oceana turbine was tested in the silty waters of the Tanana River at AHERC's testing site. The BRI and ORPC systems were tested in the clear waters of the Kvichak River near Igiugig.

The Tanana River is located in Interior Alaska; it has a high suspended sediment load that originates in glaciers of the eastern Alaska Range. River flow velocities at the Tanana River test site average 1.9 m/s, with peak local velocities of up to 3.1 m/s during the summer months. Winter under-ice flow velocities range from 0.5 to 0.8 m/s (Johnson et al., 2013). The AHERC Tanana River test site has been exhaustively studied to characterize the river current and debris. River turbulence and power density were characterized from current velocity measurements. Fall and winter ice formation was observed. A fish study generated baseline information about the spatial and temporal patterns of fish activity. Bathymetry studies resulted in maps of the river bottom, which are used to create computer models of the river flow (Johnson et al., 2013).

Woody debris poses a significant threat to the successful operation of hydrokinetic systems in large uncontrolled rivers, and was responsible for the premature termination of two Alaska pilot river hydrokinetic projects in 2010 in Ruby and Eagle (Johnson and Pride, 2010). Through multiple years of testing at the Tanana River test site, AHERC has developed a "research debris diversion platform" (RDDP) to protect surface-deployed hydrokinetic systems from floating debris (Kasper et al., 2015). The debris diverter, pictured in Figure 9, was instrumented and monitored for debris impacts to allow characterization of river debris exposure. Load cells on

the RDDP recorded impact forces as high as 6600 pounds; some debris took more than 6 hours to clear. Additional data were collected to determine the hydrodynamic effect of the RDDP on river velocity and turbulence. Data indicated an approximately 8% reduction in turbine output when tested 14.5 m downstream of the RDDP (Johnson et al., 2014).

During AHERC's Tanana River hydrokinetic characterization study from 2009–2011, river discharge, current, and turbulence were measured; suspended sediment and riverbed characteristics were quantified; bathymetry measurements of the river bottom were completed; flow behavior was modeled; and fish movements, debris movements, and ice formation were observed (Johnson et al., 2013). This information makes the Tanana River test site uniquely prepared to facilitate the development of hydrokinetic technologies.

The ORPC and BRI devices were tested in the Kvichak River near the village of Igiugig. The river flows out of Lake Iliamna, the largest lake in Alaska. The lake forms a natural debris sink, which creates a clear flowing river with minimal sediment and debris, an ideal spot to extract river power with a hydrokinetic device. During the summer months, peak river flows vary from 1.5–2.5 m/s. The river is home to a world-class salmon fishery, and several high-end lodges are located in the region.

In summer and fall 2011, TerraSond conducted an extensive bathymetric survey and hydrokinetic energy assessment of the Kvichak River near Igiugig. The study identified three areas that offer the most potential for hydrokinetic development. The findings are based on a well-defined and stable zone of high river current, a large channel that allows ample room for navigation of vessels, and proximity to the Igiugig power grid. These three areas are designated as sites 6, 9, and 10. The TerraSond report identifies site 6 as the most

favorable site due to its location near the powerhouse and good energy density. Site 10 has a large, deep channel that could accommodate multiple turbines; however, its longer distance from the powerhouse is a disadvantage. Site 6 was the site for BRI testing in 2014; mid-river velocities measured by TerraSond varied from 2.0–2.7 m/s. Site 10 was used for ORPC turbine testing in 2014 and 2015 (see Figure 10). The mid-river flow velocities measured by TerraSond ranged from 1.7–2.6 m/s. More detail can be found in the report by TerraSond (TerraSond Ltd., 2011).

Boschma Research, Inc.

The characterization by BRI of the Kvichak River was built on information initially contained in a study, conducted in 2008 by the Electric Power Research Institute, of the hydrokinetic potential of several rivers in Alaska, as well as on a site visit by BRI staff in 2008 at the village of Igiugig (Jacobson, 2012). According to its initial funding application, BRI indicated that both river depth and flow velocity are favorable, and the river bottom is gravel and void of substantial vegetation. In addition, BRI reported that the powerhouse is close to the river, and Igiugig has Federal Energy Regulatory Commission authority for a pilot hydrokinetic plant. BRI was depending on the velocity sensors mounted on the turbine to get accurate flow velocity data. Unfortunately, these sensors failed to operate, and BRI's best approximation of river velocity was based on tests conducted by the University of Washington (UW) at a nearby location, as described later in the report.

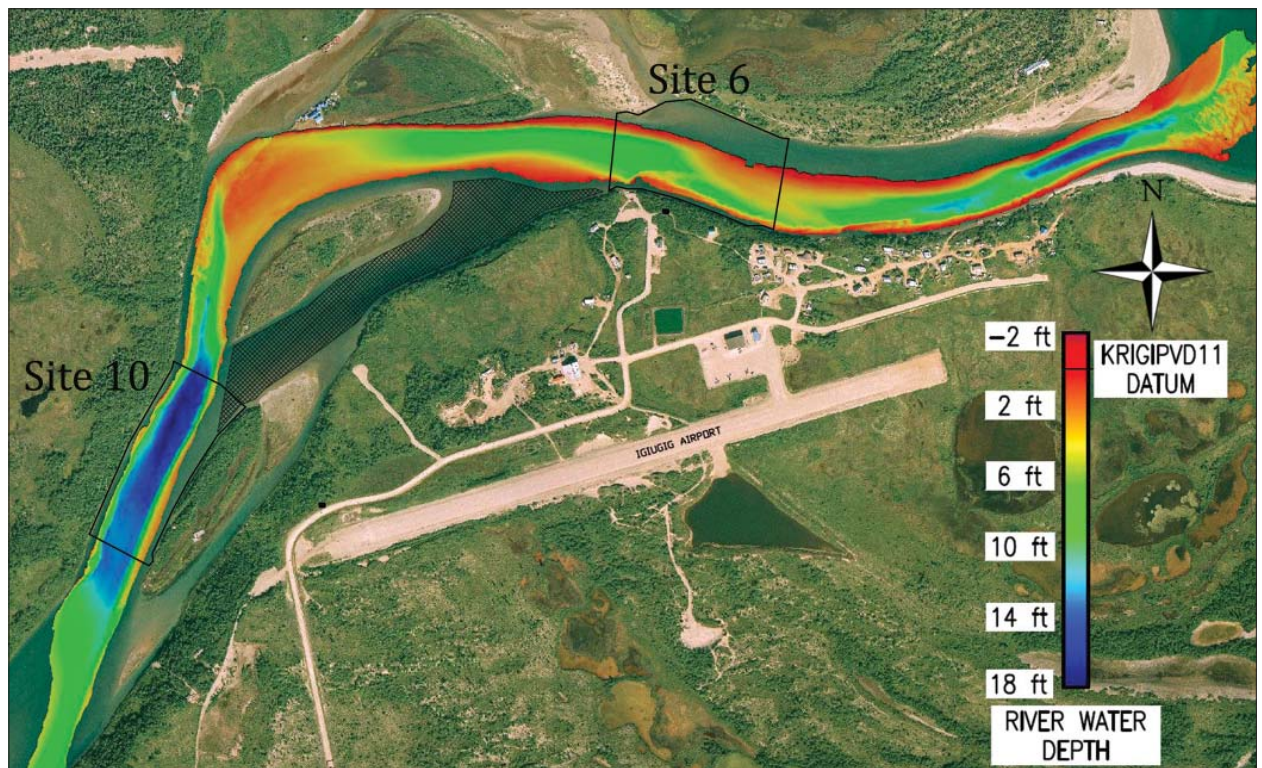
Oceana

Oceana testing at the Tanana River test site built upon knowledge of river depth and debris already developed by AHERC. The system, which was tested in a well-characterized stretch of the river, used the RDDP. In a parallel study during Oceana testing, UAA graduate student Elan Edgerly sought to isolate and measure the effects of the hydrokinetic turbine on river hydrodynamics. Edgerly used Doppler instruments to measure the river velocity upstream and downstream of the turbine installation location, both with and without the turbine present. This work showed that reduced river velocities are present downstream of the turbine for approximately 20 turbine diameters (Edgerly, 2015).

Ocean Renewable Power Company Alaska, LLC

Testing of the ORPC RivGen system was performed in conjunction with several efforts to characterize the river environment and the possible effects of the presence of a hydrokinetic device. University of Washington researchers published work characterizing the variation of river current across the hydrokinetic turbine due to lateral and vertical shear layers in the water velocity (Forbush et al., 2015). Research findings indicate that variations in velocity across the turbine significantly influence performance, which suggests that velocity shear should be considered during turbine placement and accounted for when evaluating system performance.

Figure 10. Sites 6 and 10, identified in TerraSond Ltd. (2011) as areas of the Kvichak River that show high potential for hydrokinetic energy extraction



Another UW study compared a simulated hydrokinetic system with the performance of the ORPC system during real-world testing (Cavagnaro et al., 2015). An electric motor-driven generator was used to emulate the dynamic nature of hydrokinetic turbine behavior. The hydrokinetic emulator proved a valuable tool for developing control and grid integration strategies for hydrokinetic systems.

Suspended sediments in rivers pose a significant threat of abrasion damage to bearings and seals in hydrokinetic devices. ORPC worked with UAA to conduct small-scale laboratory testing of bearings and seals in high suspended sediment conditions. These tests quantified wear rates for competing bearing and seal designs to provide better information for future system design. The study found that polycrystalline diamond bearings had significantly lower wear rates than Vesconite, CIP Marine, and Feroform T814 bearings, although future testing was recommended to quantify shaft wear as well (Worthington et al., 2013).

An acoustic study was performed by UW researchers to evaluate the sound produced by the ORPC system during testing on the Kvichak River. Hydrophones and GPS (global positioning system) loggers were used to characterize the temporal and spatial variability of sounds produced by the turbine blades and electric generator (Polagye and Murphy, 2015). A UW graduate student, P.G. Murphy, examined the hydrophone data and found that the turbine produced noise with frequencies in the known sensitivity level of sockeye salmon; however, it remains unclear if salmon actually detect the sound and whether the noise would affect their behavior (Murphy, 2015). As part of the testing that took place in Igiugig, a fish monitoring study was performed in 2014 and 2015 by LGL Alaska Research Associates. During the 2014 study, fish were observed traveling near the device, but no negative effects from the device were observed. In the 2015 study, 359 fish events were observed during the video period reviewed, involving approximately 1202 individual fish. In general, the fish observed near the device were adult salmon during the day and smolt during the night. Several instances of fish moving through the turbine were observed. No obvious physical injuries to the fish were observed (Nemeth et al., 2014; LGL Alaska Research Associates, 2015).

Performance

The hydrokinetic technologies investigated in this study generate electricity by harnessing energy in flowing rivers. Each system employs a unique geometry of turbines to generate mechanical force from the kinetic energy of flowing water and use that force to turn an electrical generator. The power in watts, P , present in flowing current is calculated by

$$\text{Equation (1): } P = \frac{\rho A v^3}{2} \quad (1)$$

where ρ is the density of the water (~1000 kg/m³), v is the velocity of the current in m/s, and A is the area of flow impacting the turbine in m². Note that the power available in river current increases with the cube of current velocity, meaning that large increases in power can come from small increases in velocity.

Hydrokinetic energy systems are evaluated in a manner consistent with wind turbines. In this report, the power coefficient, C_p , represents the “water to wire efficiency,” the portion of kinetic energy flowing through the turbine that is converted to electricity. C_p is plotted as a function of the tip speed ratio, λ , which is the ratio of the tangential speed of the turbine blade tips to the speed of the river current. Total power output is also presented as a function of river current speed.

Boschma Research, Inc.

BRI testing was hindered by multiple issues that are outlined in the section Lessons Learned. After multiple setbacks, testing occurred during the period of August 30 and 31, 2014. Approximately 36 hours of instrumented testing were completed while providing power to the grid, generating just over 7 kWh and averaging 2.3 kW of power output. The system power output during this period is shown in Figure 11. The experimental power curve is shown in Figure 12. One important point to bear in mind is that detailed river current data were unavailable, and an estimated river velocity of 2.5 m/s is used for this analysis. While not ideal, this estimate was based on the best information available.

Oceana

Testing at the Naval Surface Warfare Center, Carderock Division, David Taylor Model Basin allowed for data collection under highly controlled conditions. The Oceana turbine was installed on a mobile carriage and driven through stationary water in the test channel. The electrical power output of the turbine is plotted as a function of the carriage speed in Figure

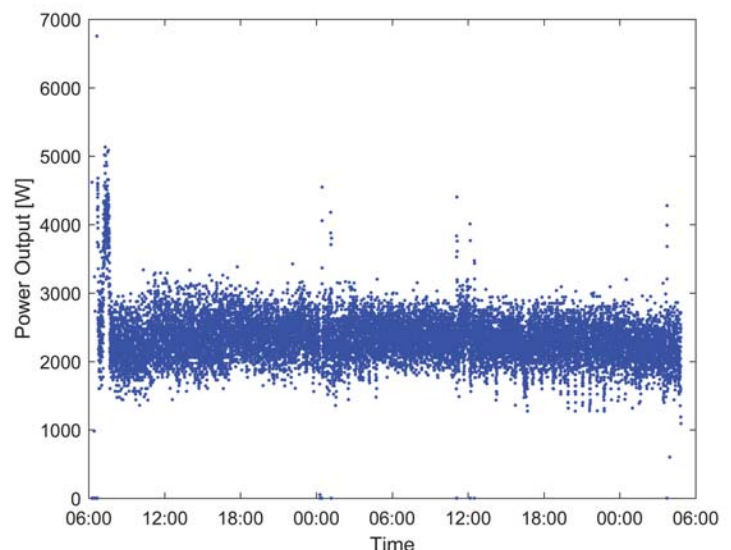


Figure 11. BRI power output August 30 and 31, 2014.

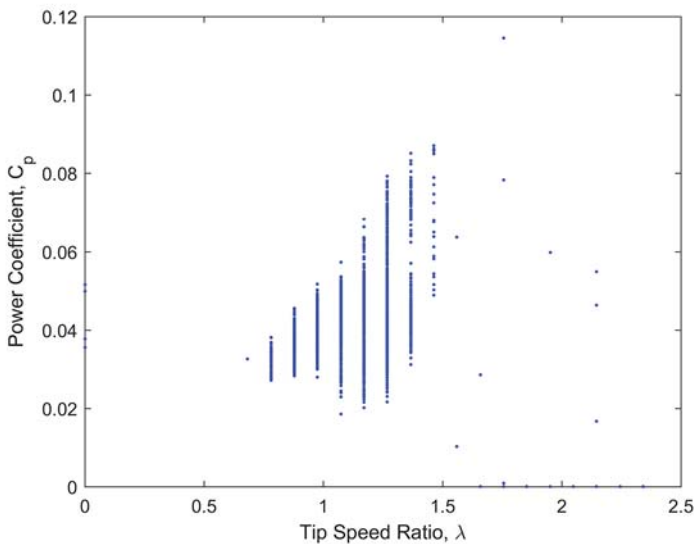


Figure 12. BRI power curve.

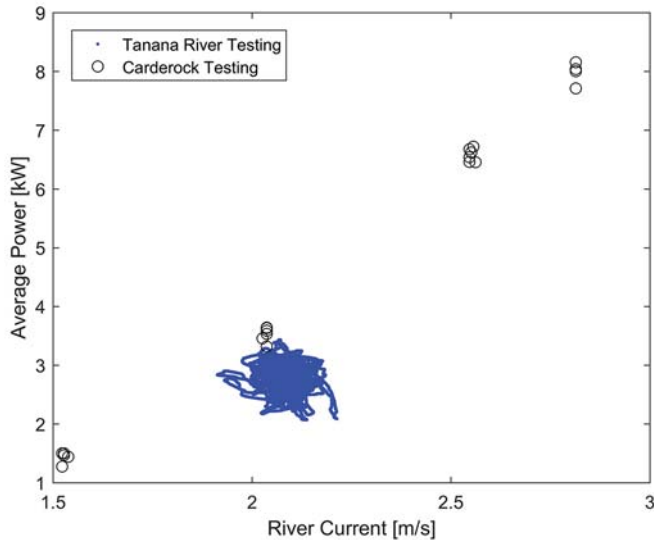
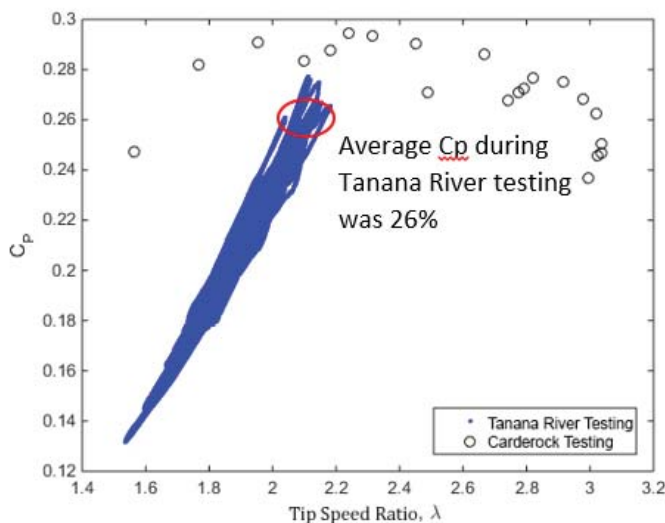


Figure 13. Oceana power output vs. river velocity.



13. The power coefficient, C_p , is plotted as a function of the tip speed ratio, λ , in Figure 14. Peak output of 8 kW was observed at 2.8 m/s (5.5 knots). Peak efficiency of 29.5% was observed at a tip speed ratio of 2.2.

Testing at the Tanana River allowed for evaluation of turbine performance in real-world Alaska riverine conditions. Data were generated during 8 days of testing in September 2014 and 9 days of testing in July 2015. Data collection evolved during testing, with improvements made and measurements added over time. This report specifically analyzes data collected on July 30 and July 31, 2015, a time during which a study by Elan Edgerly (2015) yielded reliable river current velocity data. Edgerly's upstream river current data are used for evaluating Oceana turbine performance. During these two days, 12.4 hours of instrumented testing were completed. The average river current was 3.9 knots (2.0 m/s), and the system averaged 2.9 kW of power, with a peak output of 5.2 kW. Across these 2 days, the Oceana turbine generated 36 kWh and demonstrated an average power coefficient of 26%.

Ocean Renewable Power Company Alaska, LLC

During 2014 testing on the Kvichak River, the ORPC RivGen turbine operated for approximately 80 hours, with total energy generation of 800 kWh. At optimal load bank settings, the system produced an average power output of 13 kW and peak power output of 16 kW. The UW analysis, which accounted for velocity shear across the turbine, reported peak efficiency (C_p) of 27% at a tip speed ratio of 1.6 (Forbush et al., 2016). In 2015, ORPC redeployed an improved version of its turbine with the addition of a lower fairing. This improved unit supplied power to the Igiugig grid during periods of testing, and was able to meet up to one-third of the village's electric load.

Data measured during testing of the ORPC RivGen on the Kvichak River from July 20 through September 30, 2015, were analyzed. River velocity, which is based on algorithms developed by UW researchers, was measured using two acoustic wave and current (AWAC) profilers mounted on the turbine pontoons (see Figure 15). The RivGen system produced power for approximately 310 hours. During this testing, the ORPC turbine averaged 6 kW of power for a total energy generation of 1855 kWh. The highest daily generation average was 9.0 kW, and the peak 1-minute average output was 17.8 kW Figure 16).

The power of moving water is calculated in Equation (1). The V^3 component of the equation means that small changes in flow velocity can have large changes in the available power in moving water. Figure 15 shows the 1-hour average flow

Figure 14. Oceana power coefficient vs. tip speed ratio. Data collected during the Tanana River testing showed a lot of noise, but the average power coefficient was 26% during the two days of testing used to construct this graph.

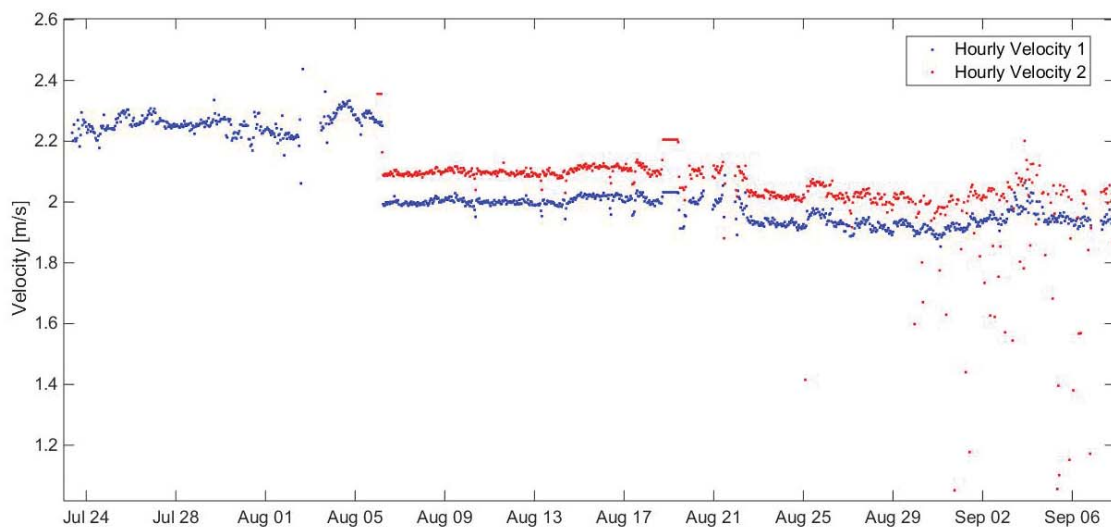


Figure 15. Hourly average river velocities at the RivGen turbine.

velocity as measured from each AWAC device. The cleanest power-production data curves were obtained during July 24. Figure 15 demonstrates that before August 5, only one AWAC was functioning; after this day, the flow velocity appears to drop suddenly. The reason for this is unknown; however, given that two AWACs show lower velocities after August 5, the higher flow velocities before this date are likely related to data collection and do not reflect actual flow velocities in the Kvichak River. Figure 17 shows the difference in the power curve when a reduction in flow velocity of .13 m/s occurs. As a reference, .13 m/s is equivalent to .29 mi/hr.

Lessons Learned

The Emerging Energy Technology Fund (EETF) seeks to advance energy technologies that have an expectation of becoming commercially viable within 5 years. The hydrokinetic system development and testing completed under EETF funding challenged the three systems that operated in remote Alaska rivers. Valuable lessons about each system were learned from the EETF endeavors that will prove critical to the commercialization of the technology.

Boschma Research, Inc.

The BRI system, developed in Alabama, was driven to Anchorage before being flown to Igiugig. The system faced both engineering and logistics challenges throughout its implementation. Transportation delays caused the system to miss the barge leaving from Homer for Igiugig, necessitating the more expensive air transport from Anchorage. Despite having conducted a site visit, the BRI team commented that they were surprised by the remoteness of Igiugig and the difficulties of working in rural Alaska. BRI ran into complications working in the swift currents of the Kvichak River. Initial floatation was insufficient to reduce drag to a level at which available boats could maneuver to position the system, requiring that float bags be purchased and installed.

Mooring lines failed and anchors slipped, causing structural damage to the Venturi section. Ultimately, the system suffered catastrophic failure due to bushing misalignment attributed to damage sustained during the anchor slippage incident. While ORPC and Oceana either contracted out the barge used to lower the machine and associated mooring systems, or in the case of ORPC spent years testing a pontoon structure on which the actual turbine unit would be mounted, BRI spent significant time struggling to deploy its turbine in the swift waters of the Kvichak River. It is a testament to the skill and determination of the workers on the ground that they were able to extract power from the river and connect the turbine to the grid.

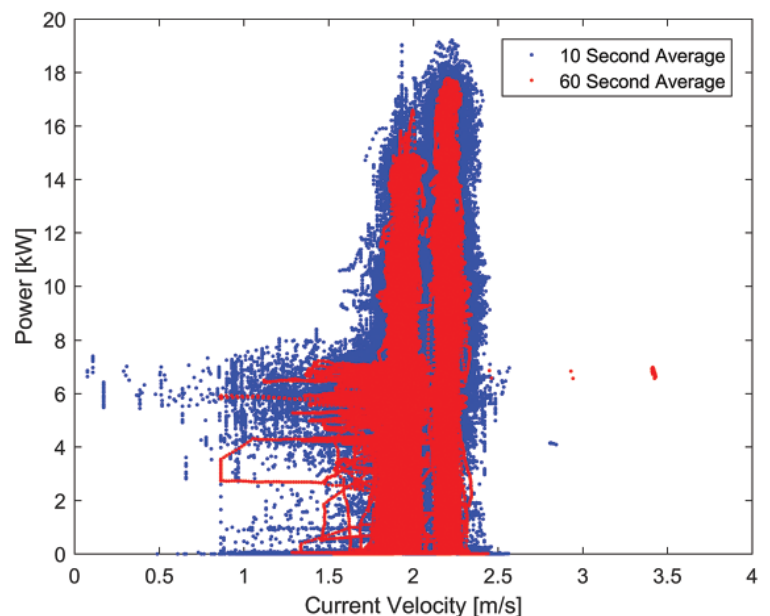


Figure 16. ORPC power output vs. current velocity.

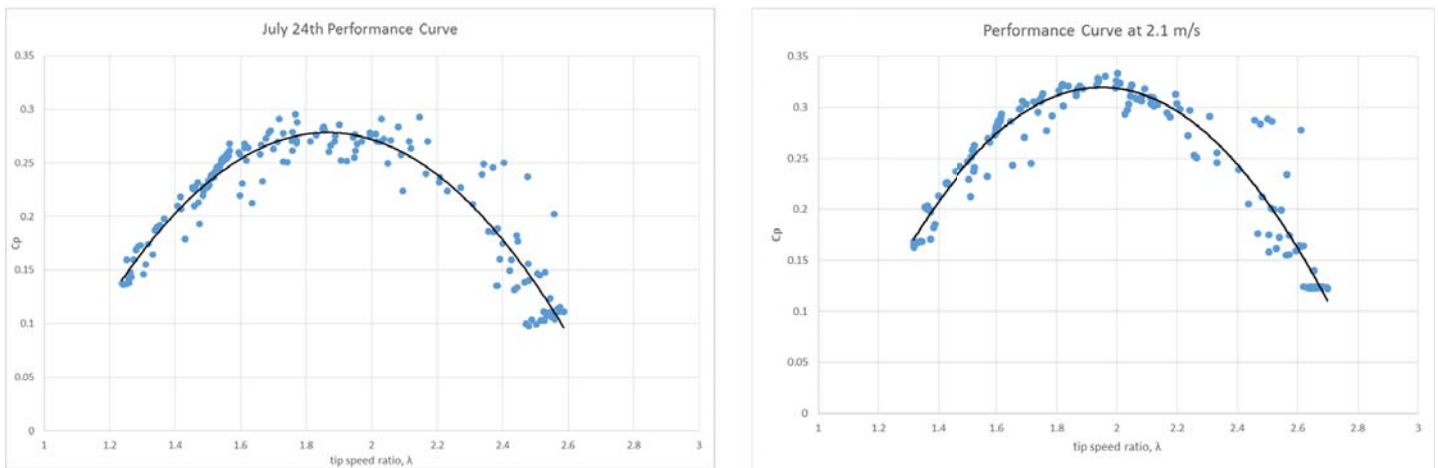


Figure 17. July 24, 2015, data (cleanest day of data) and average recorded flow velocity of 2.23 m/s (left). The curve in the right panel shows the same data at a flow of 2.1 m/s. In this scenario, the coefficient of performance increases to 33%. A discussion on the rationale for this change is found in the description of the ORPC RivGen performance.

Oceana

Oceana's testing involved using the AHERC test barge and debris diverter. The debris diverter, combined with research on debris flow in the river, spared the system from surface debris impacts. One impact by a submerged log was observed, though operation of the device was not interrupted and no significant damage was caused. Oceana reported that the design and testing effort resulted in several ideas for design and assembly improvements to simplify the system and increase its robustness. River turbulence magnitude was more significant than expected, although within the capabilities of invertors. Data collection was suspended several times during testing because of system damages from stray voltages. Oceana recommends optical isolation of sensors in future testing.

Ocean Renewable Power Company Alaska, LLC

ORPC's testing developed and demonstrated the ability to deploy the hydrokinetic turbine to the river bottom and retrieve it in swift-moving current. The system is mounted on two long pontoons that allow the turbine to be floated into position. When positioned and moored to upstream anchors, the pontoons are flooded and the system is sunk to the river bottom. The anchor lines are run through a load-equalizing chain block to accommodate variations in anchor placement. ORPC developed this integrated pontoon structure during extensive multi-year testing in Cook Inlet at Nikiski, Alaska. Testing the pontoon support structure in a tidal environment proved beneficial, because the strong tides of Cook Inlet simulated a fast-moving river, and the slack tides enabled the deployment and retrieval of equipment.

During testing in 2014, the RivGen device stopped spinning and was retrieved for inspection; the system brake had engaged and would not release. Troubleshooting revealed that while significant sediment had accumulated around the cable connectors, the sediment had not affected the actual electrical

contacts. The generator casing was tested and found to hold a vacuum, indicating that no leaks had occurred. Ultimately, it was found that the data cable had come under strain and partially disconnected. Alleviating the strain caused the brake to release, and the system was redeployed.

University of Washington researchers collected field measurements of river velocity, turbine acoustic behavior, and fish monitoring. Their velocity measurements showed significant variation in river current velocity across the turbine, ranging at one time from 1.5 m/s on the starboard end to 2.5 m/s on the port end, indicating that available hydropower was more than 4 times greater on the port end than the starboard end. This velocity gradient impacts the calculation of the turbine power coefficient and power curve, and required the development of an experimental velocity algorithm (Forbush et al., 2015).

The ORPC turbine was deployed for two seasons on the Kvichak River near Igiugig, and lessons learned during testing in 2014 allowed ORPC to make several modifications prior to deployment in 2015.

During the 2014 testing, a solar inverter was used to attempt to invert the rectified power coming from the turbine to grid quality AC power. The inverter would not accept the power coming from the turbine generator and, thus, never successfully sent power to the grid. Before the testing season in 2015, seals and bearings were evaluated for wear, and the turbine system was refurbished. A lower fairing was added to the RivGen device to enhance energy extraction efficiency. A new DC filter design was implemented and used with the inverter, which was verified with the RivGen generator in a simulated diesel test bed constructed at Marsh Creek facilities in Anchorage prior to shipping the system components to Igiugig. The pontoon ballast chamber filling and purging systems were upgraded and additional cleats and mooring pad-eyes were added.

Findings and Conclusions

As EETF funding strives to develop pre-commercial technologies, it is important to consider both the demonstrated technology successes and the lessons learned through failures.

Table 1 presents the demonstrated performance of the three tested hydrokinetic systems, including peak power, peak efficiency, and total energy generation. Figure 18 plots the power curves of all datasets for comparison. The power curves show that a realistic expectation of power coefficient is between 25% and 30%. Just as with wind turbines, however, the most robust turbine—not necessarily the most efficient one—will have the advantage in Alaska installations.

The three projects funded by the EETF were performed in conjunction with academic research efforts to further the understanding of river environments and hydrokinetic systems, and the interactions of both. Work by UW, UAF, and AHERC has advanced the understanding of river velocity and turbulence and their influence on turbine performance. AHERC and BRI demonstrated a successful debris-diversion mechanism, which

was able to shed large debris and avoid a strike to the barge that deploys the turbine. It is unknown if the BRI debris-diversion system was subjected to a debris strike to fully test its effectiveness. With U.S. Department of Energy funding, UAA and ORPC researchers performed scientific analysis of bearing wear rates due to suspended sediments. Fish studies have not yet indicated significant environmental effects from hydrokinetic turbines, although new studies should be performed with every installation.

To achieve successful commercialization and operation in Alaska, hydrokinetic technologies would benefit from the lessons learned to date. Anchoring systems must be improved, and the complexity of installation and removal must be reduced. The mitigation of debris hazards must continue to improve, and the performance of bearings and seals in abrasive environments must be ensured. Hydrokinetic technology, while in many ways similar to wind turbines, benefits from river energy sources being steadier and far more predictable than wind. For small remote communities, hydrokinetics show good prospects for reducing consumption of expensive imported fuels.

Table 1. Demonstrated performance

	Rated Power	Peak Demonstrated Power		Total Data Used for Analysis	Total Energy	Best Efficiency	
	kW	m/s	kW	hr	kWh	λ	CP
BRI – 2014	5	2.5 est ¹	4.6	36	7	1.5	.09
Oceana – Carderock	17	2.81	8.15	n/a	n/a	2.2	.29
Oceana – 2015 Nenana	17	2.07	3.43	12.4	36 ²	2.1	.28
ORPC – 2015	50	2.2 ³	17.8	310	1855	1.9	.33 ⁴

Notes:

¹No flow velocity was measured by BRI. Velocity of 2.5 m/s was reported to Jim Boschma by UW.

²The 36 kWh of energy shown only accounts for the 12.4-hour period that was used for analysis. In total the turbine generated power whenever it was deployed in the water during 2014 and 2015.

³The river velocity at peak output was measured at 2.2 m/s; however, it appears based on the dataset that actual velocity was slightly lower, around 2.1 m/s.

⁴The Cp of 33% was based on an assumed flow velocity of 2.1 m/s.

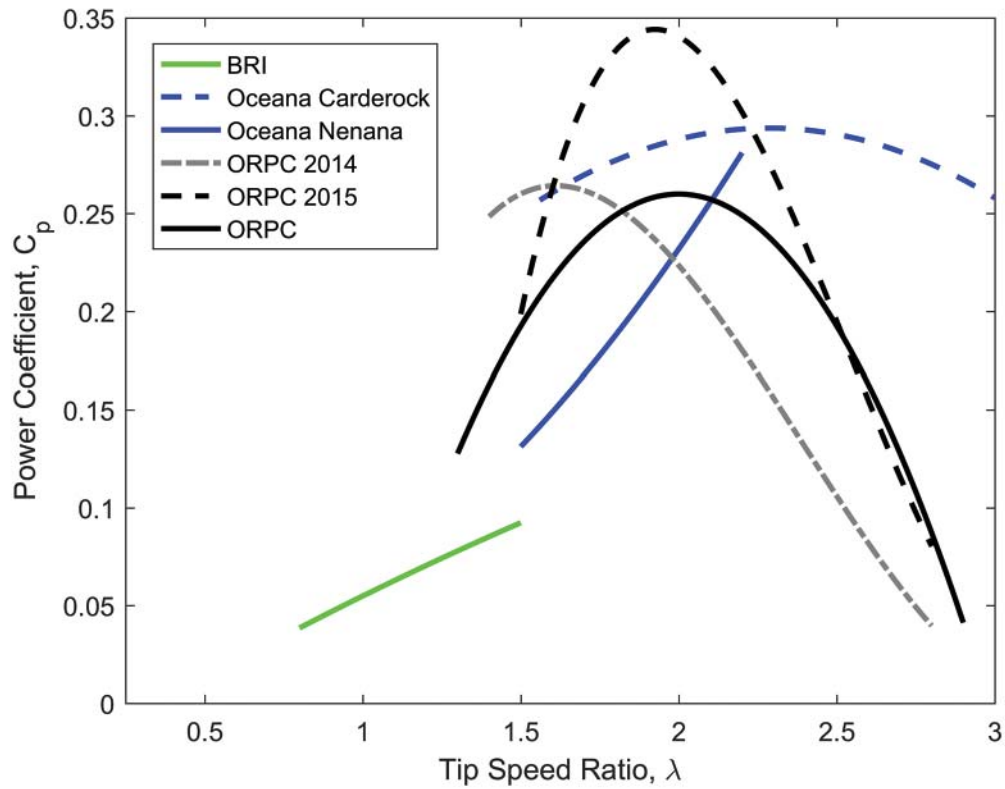


Figure 18. Power curve comparison of hydrokinetic systems. The solid lines were calculated by ACEP. The Oceana Carderock dashed line was calculated by the manufacturer. ORPC 2014 and ORPC 2015 dashed lines were plotted by the University of Washington.

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