In-Stream Hydrokinetic Power: Review and Appraisal

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Abstract: The objective of this paper is to provide a review of in-stream hydrokinetic power, which is defined as electric power generated by devices capturing the energy of naturally flowing water—stream, tidal, or open ocean flows—without impounding the water. North America has significant in-stream energy resources, and hydrokinetic electric power technologies to harness those resources have the potential to make a significant contribution to U.S. electricity needs by adding as much as 120 TWh/year from rivers alone to the present hydroelectric power generation capacity. Additionally, tidal and ocean current resources in the U.S. respectively contain 438 TWh/year and 163 TWh/year of extractable power. Among their attractive features, in-stream hydrokinetic operations do not contribute to greenhouse gas emissions or other air pollution and have less visual impact than wind turbines. Since these systems do no utilize dams the way traditional hydropower systems typically do, their impact on the environment will differ, and a small but growing number of studies support conclusions regarding those impacts. Potential environmental impacts include altered water quality, altered sediment deposition, altered habitats, direct impact on biota, and navigability of waterways. **DOI: 10.1061/(ASCE)EY.1943-7897.0000197.**

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Introduction

Purpose

The objective of this paper is to provide a review of in-stream hydrokinetic power, which is defined as electric power generated by devices capturing the energy of naturally flowing water—stream, tidal, or open ocean flows—without impounding the water. The intent is to summarize the state of the engineering science and art for the United States so as to provide a foundation from which new developments can be launched and evaluated.

Background

Traditional hydropower is a proven power source within the United States that, in the early part of the 20th century, generated nearly half of the nation's electricity. In 2009, a robust hydropower capacity of 75,000 MW constituted only seven percent of the U.S's electrical capacity, but it was still the fourth highest amount of electrical power generation by source within the United States. Hydroelectric power is a reliable and proven source of energy that contributes to the stability and reliability of the United States electric grid due to its flexible generation potential (U.S. Energy Information Administration 2010; United States Geological Survey 2014).

While maintenance and operation costs are low, construction of these plants requires a large initial investment to support the construction of a large infrastructure consisting of a dam, reservoir, turbines, and generators. However, construction on new hydroelectric power plants has waned, not because of the capital cost and environmental impacts, but mainly due to the lack of available resources (USGS 2011). The Department of Energy (DOE) estimated that in 49 states there are 5,677 sites with an undeveloped capacity of approximately 30,000 MW, averaging only 5 MW of capacity per site (EERE 2010). A more recent assessment lowered the practical available capacity to 12,000 MW (Hadjerioua et al. 2012).

In order for the United States to increase the amount of electricity generated by water, new technology is needed to harness the power of the waves, rivers, tides, and ocean currents. North America has significant in-stream energy resources, and hydrokinetic electric power technologies to harness those resources are

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available. Thus this industry has the potential to make a significant contribution to U.S. electricity needs by adding as much as 13,700 MW (EPRI 2012) to the present 78,000 MW of hydroelectric power capacity (Hadjerioua et al. 2012) generated from riverine resources. Additionally, U.S. tidal and ocean current resources respectively contain 50,000 MW (Georgia Tech 2011) and 18,600 MW (Georgia Tech Research Corporation 2013) of extractible power. Among their attractive features, in-stream hydrokinetic operations do not contribute to greenhouse gas emissions or other air pollution and because the installations are underwater, they have less visual impact than wind turbines. Since these systems do not utilize dams the way traditional hydropower systems typically do, their impact on the local ecosystem will differ and is presently not well documented. The first U.S. in-stream hydrokinetic installations were on the Yukon River in Ruby, Alaska, on the Mississippi River just below Hastings, Minnesota, and on the East River in New York City. More recent installations also exist, and the Federal Energy Regulatory Commission (FERC) has issued or is considering permits for over 100 studies of potential hydrokinetic installations in 15 states from coast to coast, as of March 2013 (Fig. 1).

Hydrokinetic Power Generation

Principles

Moving water such as rivers, tidal channels, and ocean currents often contain a significant amount of kinetic energy. The kinetic energy flux in a fluid flow can be calculated from

$$E_k = \frac{1}{2}\rho A V^3 \tag{1}$$

where ρ is the density of the fluid, A is the cross-sectional area perpendicular to the flow, and V is the flow speed. Using this relationship, it can be seen that a water flow with a density of 1,025 $\mathrm{kg/m^3}$ only needs to have a velocity that is 10.6% that of an air flow with a density of 1.22 $\mathrm{kg/m^3}$ to have the same kinetic energy flux. Some of this kinetic energy can be converted to electrical energy using electro-mechanical energy extracting systems. The majority of these energy extracting systems produce electrical energy by using the moving water to rotate a rotor coupled to a generator, typically via a gear box or hydraulics. The fundamental operating principles of these systems are the same as most wind turbines: lift forces from rotor blades, comprised of varying hydrofoil

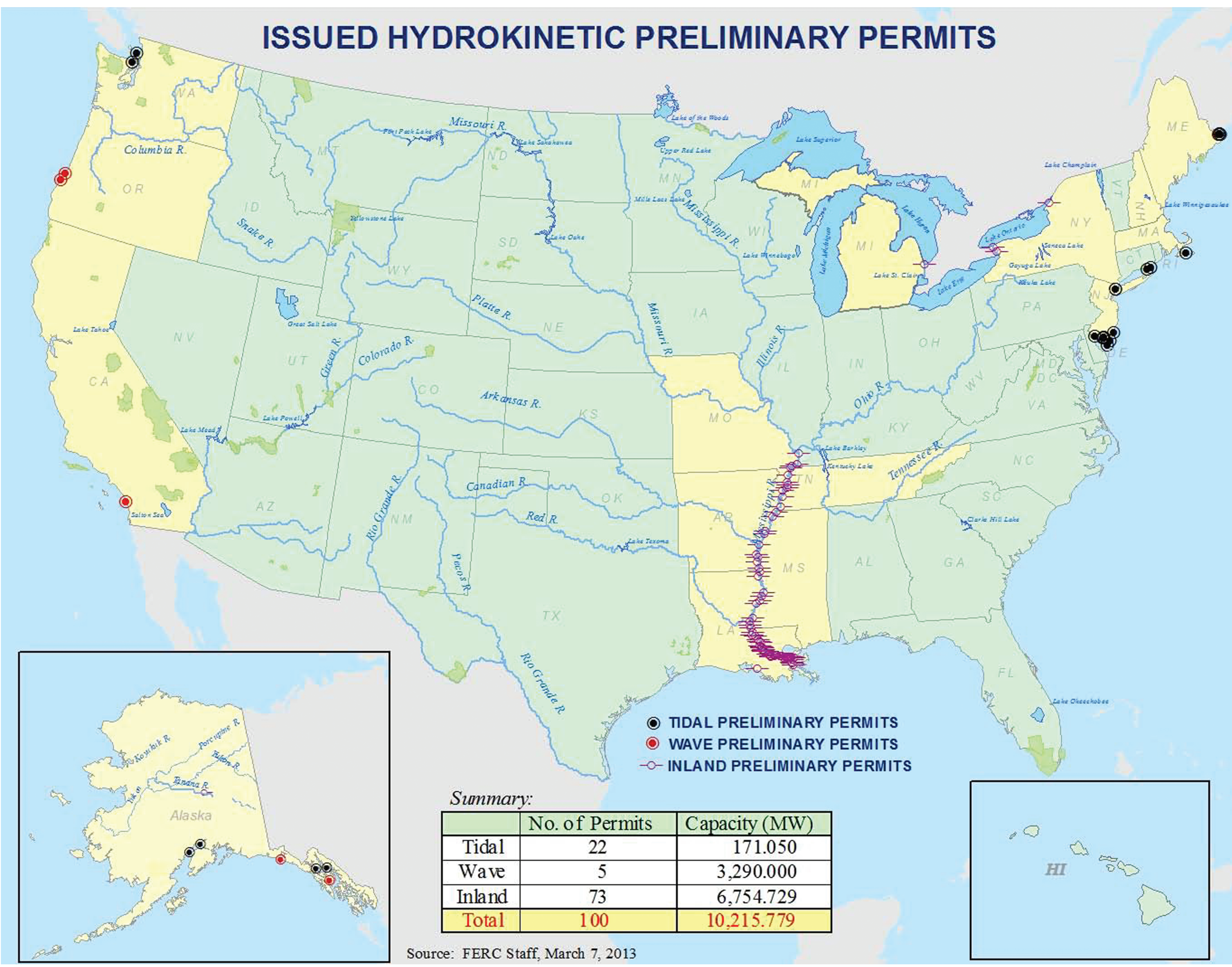

Fig. 1. (Color) Map of FERC permits in 2013 (FERC 2013)

shapes, create a net torque about the rotor's shaft, causing it to rotate. Once rotating near the rotor's design speed, the hydrofoils will all be producing near peak lift forces. The kinetic energy that is converted to mechanical energy at the rotor shaft (shaft power) is calculated by

$$P_S = \omega\tau \quad (2)$$

where τ = torque and ω = rotational velocity of the rotor. For horizontal axis turbines, the theoretical maximum amount of shaft power, or power coefficient, that can be extracted from an unrestricted flow is called the Betz limit, which has a value of 59.3% (Sheets 1974). The percent of the power that can typically be extracted from a flow by a single device (hydrodynamic efficiency) will be significantly below the Betz limit; model testing of a representative marine tidal turbine resulted in a peak rotor efficiency of 46% (Bahaj et al. 2007). Using this rotor efficiency and a water density of $1{,}025\ \mathrm{kg/m^3}$, a 1-m-diameter rotor will produce a shaft power of 0.624 kW in a 1.5 m/s current and 2.89 kW in a 2.5 m/s current, while a 10-m-diameter rotor will produce a shaft power of 62.5 kW in a 1.5 m/s current and 289.3 kW in a 2.5 m/s current.

Alternative designs exist that do not use rotors. These designs can use the fluid flow to produce oscillatory motions, either linear or partial rotations, on system components to generate electric power. Cylinders, air-foils, or bio-inspired shapes are often considered in these designs, and fluid flow phenomenon such as vortex shedding are sometimes utilized to induce the oscillatory motion.

Equipment

Over the past few decades, numerous entrepreneurs and inventors have come up with a wide variety of systems designed to extract power from river, tidal, or open-ocean currents. Most of these systems can be grouped into two main design types. The most common turbine design type is the horizontal axis turbine, where the rotor axis is parallel with the current (Fig. 2). Several turbines are also designed with the rotor axis perpendicular to the flow, such as the one shown in Fig. 3. Alternative designs also exist that do not fit into either of these design types because they do not utilize rotors. One such system utilizes vortex induced forces to oscillate cylinders perpendicular to the flow.

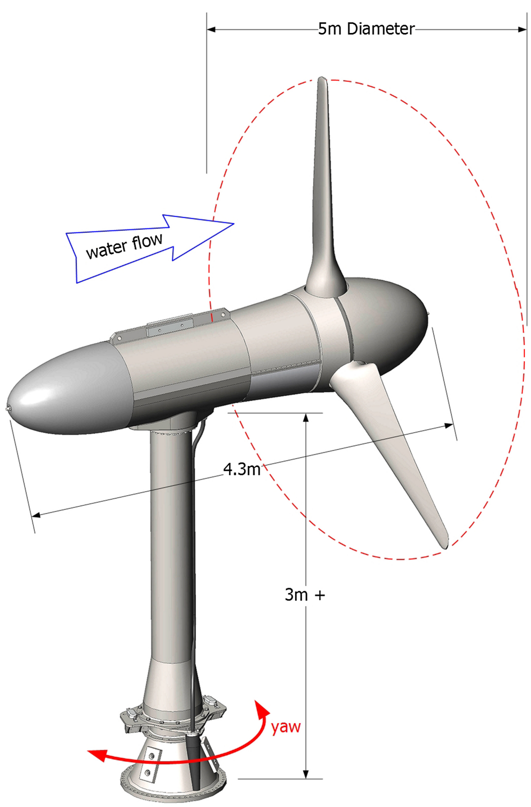

Fig. 2. Verdant Power's single Gen5 turbine drawing (Verdant Power 2014, with permission)

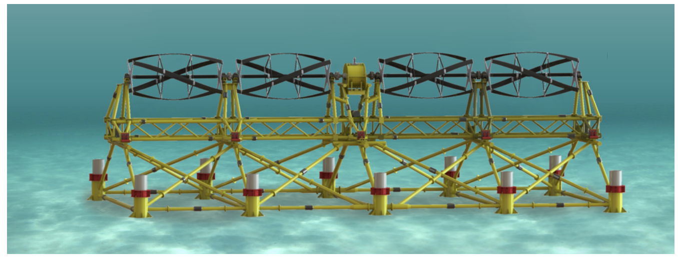

Fig. 3. Ocean Renewable Power Company's TidGen Power System (TidGen Power System, with permission from Ocean Renewable Power Company 2014)

Many technological advances associated with in-stream hydrokinetic power production have originated in the UK, with several other countries including Canada, the United States, and Australia contributing to the industry. Overviews of companies that are developing these technologies are presented by Johnson and Pride (2010) and Department of Energy (2013a). Johnson and Pride (2010) provide information on 21 companies that have developed horizontal axis systems to technology stages between scale model sea trials and commercial. They also provide information on six companies with vertical axis systems developed to technology stages between scale model sea trials and full scale prototypes and four companies with alternative designs developed to technology stages from conceptual to scale mode sea trials. The Department of Energy (2013a, b) has a searchable database that provides information on both companies and projects. Included in this database are eight companies that have in-stream hydrokinetic systems that were classified as deployed and grid connected and nine companies that have technologies that are at the device testing/commissioning stages for pilot projects. The project capacity planned for these systems extend into the MW range, with six companies suggesting project capacities of 10 MW (Department of Energy 2013a).

Some of the many hydrokinetic energy-harvesting devices that have been developed and tested for relatively shallow water tidal/river currents, include those developed by: Verdant Power (2014), Marine Current Turbines (2013), Hammerfest Strom (2013), Nautricity (Clarke et al. 2009), Ocean Renewable Power Company (2014), Free Flow Power (2013), Vortex Hydro Energy (2013), and the Korean Ocean Research and Development Institute (Yi et al. 2009). Of these designs, the hydrokinetic current turbines developed by Verdant Power (Fig. 2), Marine Current Turbines, and Hammerfest Strom are axial flow horizontal axis turbines that are similar in many ways to standard wind turbines. Nautricity has an axial flow horizontal axis turbine with two co-axial counter-rotating blades, while Free Flow Power has a horizontal axis turbine that is enclosed in a shroud. The Ocean Renewable Power Company (Fig. 3) and the Korean Ocean Research and Development Institute have designed turbines with helical designs, such that the rotor shaft is perpendicular to the flow. The only system listed by Johnson and Pride (2010) and Department of Energy (2013) as having undergone field trials that does not use a rotor is the VIVACE system. This system uses vortex-induced forces to move cylinders perpendicular to the flow (Vortex Hydro Energy 2013).

Most tidal and river in-stream hydrokinetic devices are either rigidly attached to the channel floor or attached to a floating platform, such as a barge. Examples of barge-mounted turbines are the relatively small-scale vertical axis devices deployed in Ruby and Eagle Alaska, which were mounted to the center of moored catamaran barges (Johnson and Pride 2010). This mounting configuration keeps the electronics above the water line, which minimizes both equipment and maintenance costs. Drawbacks to this mounting approach include the installations being easily visible and the fact that power cables often need to be run from the floating platform to the river bed before running to shore, leaving them exposed to possible entanglement with floating and midwater debris. Bottom mounted devices can either be partially or complete submerged. The tidal device deployed by Marine Current Turbines (2013) is attached to a monopile, with the control room above the water. The two horizontal axis rotors on the system can be lowered into the water during normal operation or pulled out of the water for maintenance. While this does have the surface signature of a single pylon, it is much smaller than if the system were mounted from a floating platform. Alternatively, the bottom-mounted tidal devices deployed by Verdant Power (2014) were completely submerged. While systems such as these are attractive for many reasons, maintenance and monitoring can be challenging.

Device designs are typically driven by site-specific requirements, including water depth and flow characteristics. The flow type, tidal verses non-tidal, is an important topic to consider. Non-tidal flows are nearly unidirectional; therefore, devices are optimized to take advantage of the known flow direction. The magnitudes of these flows are driven by snowmelt or rainfall and therefore are more seasonal and event-driven. Because specific events contribute to the magnitude of these flows, the power is less predictable than tidal flows. However, most large river systems that are good candidates for in-stream hydropower will be able to produce power year-round. Conversely, devices deployed in tidal flows are typically designed to produce power from flows coming in two discrete directions. Vertical axis systems are not typically impacted by flow direction, and their performance does not degrade in these flows. However, it is important to note that vertical axis systems have higher drag loads and reduced power coefficients compared to their horizontal axis counterparts (Ragheb 2011). Horizontal axis turbines are more impacted by a change in flow direction, and therefore these devices often have rotors that have similar efficiencies regardless of the flow direction [OpenHydro (2013) for example] or rotate so that the propeller is always oriented in the optimal direction [Verdant Power (2014) and Nautricity (Clarke et al. 2009) for example]. Since tidal cycles are the primary drivers of these flows, the power potential for these installations is more predictable. However, systems operating in tidal flows do have a period of time between tidal cycles when no power is produced.

No deep water Ocean Current Turbine (OCT) has been evaluated in deep water currents for longer than a couple of hours. On-site prototype testing for turbines designed to operate in deep water offshore currents includes only the Vertical Axis Hydro Turbine, which was developed by Nova Energy Limited and the National Research Council of Canada (Davis et al. 1986). This turbine was successfully tested in the Gulf Stream from an anchored vessel during a one day mission in April 1985. While no experimental or prototype systems have been tested on-site over the past few decades, several companies are developing technologies to harness this resource. The Ocean Renewable Power Company is planning to adapt its tidal energy devices so that they can be used in the Gulf Stream (Ocean Renewable Power Company 2014) and has obtained six preliminary permits from FERC for ocean current energy sites off Southeast Florida (Department of Energy 2011). Other companies such as Aquantis LLC (2011), the THOR Energy Group (2011), and Cyclo Ocean (2011) are developing technologies specifically to harness ocean currents. These systems are being designed so that they can vary their depth and are designed to be moored to the sea floor using flexible mooring lines. With some modifications, tidal devices such as the singled point moored tidal turbines marketed by Nautricity (Clarke et al. 2009) and ADAG (2012) may also be transferable to the offshore environment. As these systems are nearing the offshore testing phases, infrastructure is being developed to test these systems offshore Southeast Florida near the core of the Gulf Stream (SNMREC 2013).

Power Potential

Hydrokinetic resources applicable for producing in-stream hydrokinetic power can be divided into three primary categories: tidal flows, rivers and streams, and ocean currents. Each of these represents a significant energy resource that could significantly impact the power portfolios in the regions where they are located. To help quantify the potential of these resources along with the locations where they exist, the Department of Energy funded national resource assessment projects for each of these resources. These projects rigorously predicted the national potential for each of these resources, as well as create publicly available geographic information system (GIS) databases that map them (Department of Energy 2013b).

In the United States, the tidal energy locations with the largest power potential can be found in northern locations such as: Maine, Puget Sound in Washington State, and Alaska (Previsic 2009). Detailed information on U.S. tidal resources is available from the Georgia Tech (2011) with the predictions in this report made using the ocean circulation numerical model (ROMS). These numeric predictions were used to calculate both tidal hotspots nationwide and the total available power on estuary scales, which were summed to yield statewide and national tidal potential estimates.

The hotspots in this study are defined as areas where the annually averaged power density is at minimum 500 W/m^2, the water depth is at least 5 m, and the surface area where these two criteria are met is over 0.5 km^2. Nationally, 151 hotspots are identified in this study, and this number would have been more than triple if the size criterion were relaxed (Georgia Tech 2011). These hotspots are located in Alaska, Maine, Washington, Oregon, California, New Hampshire, Massachusetts, New York, New Jersey, North Carolina, South Carolina, Georgia, and Florida (Georgia Tech 2011).

This study also calculated total theoretical available power estimates. The analytic methods used to create these estimates came from Garrett and Cummins (2005). This method accounts for the cumulative effects of dissipating energy and provides information on an estuary scale. Using this approach, the national available energy from tidal streams is calculated at 50 GW, with 47 GW of this power potential located in Alaska (Georgia Tech 2011). In Alaska, Cook Inlet has the maximum calculated available power (18 GW) and Chatham Strait has 12 GW (Georgia Tech 2011). Following Alaska, other U.S. states have the following estimated power potential: Washington (683 MW), Maine (675 MW), South Carolina (388 MW), New York (280 MW), Georgia (219 MW), California (204 MW), New Jersey (192 MW), Florida (166 MW), Delaware (165 MW), Virginia (133 MW), Massachusetts (66 MW), North Carolina (66 MW), Oregon (48 MW), Maryland (35 MW), Rhode Island (16 MW), and Texas (6 MW) (Georgia Tech Research Corp

2011). This report identifies the specific locations where these resources are located within each state. The tidal energy estimates throughout the United States can be easily viewed graphically using a GIS database (Georgia Tech 2011). These estimates are not sufficiently detailed to evaluate individual project economic justifications, which are specific to the site, equipment, and demand and must account for downtimes for any reason. The purpose of these estimates is to identify the potential for power generation and provide a relative comparison of where projects might be feasible.

New York University conducted a U.S. DOE-funded in-stream resource assessment for rivers systems in the United States, with the final report published in August 1986 (Miller et al. 1986). This resource assessment only considered rivers with volumetric flow rates greater than 113.3 m^3/s (4,000 ft^3/s) and mean velocities greater than 1.31 m/s (4.3 ft/s). For river sections that met these criteria, this study assumed that 1/16 of the rivers' cross-sectional area was occupied by turbine arrays, with each device having an efficiency of 40%. Within these arrays, this study assumed that each device had a diameter equal to 80% of the water depth and that devices were separated by ½ of a diameter across the flow and 5 diameters down-stream. Using these assumptions, the average estimated power potential from all U.S. rivers is 12,600 MW. This study also estimated the average power potential for 16 distinct regions within the United States with an estimated 4,500 MW for Alaska; 3,200 MW for the Northwest United States including northern Washington State, northern Idaho, and western Montana; and up to 1,500 MW in each of the other regions.

Assessment of potential river flow contributions to electrical power generation was also obtained (EPRI 2012) by applying a form of Eq. (1) to data on the lower 48 states' rivers from the USGS National Hydrography Dataset provided with the National Map enhancements (USGS 2013) and various sources on Alaskan Rivers. For rivers with mean flows of over 93 m^3/s (1,000 ft^3/s) and water depths greater than 2 m (95% of the time), the theoretical power general potential was 1,381 TWh/year for the continental United States. The technically recoverable fraction of this potential was estimated at 120 TWh/year (an average power of 13,700 MW, 9% greater than the New York University study) by using the Corps of Engineers' Hydrologic Engineering Canter's-River Analysis System (HEC-RAS) numerical hydrodynamic model (USACE 2013) to account for flow statistics, maximum number of devices, and device efficiency, etc., and an empirical recovery coefficient (EPRI 2012). Table 1 shows the distribution of theoretical and technically recoverable power by region.

Ocean currents can be found throughout the world's oceans with the greatest electricity-producing potential primarily found in western boundary currents. These currents can contain significant amounts of extractable energy, with the entire Gulf Stream current system having an estimated 44 GW of theoretically extractable energy (Yang et al. 2013). Of this resource, it is estimated that about 5.1 GW can be extracted from the Florida Current portion of the Gulf Stream alone extracted (Georgia Tech Research Corporation 2013). If the entire portion of the Gulf Stream within 200 miles of the U.S. coast from Florida to North Carolina is considered, then 18.6 GW can be extracted (Georgia Tech Research Corporation 2013).

To help estimate the average amount of power that a single device, or small array of devices, could produce, data from the hybrid coordinate ocean model (HYCOM) ocean circulation model (HYCOM 2012) is utilized. These data are taken from water velocity snapshots calculated each day for 00h GMT, and do not include tidal components. HYCOM is a three-dimensional, real-time, ocean prediction simulator with a global 1/12° resolution (Chassignet et al. 2009). The HYCOM versions (90.6, 90.8 and 90.9) used to calculate the values represented pictorially in this paper assimilate observed data from both historical and near real-time measurements collected by satellites and in situ instruments (ocean currents, sea-surface temperature and sea-surface height), conductivity temperature and depth sensor (CTDs) and moorings (temperature and salinity profiles), and the Special Sensor Microwave Imager (Chassignet et al. 2007). The four vertical coordinate schemes utilized by HYCOM in different regions are one of its notable features, and these include: an isopycnal structure utilized for deep ocean modeling, constant depth or pressure schemes utilized for mixed layer modeling, terrain-following coordinate approach utilized for coastal regions, and level coordinates utilized for very shallow regions.

Table 1. Theoretical and Technically Recoverable River Power by Region for the Continental United States (EPRI 2012, with permission)

Hydrologic region	Theoretical power (annual energy, TWh/year)	Technically recoverable power (annual energy, TWh/year)
New England	14.4	0.2
Mid Atlantic	33.5	1.0
South Atlantic Gulf	38.5	1.2
Great Lakes	6.2	0.01
Ohio	79.2	6.9
Tennessee	20.4	1.0
Sauris Red-Rainy	1.8	0.03
Upper Mississippi	47.0	5.1
Lower Mississippi	208.8	57.4
Texas Gulf	8.9	0.05
Arkansas Red	45.1	1.3
Lower Missouri	79.8	5.6
Upper Missouri	74.3	2.8
Rio Grand	29.5	0.3
Lower Colorado	57.6	3.9
Upper Colorado	46.9	1.1
Great Basin	6.9	0
California	50.9	0.7
Pacific Northwest	296.7	11.0
Alaska	235	20.5
Total	1,381	119.9

HYCOM data utilized for this analysis were taken for a depth of 50 m. This depth was chosen as it will be an approximate operating depth for ocean current turbines as they will typically be operated below the impact of ship traffic and surface waves, while remaining as close as possible to the sea surface where ocean currents are typically the strongest. The kinetic energy flux [Eq. (1)] is calculated each day from January 1, 2009 to December 31, 2011, averaged over these three years, and presented in Fig. 4 (VanZwieten et al. 2013). The white areas are the locations where the water depth is less than 50 m, the grey areas are those where the mean kinetic energy flux is less than 0.5 kW/m^3, and the black rectangles are the eight regions with the largest areas where the kinetic energy flux is greater than 0.5 kW/m^3. This cutoff was chosen to be consistent with the definition of hotspots used in the tidal resource assessment (Georgia Tech 2011). Globally, at a depth of 50 m, 844,500 km^2 is calculated to have a kinetic energy flux over 0.5 kw/m^2, 87,600 km^2 has a kinetic energy flux over 1.0 kw/m^2, and 14,300 km^2 has a kinetic energy flux over 1.5 kw/m^2 (VanZwieten et al. 2013). For each of the selected eight regions, the maximum temporally averaged kinetic energy flux are as follows: 1.93 kW/m^2 off the SE U.S. mainland, 1.78 kW/m^2 off Japan, 1.66 kW/m^2 off SE Africa, 1.57 kW/m^2 off the Philippines, 1.34 kW/m^2 off NE Africa, 1.08 kW/m^2 off Northern Brazil, 0.86 kW/m^2 off Eastern Madagascar, and 0.73 kW/m^2 off eastern Australia (VanZwieten et al. 2013). It is worth noting that

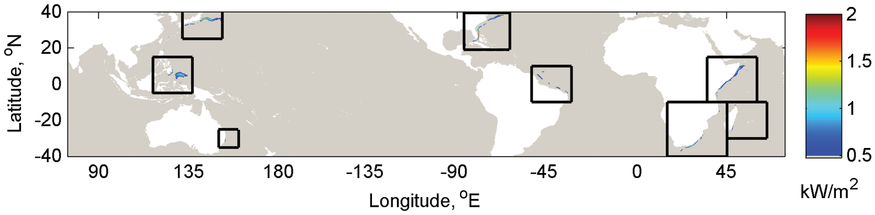

Fig. 4. (Color) Three year averaged (2009–2011) HYCOM calculated kinetic energy flux. The white areas are the locations where the water depth is less than 50 m, the grey areas are those where the mean kinetic energy flux is less than 0.5 kW/m^3, and the black rectangles are the eight regions with the largest areas where the kinetic energy flux is greater than 0.5 kW/m^3

the HYCOM model has been shown to slightly underestimate resources at several locations and therefore these can be viewed as conservative estimates.

The portion of the Gulf Stream off the coast of southeast Florida is located between Florida and the Bahamas near a major load base. Water velocity measurements taken over a 19 month period during 2001 and 2002 show that approximately 21 km from the coast of Southeast Florida, there is a mean water speed of 1.6 m/s near the surface, with this near surface speed ranging between 0.2 and 2.4 m/s (Raye 2002). A second set of measurements taken at a nearby location over a 13 month period during 2009 and 2010 also show a mean water speed of 1.6 m/s near the surface, with a similar surface speed range of between 0.4 and 2.5 m/s (VanZwieten et al. 2011). While it is neither feasible nor desirable to extract all of the energy from an ocean current, the kinetic energy flux does give an idea of the magnitude of these flows. The entire average kinetic energy flux in the portion of the Gulf Stream, between southeast Florida and the Bahamas, has been estimated by Duerr et al. (2012) at 19 GW. The Kuroshio Current off the coast of Taiwan has lesser kinetic energy flux, with an estimated value of 5.5 GW at several representative cross sections (Chen 2010). While an estimate of the kinetic energy flux of the Agulhas current could not be found, this current is suggested to have the largest volumetric transport of any western boundary current and a mean water velocity near the surface of 1.2 m/s (Bryden et al. 2005).

U.S. Installations

In-stream hydrokinetic power generation is in the early stages of development, both in the United States and abroad. The United Kingdom is currently the largest marine renewable market followed by Canada (Jones and Wright 2011). The United States is also making progress in this area, with research and development funding attracting developers (Jones and Wright 2011). While this industry is relatively young, it is expected that it will grow dramatically in the next few years. By the end of 2015, it is expected that 91 MW of tidal current stream installations will be installed globally (Jones and Wright 2011). In the United States, hydrokinetic power generation has the potential to double the share of hydropower to the nation's supply from the current about 10% to about 20% (FERC 2006). However, this potential may take years or even decades to materialize. Existing installations in the United States are all pilot projects of an exploratory nature.

The Department of Energy (2013a) has a searchable database that provides information on planned and ongoing in-stream hydrokinetic energy projects. While the information in this database is not independently verified and does not list up-to-date information on all ongoing projects, it does provide a significant amount of valuable information on the state-of-the-art for in-stream hydrokinetic installations. This database classifies projects as "Deployed—commercial projects that have been completed with all device units in water or past commercial projects that have had a removal of all devices and environmental remediation" or "Device Testing—projects where devices are undergoing or have undergone testing/commissioning before deployment" with additional classifications for projects that are not as advanced (Department of Energy 2013a). This database lists 10 projects as "Deployed" with one project located in the United States: the-New Energy Corporation's project in Ruby, Alaska. It also lists 16 projects as "Device Testing" with six located in the United States: four projects utilizing Gorlv Helical Turbines developed by GCK Technologies, with two located in Massachusetts, one in New York, and one in Maine; Verdant Power's RITE project located in New York; and Vortex Hydro Energy's project, which has been tested in Michigan. This database did not however include the Free Flow Power full scale turbine that commenced operation in the Mississippi river in June 2011 (Free Flow Power 2013) or the New Energy Corporation's project that began operating near Eagle, Alaska, in the spring of 2010 (Johnson and Pride 2010) in either the "Device Testing" or "Deployed" categories. It also does not include information on the project status for the work that the Ocean Renewable Power Company has been conducting in Maine (Ocean Renewable Power Company 2014). Four U.S. river installations are reviewed in more detail in the following paragraphs, followed by two tidal installations.

The first in-stream hydrokinetic device deployed on a river system in the United States was deployed in Ruby, Alaska, for one month in 2008, and briefly redeployed in 2009 and 2010 (Johnson and Pride 2010). This 5 kW in-stream hydrokinetic device was developed by New Energy Corporation to harness electricity from the free-flowing Yukon River and to test the viability of using a hydrokinetic generator to offset the high-cost diesel fuel used to power the community's electrical grid (Johnson and Pride 2010). This vertical axis turbine was deployed from a moored catamaran barge, and the power was transmitted to shore using a cable laid on the river bed. This project had a budget of $65,000, which covered the generator, pontoon barge, transmission cable, anchoring equipment, and V-shaped debris boom attached to the front of the boat to protect the generator from debris (Johnson and Pride 2010). While this test was in large part successful, it did experience significant problems caused by in-water debris.

A 25 kW New Energy Corporation turbine was also briefly installed in the Yukon River in 2010, this time near Eagle, Alaska, (Johnson and Pride 2010). Similar to the installation in Ruby, Alaska, this vertical axis turbine was deployed from a moored catamaran barge and the power was transmitted to shore using a cable laid on the river bed. This system was installed in late spring 2010 and was in service until early July, when it was damaged during a period of very heavy debris drift. During this event, surface debris piled up in front of the turbine barge and large submerged debris damaged the barge's mooring equipment. After repairs to the turbine barge were made, it was redeployed in August 2010, supplying power to the grid at Eagle. The generating and power conversion equipment performed well during this deployment until later that month when a heavy debris drift damaged the generator power cable (Johnson and Pride 2010).

The City of Hastings, Minnesota, in conjunction with Hydro Green Energy, began operating an in-stream hydrokinetic project in December 2008 that can generate up to 250 kW of power (Hydro Green Energy 2011). This is the first commercially operated, FERC licensed in-stream hydrokinetic power facility in the United States (Hydro Green Energy 2011). This in-stream hydrokinetic project utilizes a shrouded horizontal axis turbine that is rigidly attached to a fixed structure. This project operated until 2012, when it was retired due to a shift in the company's focus (Hydro Green Energy 2013).

Free Flow Power Corporation operated its first full-scale hydrokinetic turbine generator in the Mississippi River starting June 20, 2011. This operation was funded with a combination of private capital and a US$1.4 million Advanced Water Power grant from the U.S. Department of Energy. The 3-m-diameter shrouded horizontal axis turbine, rated at 40 kW, is installed on a floating research platform in Plaquemine, Louisiana (Free Flow Power 2013).

Verdant Power installed and operated a tidal energy project in the East River in New York City that used six turbines and delivered 70 megawatt hours of energy to end users during the two-year period 2006–08. These horizontal axis turbines (Fig. 2) were attached to vertical monopiles and were completely submerged during operation. To optimize performance, these systems rotated with tidal change to align themselves with the direction of the flow. On January 03, 2012, FERC issued Verdant Power a pilot project license for their 1 MW, 30 turbine, RITE Project, which is the first commercial license for a tidal project in the United States (Verdant 2014).

The Ocean Renewable Power Company became the first company to generate electricity from Bay of Fundy tidal currents without the use of dams in 2008, during a yearlong program of in-water testing. In 2010, they operated a precommercial version of their device, which was the largest in-stream hydrokinetic device to ever be deployed in the United States—a power generation capacity of 150 kW. These systems, which were deployed from custom barges, were both horizontal axis turbines designed to operate with the flow perpendicular to the rotor axis (Fig. 3). In September 2012, an Ocean Renewable Power Company turbine deployed in Cobscook Bay became the first tidal energy system to deliver power to the U.S. electrical grid (Ocean Renewable Power Company 2014).

Regulatory Issues

Regulatory entities that have jurisdiction over hydrokinetic renewable energy technologies include:

- The Federal Energy Regulatory Commission (Federal Powers Act, 16 U.S.C. 791a);
- Bureau of Ocean Energy Management (43 U.S.C. 1337(p) of Outer Continental Shelf Lands Act Amendments);
- U.S. Army Corps of Engineers (Clean Water Act, Section 404; Rivers and Harbors Act, Section 10);
- U.S. Coast Guard (PWSA, Pub.L. 92-340; 14 U.S.C. 83; 43 U.S.C. 1333; & NVIC 02-07 as policy guidance); and
- State agencies responsible for Coastal Zone Management Act (16 U.S.C. 1451), Clean Water Act (33 U.S.C. 1251-1387), and state law provisions.

Each is summarized in subsequent paragraphs. Memorandums of Understanding (MOU) exist between most of these agencies that govern how they will work together on hydrokinetic energy projects.

The Federal Energy Regulatory Commission (FERC)

FERC has exclusive jurisdiction to issue licenses and exemptions from licensing for the construction and operation of hydropower projects in accordance with the Federal Power Act (FPA), including hydrokinetic devices in U.S. waters from the shoreline onto Outer Continental Shelf (OCS) and including rivers. FERC conducts any necessary analyses, including those under the National Environmental Policy Act, related to those actions. FERC's licensing process actively involves relevant federal land and resource agencies, including the Department of the Interior Bureau of Ocean Energy Management, U.S. Army Corp of Engineers, and the U.S. Coast Guard. FERC will not issue preliminary permits for hydrokinetic projects on the OCS. Additionally, FERC will not issue a license or exemption for an OCS hydrokinetic project until the applicant has first obtained a lease, easement, or right-of-way from the BOEM for the site.

The FERC pilot project licensing process for hydrokinetic projects is contained on their website (http://www.ferc.gov/industries/hydropower/gen-info/licensing/hydrokinetics.asp). FERC encourages developers to first seek a preliminary permit which would be issued for three years and give the developer priority to study a project at the specified site for the duration of the permit. In order to allow testing of new hydrokinetic technology devices, FERC has developed expedited procedures for licensing small/low-impact hydrokinetic pilot projects of 5 MW or less, which have a short (five year) licensing term. FERC anticipates that developers will then be able to transition from a pilot project license to build-out license, which will be handled as a relicensing of the pilot project and will entail a standard (30 to 50 years) licensing process, including a National Energy Policy Act (NEPA) review and full opportunity for participation by all stakeholders. A pilot project license is not a prerequisite to applying for a standard or build-out license.

The preliminary permit process and pilot project license are elements of a larger process towards licensing. Since July 23, 2005, the Integrated Licensing Process (ILP) has been the default process and approval by FERC has been required to use the Alternative Licensing Process (ALP). Under the ILP, a federal or state agency, or Tribe with mandatory conditioning authority may request that a study dispute be referred to a dispute resolution panel. Regulations on the ILP are found at 18 CFR part 5 (Code of Federal Regulations 2013a).

For applications filed before July 23, 2005, potential license applicants were permitted to elect to use the traditional or the integrated licensing process, or to request authorization to use the ALP.

Department of Interior (DOI)

DOI has formally established two new, independent bureaus—the Bureau of Safety and Environmental Enforcement (BSEE) and the Bureau of Ocean Energy Management (BOEM)—to carry out the offshore energy management and safety and environmental oversight missions previously under the jurisdiction of the Minerals Management Service (MMS) and then the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE).

BOEM was given exclusive jurisdiction under Section 388 of the Energy Policy Act of 2005 [43 U.S.C. §1337(p)], to issue leases, easements, or rights-of-way with regard to the production, transportation, or transmission of energy from nonhydrokinetic renewable energy projects on the Outer Continental Shelf (OCS), including wind and solar. BOEM was also given exclusive jurisdiction to issue leases, easements, and rights-of-way on OCS lands for hydrokinetic projects. The Energy Policy Act of 2005 (EPACT 2005) gave BOEM two additional authorities: (1) authority to allow a previously-permitted offshore oil and gas structure to remain in place for use in connection with other permitted energy and marine-related activities, and (2) authority to share with nearby coastal states a portion of revenues received by the federal government.

BOEM plan and information requirements for issuance of OCS leases and rights-of-way grants and start of construction or installation are contained in 30 CFR part 585 (Code of Federal Regulations 2013b), Renewable Energy and Alternate Uses of Existing Facilities on the OCS. BOEM regulations for shallow hazards survey and archeological resource report requirements are contained in Notices to Lessees and Operators (NTLs) that supplement the regulations that govern operations on the OCS.

Army Corps of Engineers (USACE)

The USACE derives its primary regulatory authorities over the waters of the United States from the two Federal laws that are central to the USACE regulatory program. Section 10 of the Rivers and Harbors Act of 1899 applies to all navigable waters of the United States and Section 404 of the Clean Water Act applies to all waters, including wetlands that have sufficient nexus to interstate commerce. For hydropower projects, the USACE works as a cooperating agency to review and authorize the Section 10 permit application. If components of a hydropower project are not addressed by the application to FERC, the USACE may then exert Section 10 authority.

Rivers & Harbors Act 1899 §10. Section 10 of the Rivers and Harbors Act of 1899 requires approval prior to the accomplishment of any work in or over navigable waters of the United States, or which affects the course, location, condition, or capacity of such waters. Typically, Section 10 permits are required for structures and cable or pipeline crossings, as well as other activities. This authority is subsumed by the FPA, provided the activities are included in the application and the NEPA analysis. The USACE applies the same criteria to hydrokinetic installations whether providing recommended terms and conditions to FERC or issuing a USACE Section 10 Permit.

Clean Water Act - §401 and §404. Section 401 of the Clean Water Act requires that any applicant for a federal license or permit to conduct any activity including, but not limited to, the construction or operation of facilities which may result in any discharge into the navigable waters, shall provide the licensing or permitting agency a certification from the State in which the discharge originates that any such discharge will comply with the applicable provisions of the Clean Water Act. Section 404 of the Clean Water Act requires approval prior to discharging dredged or fill material into the waters of the United States.

United States Coast Guard (USCG)

The Navigation and Vessel Inspection Circular (NVIC 02-07) is a guidance document, not a statutory citation of primary jurisdiction. The USCG is a cooperating agency under the NEPA with the lead permitting agency considering the issuance of a permit, lease, right of use and easement, or right of way for a renewable energy initiative (REI). As such, the role of the USCG is limited to providing any such lead permitting agency with an evaluation of the potential impacts of the proposed facility on the safety of navigation, the traditional uses of the particular waterway and other USCG missions in order for the lead permitting agency to prepare their environmental impact statement (EIS). The USCG will not approve or disapprove a REI application. The USCG's role is limited to assessing navigation impacts of a REI and forwarding such considerations to the lead permitting agency.

Coast Guard statutory authorities and guidance for navigation safety are contained in

- Ports and Waterways Safety Act of 1972 (Public Law 92-340),
- 14 U.S.C. § 83—Unauthorized aids to navigation; penalty,
- 43 U.S.C. § 1333 (d)—Coast Guard regulations; marking of artificial islands, installations, and other devices; failure of owner suitably to mark according to regulations, and
- Navigation and Vessel Inspection Circular (NVIC) No. 02-07

Other Federal Agencies

Other federal agencies that may be involved in the process include the Departments of Commerce, Defense, Energy, and Transportation, and the Environmental Protection Agency (EPA). In addition, appropriate state agencies and tribal governments may also be involved.

The following authorities are given broadly to federal agencies:

- Coastal Zone Management Act (CZMA)—§ 307. Section 307 of the CZMA of 1972, as amended [16 U.S.C. 1458(c)], requires the applicant for a required federal license or permit to conduct an activity affecting any land or water use or natural resource of the coastal zone of a state to certify that the project is in compliance with the state's approved Coastal Zone Management Program and that the proposed activity will be consistent with the state's program. This provision also requires the applicant to furnish the state or its designated agency a copy of the certification with all necessary information and data. Within six months, the state is to advise the federal agency that the state concurs with or objects to the applicant's certification. In general, no license or permit shall be granted by the federal agency until the state or its designated agency has concurred with the applicant's certification.
- Endangered Species Act—§7. Section 7 of the Endangered Species Act of 1973 (ESA) requires federal agencies (not only USACE) to ensure that any action authorized, funded, or carried out by them is not likely to jeopardize the continued existence of any endangered or threatened species, or result in the destruction or adverse modification of their critical habitat. Section 7 outlines the process for interagency coordination by which all agencies consult with the United States Fish and Wildlife Service (USFWS) and/or National Oceanic and Atmospheric Administration (NOAA) Fisheries on a proposed project's potential to affect listed species. For the FERC licensing process, FERC will typically coordinate all ESA issues raised by federal agencies with USFWS and/or NOAA.
- National Historic Preservation Act—§106. Section 106 of the National Historic Preservation Act (NHPA) requires that the head of any Federal agency having direct or indirect jurisdiction over a proposed federal or federally assisted undertaking in any state and the head of any federal department or independent agency having authority to license any undertaking shall, prior to the approval of the expenditure of any federal funds on the undertaking or prior to the issuance of any license, take into account the effect of the undertaking on any district, site, building, structure, or object that is included in or eligible for inclusion in the National Register. Under Section 106 of the NHPA, the head of any federal agency is required to consult with the Advisory Council on Historic Preservation to determine a project's potential to impact resources of historic or cultural significance.

State Agencies Responsible for CZMA and CWA Provisions

Section 307 of the Coastal Zone Management Act of 1972, as amended [16 U.S.C. 1458(c)], requires the applicant certify that the project is in compliance with an approved State Coastal Zone Management Program and that the state concurs with the applicant's certification prior to the issuance of a permit or license. If the state or its designated agency fails to notify the federal agency within six months after receipt of its copy of the applicant's certification, the state's concurrence with the certification shall be conclusively presumed.

As of this writing, these are the existing MOUs between FERC and states:

- The State of Washington for hydrokinetic energy projects;
- The State of Maine for tidal energy projects; and
- The California Natural Resources Agency, the California Environmental Protection Agency, and the California Public Utilities Commission for coordinating the review of hydrokinetic energy facility authorizations.

Economics

At the present time, only a small number of pilot-scale hydrokinetic projects are in operation or have previously been operated in the United States (See the "U.S. Installations" section of this paper). With a view toward obtaining a FERC license, the developers of these projects have allocated a substantial part of the project's budget to install, operate, collect, and analyze environmental, fisheries, and other relevant data to satisfy FERC's licensing requirements. As a result, the available cost data from these pilot projects cannot be used realistically to estimate the cost of hydrokinetic production for future large-scale projects. However, several hypothetical cost estimates have been created in an effort to predict the economic feasibility of producing in-stream hydrokinetic power. To help evaluate the feasibility of potential projects, the projected costs of producing electricity at a particular site are compared with the expected price at which the electricity can be sold in this section.

The Electric Power Research Institute (EPRI) studied hypothetical in-river hydrokinetic installations at Igiugig, Eagle, and Whitestone (Previsic et al. 2008). In this study, representative devices were assumed to have a rotor efficiency of 40%, gearbox efficiency of 95%, generator efficiency of 95%, frequency converter efficiency of 98%, and step up transformer efficiency of 98%; resulting in a total system efficiency of 34%. The device availability at these three sites were predicted to be 90% for Igiugig, 38% for Eagle, and 90% for Whitestone, and the capacity factors were estimated to be 65%, 71%, and 29% respectively. These costs have been updated to 2010 U.S. dollars by Johnson and Pride (2010). The Igiugig study proposed a 40 kW installation, which would produce 207 MWh/year. This installation was predicted to have associated capital cost for installation of about US$ 315,000, annual operations and maintenance cost of roughly US $ 12,600, and an electricity sale price of US$ 0.68/kWh (Johnson and Pride 2010). The proposed 60 kW installation in Eagle Alaska, on the Yukon River, was expected to produce 107 MWh/year (Johnson and Pride 2010). This installation was predicted to have a capital cost of about US$ 283,000, annual operations and maintenance cost of about US$ 6,800, and expected electricity sale price of US$ 0.68/kWh (Johnson and Pride 2010). The proposed 590 kW hydrokinetic installation in Whitestone, Alaska, on the Tanana River, was predicted to produce approximately 1,325 MWh/year of electricity (Johnson and Pride 2010). The installation's capital cost was estimated at US$ 1.9 million, with annual operations and maintenance costs of roughly US$ 135,000, and electricity sale price of US$ 0.19/kWh (Johnson and Pride 2010). If these cost estimate proved true for 20 years of operation, electricity would be produced at an average cost of US$ 0.14 for Igiugig, US$ 0.20 for Eagle, and US$ 0.08/kWh for Whitestone (excluding financing costs etc.), far under the expected sale prices at each location.

A separate study on in-stream tidal power was conducted by EPRI for Knik Arm in Cook Inlet (Polagye et al. 2006) and these costs have also been adjusted to 2010 U.S. dollars by Johnson and Pride (2010). The study concluded that the proposed commercial installation of an array of devices would extract an average of 17 MW of electricity from the tide (Johnson and Pride 2010). The estimated capital cost of the array was US$ 123 million, the annual operations and maintenance cost was predicted to be US$ 4.5 million, and the cost of electricity for utility generation was predicted to be US$ 0.11/kWh (Johnson and Pride 2010).

Some companies have also published predicted cost of electricity estimates, such as Hydrogreen Energy, who is predicting that it can produce electricity at a cost of 3–7 cents/kWh (Hydro Green Energy 2012). Hydrokinetic power is a renewable energy eligible for a 1.1 cent/kWh production tax credit (DSIREUSA 2013). It is expected that the emergence of large-scale hydrokinetic projects will be accompanied by major technological improvements that will substantially bring down the costs.

Effects on Other Water Uses

Water and waterways serve multiple purposes, including

- Navigation;
- Recreation;
- Municipal and Industrial (drinking and process water, waste assimilation); and
- Agriculture (irrigation and livestock, including aquaculture).

All of these may be affected by hydrokinetic power generation, either positively or negatively.

Navigation

Navigable waterways are important to local and national economic viability. Most inland waterways utilize a tow configuration for transport of goods, while some are capable of accommodating deep draft vessels. Modifications to an existing channel/waterway may require vessels to make changes to typical navigation procedures, some of which could be extreme. One major concern is the position of a proposed structure within the waterway (e.g., horizontal alignment and depth). Other concerns are future intended use of the river as a navigable waterway and unexpected extreme conditions. Pinkerton Computer Consultants (PCCI) (2009) listed potential impairments from hydrokinetic facility installation, supporting infrastructure, operation, or signage as including

- Visual navigation;
- Electronic navigation and communications;
- Search and rescue (SAR), counter pollution, or salvage operation in or around an installation;
- Tides, streams and currents;
- Navigation safety (increased likelihood of allision and collision); and
- Vessel traffic or other normal uses of the area.

The PCCI report examined these potential impairments and provided a recommended checklist of precautions that would mitigate or remove the risks.

Probability of a vessel striking a stationary object is difficult to predict, as captains, vessels, and environmental conditions are not identical. Records of past accidents may be used to establish a rough prediction of expected accidents. An analysis by Le Blanc and Rucks (1996) records 936 vessel accidents occurring in a 250 mi reach of the Lower Mississippi River between 1979 and 1987. These data are used to make a rough estimate of accidents, as in

$$\text{Rate} = \frac{936 \text{ Accidents}}{250 \text{ mi} \times 9.0 \text{ Years}} = 0.42 \frac{\text{Accidents}}{\text{Year} \times \text{mi}} \tag{3}$$

The total number of accidents includes rammings, groundings, collisions, and others of unknown designations. A collision is defined as a vessel's contact with another vessel or moving object, while allisions and groundings are limited to contact with a stationary object or bed, respectively. Further consideration of such accidents should also consider the possibility of vessel sinking. In certain areas, a vessel or large object sinking could damage or destroy structures on the bed, which could lengthen cleanup time and extend traffic delays on a waterway. Establishment of a stationary structure within a navigation channel could also reduce flexibility within the waterway. For example, future consideration of a deeper draft vessel/tow in a particular reach may be limited to characteristics, such as height, of permanent bed structures. Fig. 5 shows a schematic of a hypothetical vessel and navigation channel.

Consideration should be given to future conditions and uses of the waterway. Uses such as maintaining higher pool elevations in reservoirs, local water supply demand, channel dimensions, etc. could serve to reduce the amount of channel water flow and possibly underkeel clearance of vessels with respect to bed structures. One or a combination of these could lead to a collision between a vessel and structure, which could cause significant damage to the vessel, structure, and/or surrounding environment. Consideration should be given to possible future vessels of the inland waterway system, especially since deep-draft ships are becoming longer, wider, and deeper draft, and larger barges and tows may be introduced in some waterways.

Structures with a top elevation below the draft of the design vessel during acceptable conditions could be of concern during drought or other low water conditions. During such conditions, a non-adjustable, permanent structure could intrude into the minimum draft required by passing vessels. Such intrusions could limit or completely halt the use of the channel. Also, such structures may significantly change flow patterns causing captains or pilots to change the vessel's approach in a particular reach. Such changes should be well advertised to warn mariners to take extra precaution in the designated areas.

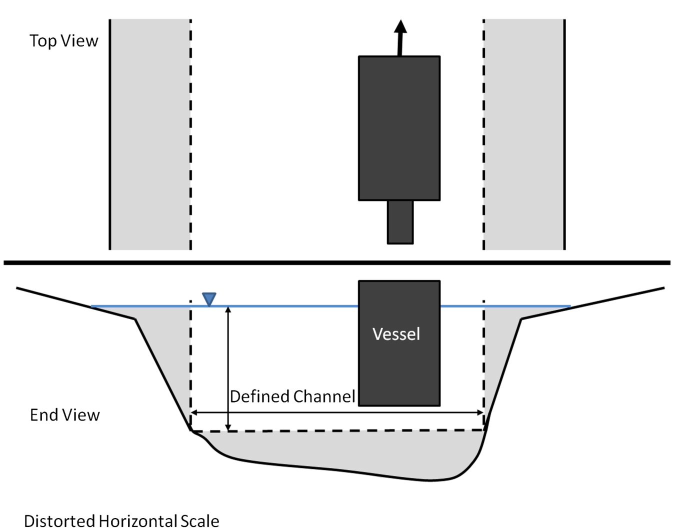

Fig. 5. Schematic of vessel in a navigation channel

Accident probability, future design vessels, extreme conditions, etc. are important to the feasibility and impact of the placement of structures in any navigable waterway, since they can lead to loss of life or large economic damages. Consideration should be given to the likeliness of each of these mentioned concerns and others. Waterborne transportation remains an important use of a waterway. Maintaining safe navigation is important for economic prosperity. Any proposed modifications to a navigable waterway should be discussed with effected shipping companies, pilot associations, and mariners in addition to the proper organizations of interest such as U.S. Coast Guard, U.S. Army Corps of Engineers, Environmental Protection Agency, etc.

For installations planned for the Mississippi River by Free Flow Power, the Army Corps of Engineers has established parameters for the maximum allowable elevation of turbine infrastructure (Free Flow Power 2010). The maximum elevation parameters were 20 feet below Low Water Reference Plane (LWRP) north of Baton Rouge and 65 feet below LWRP south of Baton Rouge

Recreation

In-stream hydrokinetic projects can potentially be located in streams, rivers, tidal areas, and the open ocean, all of which are commonly used for recreational activities. A detailed discussion of the potential recreational impact of in-stream hydrokinetic devices is presented in a report entitled "Hydrokinetic Energy Projects and Recreation: A Guide to Assessing Impacts" (Hydraulics and Recreation Work Group 2010). The "Recreation" section of this paper is primarily a summary of some of the important issues discussed in this report. Some of the recreational activities mentioned by the Hydraulics and Recreation Work Group (2010) that could be affected by either wave or in-stream hydrokinetic projects include both boat and shore based fishing, power boating, swimming, diving, kayaking, surfing, general recreation on beaches and shorelines, and wildlife viewing. Of these activities, in-stream hydrokinetic energy devices will typically not affect surfing or general recreation on beaches because they typically will not be located near beaches. Additionally, each particular installment will typically only have a few of the remaining user conflicts. Potential impacts on these recreational activities mentioned in this report include access restrictions, changes in aesthetics, changes in wave or hydraulic characteristics, wreckage and salvage impacts, displacement of individuals to other recreational areas, and cumulative impacts if multiple systems/sites are located in close proximity.

The most obvious potential impact of in-stream hydrokinetic energy production on recreation is restricted access (Hydraulics and Recreation Work Group 2010). The mentioned restrictions include both exclusion areas where no recreation is allowed and activity restriction areas where access is allowed but limited. This report suggests that these restrictions may limit vessel type, vessel speed, or specific activities such as swimming, diving, or fishing. It also mentions that some of these access restrictions may only apply during construction/deployment and maintenance, while others may apply throughout the life of the project. The presented reasons for either restriction or exclusion areas include: device security, device damage, and recreational user safety. It is also noted that potential access restrictions will need to be consistent with existing navigation-related programs, as well as regulations from the Coast Guard and/or the Army Corps of Engineers.

The type of restriction required for installing and operating in-stream hydrokinetic turbines is dependent both on installment locations and turbine design. Hydraulics and Recreation Work Group (2010) explains that surface based in-stream hydrokinetic devices may be attached to barges or other surface platform creating potential navigational hazards and are likely candidates for exclusion zones. However, some in-stream hydrokinetic devices are attached to pilings or moored in the water column, without any development above the surface. For navigational purposes, the submergence depth of these sub-surface turbines is important, as it may be possible for vessel traffic to navigate over them. Although some submerged systems may require exclusion zones, less intrusive activity restrictions may be adequate, such as restricting anchoring, fishing, and diving (Hydraulics and Recreation Work Group 2010).

Examples of the recreational access restriction impacts from in-stream hydrokinetic energy production are a subset of the access restrictions presented by the Hydraulics and Recreation Work Group (2010) for all hydrokinetic projects. This report suggests that even without full exclusions, shore based fishing will likely not be allowed near in-stream hydrokinetic devices due to interference with operations and for the safety of the anglers. It also points out that this is especially likely for recreational crabbing and bottom fishing, due to the likelihood of entanglement. For the same reasons, boat-based fishing will also likely not be allowed in access-restricted areas. These fishing restrictions could potentially be unpopular since in-stream hydrokinetic infrastructure will likely become fish attractors. This report notes that river or tidal areas with higher energy hydraulics may be desirable locations for both in-stream hydrokinetic turbines and play boating kayakers, creating a potential user conflict. This report suggests that snorkelers and divers could also be affected by the access restrictions from in-stream hydrokinetic systems. However, it mentions that this user group typically prefers slow moving currents that would not produce significant energy, minimizing this potential conflict. One exception to this generalization, not mentioned in the reference report, is that divers sometimes take advantage of slack tides to access locations where the water typically flows quickly, such as the lobster divers who commonly dive near bridges in the Florida Keys.

The in-stream hydrokinetic project located in New York City's East River offers an example of exclusion zones for a fully submerged but shallow array of devices (Hydraulics and Recreation Work Group 2010). For this project, a small exclusion zone was established for two turbines during the testing stage, and a larger exclusion zone of approximately 12 acres (approximately 0.05 km^2) is proposed for a 30 turbine build out (Hydraulics and Recreation Work Group 2010). This report suggests that this project requires an exclusion zone as opposed to a restriction zone because its clearance depth is only about 2–3 m at low tide.

While access restriction and exclusions can affect recreational usage of an area, the Hydraulics and Recreation Work Group (2010) suggests several other issues that should be considered as well. One such issue is that changes in aesthetics will occur both while in-stream hydrokinetic devices are being constructed and from the permanent device installation. These projects could potentially change the visual quality of the area by introducing structures, cables, power-substations, lights, moorings, and/or barges (Hydraulics and Recreation Work Group 2010). Besides impacting aesthetics, this report points out that in-stream hydrokinetic projects can also directly affect and alter the hydraulic characteristics of a flow. By design, in-stream hydrokinetic devices absorb and convert current energy into electric energy. These flow changes can alter opportunities for recreational users, some of whom seek higher currents while others avoid them. While some in-stream hydrokinetic devices could discourage individuals from visiting an area, this report suggests that in-stream hydrokinetic devices may attract some visitation for the purpose of viewing the technology. However, it is unclear if these projects will be sufficiently dramatic to attract substantial visitation (Hydraulics and Recreation Work Group 2010).

Environmental Impacts

The potential environmental impacts of in-stream hydrokinetic power differ from conventional hydropower in many ways, largely due to the lack of need for a dam. However, unlike conventional hydropower that has a long history of use, there is no historical record or weight of evidence for in-stream hydrokinetic power on which assessments of environmental impacts may be based. As indicated by the U.S. Department of Energy in their "Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies" (DOE 2009), while many reviews and assessments make judgments about the significance on potential environmental impacts, few of these are based on in situ monitoring or even predictive modeling. Environmental impacts may also be very site-specific depending on the design, installation, and operation of in-stream hydrokinetic power facilities. Traditional practices of avoid-minimize-mitigate (avoid critical/sensitive areas, minimize or mitigate impacts, DOE 2009) may aid in reducing impacts. However, also of concern are the cumulative impacts of the widespread use of these technologies.

In the specific case of streams, the following parameters were identified as stream ecology concerns by conventional hydropower projects and may be factors in in-stream hydrokinetic installations (Cada et al. 2007; Cada and Meyer 2005):

- Hydraulic factors. Shear stress and turbulence will be created near rotors that may injure aquatic organisms or scour nearby sediments. On a large scale, dozens or hundreds of rotating machines may alter the hydrologic regime and cause large areas of sediment scour or deposition (Cada et al. 2007).
- Sediments. Disruption of the sediments during installation will alter the bottom habitat and may increase turbidity or release buried contaminants. Sediment disruption may be a temporary event associated with installation or may continue during operation owing to movements of the rotors or of unsecured power and mooring cables. Extraction of kinetic energy affects the ability of a water body to transport sediment; indicating a possible impact on transport and suspension of bed load (Cada and Meyer 2005).
- Habitat. "Natural streams provide habitat for resident fish, plants and other types of organisms. Some organisms require cobble stream beds to spawn, whereas silt is the preferred habitat for other species. Rivers also serve as highways for upstream and downstream movements of organisms. This includes constant, passive drift of aquatic invertebrates and seasonal drift of fish eggs and larvae—these passive drifters are weak swimmers, so they don't have much ability to avoid an obstruction. Other organisms that may be affected by the presence of hydrokinetic turbines in the river include reptiles, diving birds, and mammals" (Cada and Meyer 2005).

These effects will depend on the design, size, and numbers of turbines and the site-specific characteristics of their locations. Installation-relative significance can be compared with the impacts of vessel traffic, water withdrawals and discharges, and existing structures then evaluated in that context.

Water Quality

Water quality refers to the physical, chemical, and biological characteristics of water, and as such may be directly or indirectly impacted by in-stream hydrokinetic processes. There are a wide variety of federal and state laws, regulations, executive orders, and case law impacting energy production facilities as related to water quality and as such, water quality considerations are an integral component of the licensing of hydropower facilities. For example, state agencies implement specific sections of the Clean Water Act that impact energy production including NPDES permitting and 401 water quality certifications, and participate in relicensing through Section 10(j) of the Federal Power Act, the Fish and Wildlife Coordination Act, the Clean Water Act, the Coastal Zone Management Act, and the National Historic Preservation Act. States, for example, must deny 401 certifications if compliance with state water quality standards cannot be assured (Martin et al. 2007a).

Mechanisms related to in-stream hydrokinetic power potentially impacting water quality differ from those of conventional hydropower facilities, such as those described in Martin et al. (2007b). One principal mechanism related to in-stream hydrokinetic power is the extraction of kinetic energy, which impacts the water's physical (hydraulic) characteristics. Power extraction limits of 10 to 20% are often cited in examples for in-stream hydrokinetic power installations located in tidal flows as the maximum amount that can be removed without substantial environmental effects. This range is largely based on work reported by Bryden and others (e.g., Bryden et al. 2004; Bryden and Couch 2006) who examined the average change in water level and flow velocity of power extraction from schematic tidal waterways and found that extracting 10% reduced the average current speed by 3% and extracting 20% reduced average current speed by 6%. Since it is sometimes suggested that lining large stretches of river with in-stream hydrokinetic generators will be needed to make a significant contribution to U.S. power needs (e.g., DOE 2009), they calculated the effect of a series of hydrokinetic generators over the entire 2000 m length of a representative river reach, i.e., one in each of eight computational reaches or about every 250 m and found that serial energy extraction at a rate of 10% of the kinetic energy produces 2 to 3% changes in the total energy, depth, and velocity over the 2000-m-long reach. While these studies suggest that the difference in hydraulic characteristics due to energy extraction may be small, impacts are both site-specific and cumulative. Another study suggested that if 4 GW of power was extracted from the tidal flow in the Bay of Fundy, out of a total energy supply of 7 GW, there would be a change in the tide of less than 10% (MMS 2007). Similar analyses by Ortega-Achury et al. (2010) indicated that extracting kinetic energy from streams, either tidal or non-tidal, can be expected to have a small but not insignificant effect on flow depths, velocities, and energy available for other purposes downstream, upstream, or both. They also show that cumulative effects of multiple units can be substantial. The DOE (2009) indicated that while extraction of kinetic energy will reduce water velocities in the vicinity of the project, large numbers of devices in a river will "reduce water velocities, increase water surface elevations, and decrease flood conveyance capacity."

Changes in physical characteristics such as increased depths and reduced current velocities (e.g., DOE 2009), increases in retention (or travel) time, or losses in wave energy all impact chemical and biological characteristics of water quality. One example of a chemical impact is that on dissolved oxygen, which consequently directly impacts biological characteristics. Oxygen depletion is presently the fourth most commonly reported cause of water quality impairment in the United States [6,412 listed waters per USEPA (2012) Causes of Impairment for 303(d) Listed Waters]. Hypoxic or dead zones (oxygen concentrations < 2 mg/L) are becoming more common and have, as reported in Science (Diaz and Rosenberg 2008), spread exponentially since the 1960s. The impacts of increased depths and decreased velocities, such as resulting from energy extraction, can impact oxygen in a variety of ways, one of which is by decreasing reaeration (air water exchange), the rate of which is decreased with increasing depth and decreased velocities (Chapra 1997; Martin and McCutcheon 1999). Increase retention times also commonly result in increased summertime temperatures, greater oxygen loses due to decomposition of organic materials, potential increases in plant biomass, and increased sedimentation. Increased sedimentation of organically rich sediments may result in increased sediment oxygen demands and sediment nutrient release (Chapra 1997). Increased retention times also increase potential for vertical density stratification (Martin and McCutcheon 1999), which may result in an increased potential for hypoxia in bottom waters (Chapra 1997). In addition, energy extraction could also impact the fate and transport of toxic materials such as through increased mobilization and consequent sedimentation (DOE 2009). Hypoxia could also result in mobilization of metals.

An additional potential water quality impact is sedimentation. Presently sedimentation/siltation [per USEPA Causes of Impairment for 303(d) Listed Waters] is the fifth largest reported cause of waters (6,139 listed waters out of the 71,648) not meeting basic water quality standards in the United States. Changes in sedimentation would be expected during construction and operation phases. During operation, changes in the transport regime (e.g., current velocities, wave heights, depths, etc.) will alter sediment transport, erosion, and sedimentation (DOE 2009). Substantial disturbances such as due to changes in physical characteristics (e.g., depths and velocities) may also impact stream stability resulting, for example, in scouring of the bed, destructive bank erosion, and channel widening by collapse of bank sections. The impact of sedimentation is commonly degradation of aquatic habitat.

Fisheries and Animal Habitats

There are two primary ways that in-stream hydrokinetic power-producing facilities could potentially affect commercial and recreational fisheries or other aquatic species. First, some areas will be off-limits to fishing because of potential interference and fishing gear entanglement. Second, there might be potential direct impacts from the device installations upon the local aquatic life itself, which could either adversely or beneficially affect fisheries. While the effects of restricting areas can be easily evaluated, the potential direct effects of installed devices are more complex and include: habitat alteration, noise, EMF, restricted migration, and possible fish strike or entanglement.

No-fishing zone sizes for in-stream hydrokinetic devices will depend on the device type, required mooring or mounting system, number of devices, and deployment location. The impact from these no-fishing zones is also very location-specific, due to the varied importance of areas to the local fishing community. One example of a no-fishing zone is the exclusion area proposed by Verdant Power for their RITE project (Verdant Power 2011). This proposed area will put around 12 acres (approximately 0.05 km^2) off limits to fishing in New York City's East River for their proposed 30 turbine installment (Hydraulics and Recreation Work Group 2010), which is predicted to produce on average 1 MW of electric power (Verdant Power 2014). While this area is not commercially fished, it does give an example of the relationship between the required off-limit area and produced power.

Another example of the deployment area required for tidal turbines is in the Bay of Fundy. This turbine testing area is designed to support 64 MW of electric generation capacity and has been established on a 1.6 km^2 lease area (Redden 2010). For offshore in-stream hydrokinetic energy production, the primary location being considered is in the Florida Current off southeast Florida. This resource is located approximately 20 km from shore in an area that is commonly fished for species such as mahi-mahi, tuna, and swordfish. Turbines moored at this location will most likely be located at least 50 m below the sea surface to avoid wave effects and ship traffic. While it is feasible that ship traffic will be allowed to operate above these devices, it is likely that fishing, especially for species such as swordfish where bait/lures are deployed far below the surface, would be restricted near installations. The total size of potential off-limit areas for both shallow and deep water installations will depend on the scale of the installations. Along with other considerations, the need to produce clean renewable energy must be balanced with the needs of local fishermen.

To help ensure that a balance is found when allocating areas for marine renewable energy systems, both the commercial and recreational fishing communities have been engaged and are actively involved in the site selection and permitting processes (Beutel 2010; Hall-Arber et al. 2010; Hildenbrand 2010).

The potential for in-stream hydrokinetic devices to harm aquatic life such as fish, turtles, and marine mammals is a topic of ongoing research. A study conducted by Amaral et al. (2010) investigated the potential of these systems to injure or kill fish by several different methods, including: increased pressure, rapidly decreased pressure, cavitation, strike, shear, and turbulence. This study concluded that in-stream hydrokinetic turbines do not cause the extensive and rapid changes in pressure that have been shown to damage fish during passage through conventional hydropower turbines. It also suggested that if pressure–related injury and mortality occur at all, they will be limited to small cavitation areas around the blades. This study also suggests that in-stream hydrokinetic devices will not produce the damaging shear levels encountered by conventional turbines, which sometimes can induce fish injury, and that turbulence will not likely cause injury to fish. Finally, this study suggests that blade strike may be the primary mechanism of fish injury and mortality at many hydro projects, if injuries or mortality do occur. Many fish will be able to avoid turbine blades, and if they do not, documents referenced by this study suggest that blade strike survival can be greater than 90% at strike speeds up to 12.1 m/s. Since the tip speed of many in-stream rotor blades will be less that 12.1 m/s, the survival rate of any fish that happen to be struck by a rotor blade will likely be very high. A tip speed of 12.1 m/s will occur for a three-bladed rotor operating at the Tip Speed Ratio where maximum efficiency is obtained according to standard blade theory, TSR = 5.45 (Ragheb 2009), in a current speed of 2.22 m/s. This prediction was confirmed in a study completed by Hydro Green Energy that stated that only one fish out of 402 showed evidence of direct physical harm. Even further, this incident was attributed to the balloon tag that caused the fish to rise to the surface and encounter the turbine in a manner that would not have occurred naturally (Stover 2010).

To help assess the impact on other marine animals, studies are currently underway to map the population densities, migration routes, and behavior of many different species. These studies include the sea turtle studies related to potential offshore in-stream hydrokinetic energy production devices (McMichael and Wyneken 2010). Additionally, advanced animal detection and identification systems are currently being developed and tested that monitor the sea life near hydrokinetic turbines, and these systems are capable of triggering system shutdowns based on near real-time measurements (McClure 2010).

The expectation that little or no fish mortality or injury will occur at most in-stream hydrokinetic installations is supported by an environmental assessment project that was conducted during the Verdant Power RITE project Phase 2 demonstration in New York's East River. An automated hydroacoustic monitoring system, consisting of an array of 24 split-beam transducers, was used to monitor fish interactions with the blades of six units installed during the pilot study. These data demonstrate that fish avoid zones of impact with Verdant Power's system (Verdant Power 2014).

A similar environmental assessment was conducted in Maine during the testing of the Ocean Renewable Power Company turbine in Cobscook Bay. The dual sonar system utilized in this project showed that the schools of small fish that passed through the device would become momentarily confused, but then would usually quickly re-orient themselves (Powell 2011). Larger species of fish that approached the intake of the device would stop, turn, and move upstream to avoid the device (Powell 2011). Similar to the findings at the RITE project, these environmental monitoring and fish studies yielded no evidence of fish or mammal disturbances (Merrill 2011).

Other Potential Impacts

Other environmental concerns in natural streams include (Cada et al. 2007)

- Impacts of noise;
- Impacts of electromagnetic fields (EMF); and
- Toxic effects of chemicals.

Electromagnetic fields (EMF) created from magnets in the generators of hydrokinetic devices and from transmission cables may affect fish and benthic organisms that come in very near proximity. These affects would most likely be of a behavioral basis and could affect normal movements or migration patterns, although at this time the relationships between EMF and organism response is largely unknown.

Noise during construction and operation of hydrokinetic devices could have physical or behavioral effects on aquatic organisms. Construction noises will likely be similar to noises created during other underwater construction activities (e.g., bridge piling construction, channel deepening, etc.) and should be able to be mitigated similarly. Operational cavitation noise, a direct result of the collapse of cavitation bubbles created by the turbines rotor, is a primary concern that can cause increases in noise levels in the 5–30 kHz frequency range (Wang et al. 2007). These noises may affect the normal distribution of organisms in the project's vicinity.

Toxicity as a result of the erosion of antifouling coatings or the unintended release of lubricating fluids is another concern that is being considered. Any release of toxic compounds during operations is expected to be small relative to the volume of water passing the devices, but given that these devices would be deployed by the dozens or hundreds, the concern will need to be addressed.

Environmental Research Status and Needs

There is considerable speculation concerning the potential environmental impacts of in-stream hydrokinetic power. However, as indicated by DOE (2009) there is a small but growing number of supporting studies, including both in situ monitoring and predictive modeling, to support conclusions regarding those impacts. Potential environmental impacts include altered water quality, altered sediment deposition, and altered habitats. In addition, the direct impact on biota and navigability of waterways are potential concerns.

Deployment of in-stream hydrokinetic devices in U.S. waters will require licensing, and that licensing will require compliance with a wide variety of federal statutes (e.g., CWA, CZMA, Endangered Species Act, etc.) as well as coordination with, or permits from, a wide variety of federal and state agencies (Martin et al. 2007a). That regulatory framework within which hydrokinetic systems has to operate is a key factor in determining the future of this renewable energy resource (Wellinghoff et al. 2008). However, a variety of the regulatory agencies have already expressed concerns, such as about the potential effects of a variety of stressors (e.g., blade strike, noise, habitat alteration, and EMF) on aquatic life. The ability to address these and other concerns is presently hampered by a lack of data.

One example of where data are needed is on the extent of the exposure to these stressors and on how fish will respond to that exposure. Many developers that are applying for or already have permits for test deployments (such as Free Flow Power on the lower Mississippi River and Hydro Green Energy on the upper Mississippi) are involved in studies to address environmental issues at their specific sites. Scientists at the Department of Energy's (DOE) national laboratories, with funding from DOE's Wind and Water Power Program, are undertaking a combination of laboratory, field, and modeling studies to investigate the effects of noise, EMF, benthic habitat alteration, blade strike, and toxicity from antifouling coatings on fish health, behavior, and natural movement patterns. Many of the issues can be addressed broadly, but many will need to be addressed on a site-specific and device-specific basis. These studies will likely indicate that some of these environmental concerns are minimal and can be addressed with reasonable mitigating measures or design changes. However, other issues are more difficult to assess and will likely take several years of study and analysis before the full potential for impact is understood. Based on preliminary study results and comments from regulators, the issue of greatest concern is the effect of physical encounters between aquatic organisms and the hydrokinetic devices. Areas for further study should include assessments of: (1) the ability of fish to avoid device contact through their behavioral response to device presence; (2) injury or mortality of adult fish from blade strikes; and (3) injury or mortality of larval or juvenile fish from blade strikes, shear stress, turbulence, or cavitation near the turbine blades. For some issues, such as whether fish are attracted to or repelled by hydrokinetic structures, an assessment of the effect will likely not be completed until devices have been deployed and operational for a year or more.

Lastly, there are potential environmental effects that might arise from an array of multiple devices that are difficult to assess from the study of a single device. Predictions of such cumulative effects can be modeled, but ultimately these effects will not be fully assessable until an array of devices is installed.

Conclusions

The United States has significant river, tidal, and ocean current resources which are predicted to be capable of producing a combined 60–80 GW of power using in-stream energy extraction devices. In an attempt to capture this important renewable resource, numerous devices have been designed and several small scale systems have been successfully tested on-site in both U.S. rivers and tidal flows. Economic assessments have been conducted for several proposed commercial installations that suggest that, if properly sited, this technology could be economically viable.

Among their attractive features, in-stream hydrokinetic operations do not contribute to greenhouse gas emissions or other air pollution and often have minimal visual impact. Since these systems do not utilize dams the way traditional hydropower systems typically do, their impact on the environment will differ and is presently not well understood. Those impacts will depend on the design, size, and numbers of turbines and the site-specific characteristics of their locations and their relative significance compared with the impacts of other waterway uses. Unfortunately, there are only a small, but growing, number of supporting studies quantifying in-stream hydrokinetic impacts.

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References

Aircraft Design & AeroFlightDynamics Group (ADAG). (2012). ⟨http://www.adag.unina.it/english/index.html⟩ (Mar. 25, 2014).

Amaral, S., Hecker, G., Perkins, N., Pioppi, N., and Dixon, D. (2010). "Determining the potential of injury and mortality to fish passing through hydrokinetic turbines." *Presentation at Energy Ocean Int. Conf.*, Fort Lauderdale, FL, June 8–10.

Aquantis LLC. (2011). ⟨http://www.aquantistech.com/⟩ (Aug. 01, 2011).

Bahaj, A. S., Molland, A. F., Chaplin, J. R., and Batten, W. M. J. (2007). "Power and thrust measurements of marine current turbines under hydrodynamic flow conditions in a cavitation tunnel and a towing tank." *J. Renew. Energy*, 32(3), 407–426.

Beutel, D. (2010). "RI Ocean special area management plan." *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf., No. COET014*, Palm Beach Gardens, FL, ⟨http://www.ces.fau.edu/coet/agenda.html⟩ (Mar. 26, 2014).

Bryden, H. L., Beal, L. M., and Duncan, L. M. (2005). "Structure and transport of the agulhas current and its temporal variability." *J. Oceanogr.*, 61(3), 479–492.

Bryden, I. G., and Couch, J. S. (2006). "ME1—Marine energy extraction: Tidal resource analysis." *Renew. Energy*, 31(2), 133–139.

Bryden, I. G., Grinsted, T., and Melville, G. T. (2004). "Assessing the potential of a simple tidal channel to deliver useful energy." *Appl. Ocean Res.*, 26(5), 198–204.

Cada and Meyer. (2005). "Resource concerns associated with natural streams." *Proc., Hydrokinetic and Wave Energy Technologies Technical and Environmental Issues Workshop*, U.S. Dept. of Energy, Washington, DC, 42–44.

Cada, G., et al. (2007). "Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments." *Fisheries*, 32(4), 174–181.

Chapra, S. C. (1997). *Surface water quality modeling*, McGraw Hill, New York, 844.

Chassignet, E. P., et al. (2007). "The HYCOM (hybrid coordinate ocean model) data assimilative system." *J. Marine Syst.*, 65(1–4), 60–83.

Chassignet, E. P., et al. (2009). "US GODAE: Global ocean prediction with the hybrid coordinate ocean model (HYCOM)." *Oceanogr.*, 22(2), 64–75.

Chen, F. (2010). "Kuroshio power plant development plan." *J. Renew. Sustain. Energy Rev.*, 14(9), 2655–2668.

Clarke, J., Grant, A., Connor, G., and Johnstone, C. (2009). "Development and in-sea performance testing of a single point mooring supported contra-rotating tidal turbine." *Proc., ASME 28th Int. Conf. on Ocean, Offshore and Arctic Engineering*, American Society of Mechanical Engineers (ASME).

Code of Federal Regulations. (2013a). Title 18, Chapter I, Subchapter B, Part 5.

Code of Federal Regulations. (2013b). Title 30, Chapter V, Subchapter B, Part 585.

Cyclo Ocean. (2011). ⟨http://www.cyclocean.com/⟩ (Aug. 2011).

Davis, B. V., Farrell, J. R., Swan, D. H., and Jeffers, K. A. (1986). "Generation of electric power from the Florida current." *Proc., 18th Annual Offshore Technology Conf.*, Offshore Technology Conference.

Department of Energy. (2011). "Marine and hydrokinetic technology database." ⟨http://www1.eere.energy.gov/windandhydro/hydrokinetic/default.aspx⟩ (Aug. 1, 2011).

Department of Energy. (2013a). “Marine and hydrokinetic technology database.” ⟨http://www1.eere.energy.gov/windandhydro/hydrokinetic/default.aspx⟩ (Apr. 26, 2013).

Department of Energy. (2013b). “Marine and hydrokinetic resource assessment and characterization.” ⟨http://www1.eere.energy.gov/water//marine_assessment_characterization.html⟩ (Dec. 18, 2013).

Department of Energy (DOE). (2009). “Report to congress on the potential environmental effects of marine and hydrokinetic energy technologies.” *DOE/GO-102009-2955*, Washington, DC.

Diaz, R. J., and Rosenberg, R. (2008). “Spreading dead zones and consequences for marine ecosystems.” *Science*, 321(5891), 926–928.

DSIREUSA. (2013). “Database of state incentives for renewables and efficiency.” U.S. Dept. of Energy, ⟨http://www.dsireusa.org⟩ (Mar. 14, 2013).

Duerr, A. E. S., Dhanak, M. R., and Van Zwieten, J. H. (2012). “Utilizing the hybrid coordinate ocean model data for assessment of florida current’s hydrokinetic renewable energy resource.” *Marine Technol. Soc. J.*, 46(5), 24–33.

EERE. (2010). “2009 Renewable energy databook.” U.S. Dept. Energy Efficiency and Renewable Energy, ⟨http://www1.eere.energy.gov/maps_data/pdfs/eere_databook.pdf⟩ (Mar. 2013).

Electrical Power Research Institute (EPRI). (2012). “Assessment and mapping of the Riverine hydrokinetic energy resource in the continental U.S.” *Rep. No. 1026880*, Palo Alto, CA.

Energy Policy Act (EPACT). (2005). *Public Law 109-58*, ⟨http://www.gpo.gov/fdsys/pkg/PLAW-109publ58/html/PLAW-109publ58.htm⟩.

Federal Energy Regulatory Commission (FERC). (2006). *Hydroelectric Infrastructure Technical Conf., Docket No. AD06-13-000*, December 6, 2006. transcript at 12; 22. testimony of George Hagerman.

Federal Energy Regulatory Commission (FERC). (2013). “Issued hydrokinetic preliminary permits map.” ⟨http://www.ferc.gov/industries/hydropower/indus-act/hydrokinetics/issued-hydrokinetic-permits-map.pdf⟩ (Mar. 2013).

Free Flow Power. (2013). ⟨http://free-flow-power.com⟩ (Jul. 2013).

Free Flow Power. (2010). “Mississippi River Projects 1-59 First Quarterly Study Report.” ⟨http://free-flow-power.com/documents⟩ (Nov. 2012).

Garrett, C., and Cummins, P. (2005). “The power potential of tidal currents in channels.” *Proc. R. Soc. A*, 461(2060), 2563–2572.

Georgia Tech. (2011). “Assessment of energy production potential from tidal streams in the U.S.” Georgia Tech Research, Atlanta, GA, ⟨http://www1.eere.energy.gov/water/pdfs/1023527.pdf⟩ (Mar. 2013).

Georgia Tech Research. (2013). “Assessment of energy production potential from ocean currents along the United States Coastline.” Georgia Tech Research, Atlanta, GA, ⟨http://www1.eere.energy.gov/water/pdfs/energy_production_ocean_currents_us.pdf⟩ (Dec. 2013).

Hadjerioua, B., Wei, Y., and Kao, S. C. (2012). “An assessment of energy potential at non-powered dams in the United States.” *Rep. No. GPO DOE/EE-0711*, Oak Ridge National Laboratory, Oak Ridge, TN.

Hall-Arber, M., Murray, T, Conway, F., and Pomeroy, C. (2010). “Listening and learning from stakeholders: Renewable energy space—Use conflicts on the OCS.” *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf.*, The FAU Center for Environmental Studies, Jupiter, FL, ⟨http://www.ces.fau.edu/coet/agenda.html⟩ (Feb. 2011).

Hammerfest Strom. (2013). ⟨http://www.hammerfeststrom.com/⟩ (Oct. 2013).

Hildenbrand, K. (2010). “Catching fishermen, engaging coastal communities in ocean energy development.” *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf.*, The FAU Center for Environmental Studies, Jupiter, FL, ⟨http://www.ces.fau.edu/coet/agenda.html⟩ (Feb. 2011).

Hybrid Coordinate Ocean Model (HYCOM). (2012). ⟨www.hycom.org⟩ (May 9, 2014).

Hydraulics and Recreation Work Group. (2010). “Hydrokinetic energy projects and recreation: A guide to assessing impacts.” *Public Review Draft, Prepared by the Hydrokinetics and Recreation Work Group for National Park Service Hydropower Assistance Program*, Dept. of Energy, Hydropower Reform Coalition.

Hydro Green Energy. (2011). ⟨http://hgenergy.com/index.php/projects/hastings-project/⟩ (Jul. 2011).

Hydro Green Energy. (2012). ⟨http://hgenergy.com/technologycomparison.html⟩ (Mar. 2012).

Hydro Green Energy. (2013). ⟨http://hgenergy.com/index.php/projects/hastings-project/⟩ (Apr. 2013).

Johnson, J. B., and Pride, D. J. (2010). “River, tidal, and ocean current hydrokinetic energy technologies: Status and future opportunities in Alaska.” *Technical Rep. prepared for the Alaska Energy Authority*, Alaska Center for Energy and Power.

Jones, I., and Wright, F. (2011). “World wave and tidal market.” *Marine Technology Reporter*, 54, New Wave Media, New York, 24–27.

Le Blanc, L. A., and Rucks, C. T. (1996). “A multiple discriminant analysis of vessel accidents.” *Accid. Anal. Prev.*, 28(4), 501–510.

Marine Current Turbines. (2013). “Marine current turbines .” ⟨http://www.marineturbines.com/⟩ (Oct. 2013).

Martin, J. L., Hesterlee, C., and Ballweber, J. A. (2007a). “Chapter 2: Energy production, reservoir and river water quality: Regulatory framework.” *Energy production and reservoir water quality*, J. L. Martin, et al., eds., ASCE, Reston, VA.

Martin, J. L., Higgins, J., Edinger, J., and Gordon, J. (2007b). *Energy production and reservoir water quality: A guide to the regulatory, technical, and theoretical basis for required studies*, ASCE, Reston, VA.

Martin, J. L., and McCutcheon, S. C. (1999). *Hydrodynamics and transport for water quality modeling*, CRC Press, Boca Raton, FL, 794.

McClure, B. (2010). “Active acoustic technology for biological detection, assessment, and monitoring at MHK sites.” *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf.*, The FAU Center for Environmental Studies, Jupiter, FL, ⟨http://www.ces.fau.edu/coet/agenda.html ⟩ (Feb. 2011).

McMichael, E., and Wyneken, J. (2010). “Assessing marine turtle habitat and movement within an important marine corridor.” *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf.*, The FAU Center for Environmental Studies, Jupiter, FL, ⟨http://www.ces.fau.edu/coet/agenda.html ⟩ (Sep. 2011).

Merrill, M. L. (2011). “Marine renewables in the United States.” *Sea Technology*, Vol. 52, Compass Publications. Arlington, VA, 25–28.

Miller, G., Franceschi, J., Lese, W., and Rico, J. (1986). “The allocation of kinetic hydroelectric conversion systems.” *KHECS in USA Drainage Basins: Regional Resource and Potential Power—Final Rep., NYU/DAS 86-151*, Dept. of Applied Science, U.S. Dept. of Energy, New York Univ., New York.

MMS. (2007). “Programmatic environmental impact statement for alternative energy development and production and alternate use of facilities on the outer continental shelf.” *Final Environmental Impact Statement, Publication No: MMS 2007-046*, Vol. 2, Minerals Management Service.

Ocean Renewable Power Company. (2014). ⟨http://www.orpc.co/⟩ (Mar. 31, 2014).

OpenHydro. (2013). “OpenHydro technology.” ⟨http://www.openhydro.com/technology.html⟩ (Mar. 2013).

Ortega-Achury, S. L., McAnally, W. H., Davis, T. E., and Martin, J. L. (2010). *Hydrokinetic power review*, James Worth Bagley College of Engineering, Mississippi State Univ., ⟨http://www.gri.msstate.edu/publications/docs/2010/04/9100Hydrokinetic_Power_Report_2010.04.01a.pdf⟩ (Mar. 14, 2013).

Pinkerton Computer Consultants (PCCI). (2009). “Marine and hydrokinetic renewable energy technologies: Potential navigational impacts and mitigation measures.” Office of Energy Efficiency and Renewable Energy, U. S. Dept. of Energy, Washington, DC.

Polagye, B., Previsic, M., and Bedard, R. (2006). “System level design, performance, cost and economic assessment—Knik Arm Alaska tidal in stream power plant.” *Rep. No. EPRI-TP-006 AK*, Electric Power Research Institute (EPRI), Palo Alto, CA.

Powell, C. (2011). “Tidal power: Cobscook Bay study bodes well for fish Castine Patriot web exclusive.” ⟨http://castinepatriot.com/news/2011/feb/4/tidal-power-cobscook-bay-study-bodes-well-fish/⟩ (Apr. 3, 2014).

Previsic, M. (2009). “Ocean energy in the United States—An overview.” *Proc., ASME 28th Int. Conf. on Ocean, Offshore and Arctic Engineering*, American Society of Mechanical Engineers (ASME), New York.

Previsic, M., Bedard, R., and Polagye, B. (2008). “System level design, performance, cost and economic assessment—Alaska river in-stream power plants." *Rep. No. EPRI RP 006 Alaska*, Electric Power Research Institute, Palo Alto, CA.

Ragheb, M. (2009). "Optimal rotor tip speed ratio." Univ. of Illinois, Urbana-Champaign, IL, ⟨http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Optimal%20Rotor%20Tip%20Speed%20Ratio.pdf⟩ (Feb. 25, 2011).

Ragheb, M. (2011). "Vertical axis wind turbines." Univ. of Illinois, Urbana-Champaign, IL, ⟨http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Vertical%20Axis%20Wind%20Turbines.pdf⟩ (Aug. 16, 2012).

Raye, R. E. (2002). "Characterization study of the Florida current at 26.11 north latitude, 79.50 west longitude for ocean current power generation." M.S. thesis, Ocean Engineering Dept. Florida Atlantic Univ., Boca Raton, FL.

Redden, A. (2010). "Tidal energy development in Canada." *Renewable Ocean Energy & the Marine Environment: Responsible Stewardship for a Sustainable Future Conf., No. COET044*, The FAU Center for Environmental Studies, Jupiter, FL, ⟨http://www.ces.fau.edu/coet/agenda.html⟩.

Sheets, H. E. (1974). "Energy recovery from fluid motion." *Proc., MacArthur Workshop on the Feasibility of Extracting Usable Energy from the Florida Current*, National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA.

SNMREC. (2013). "Southeast national marine renewable energy center." ⟨http://snmrec.fau.edu/⟩ (Aug. 15, 2013).

Stover, M. R. (2010). "Fish survival study on hydrokinetic power turbine shows device is ultra fish friendly." *Hydro Green Energy.*

THOR Energy Group. (2011). ⟨http://www.thorocean.com/⟩ (Aug. 2011).

United States Army Corps of Engineers (USACE). (2013). "Hydrologic engineering centers river analysis system HEC- RAS." U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, ⟨http://www.hec.usace.army.mil/software/hec-ras/⟩ (Mar. 2013).

United States Environmental Protection Agency (USEPA). (2012). "National summary of impaired waters." Environmental Protection Agency, Washington, DC.

United States Geological Survey (USGS). (2011). "Hydroelectric power water use." ⟨http://ga.water.usgs.gov/edu/wuhy.html⟩ (Aug. 2011).

U.S. Energy Information Administration. (2010). "Summary statistics for the United States, 1998 through 2009." United States Dept. of Energy, Washington, DC.

USGS. (2013). "National hydrographic dataset applications." United States Geological Survey, Reston, VA, ⟨http://nhd.usgs.gov/applications.html⟩ (Mar. 2013).

USGS. (2014). *Advantages of hydroelectric power production and usage*, Reston, VA, http://water.usgs.gov/edu/hydroadvantages.html (Apr. 4, 2014).

VanZwieten, J. H., Jr., Duerr, A. E. S., Alsenas, G. M., and Hanson, H. P. (2013). "Global ocean current energy assessment: An initial look." *Proc., 1st Marine Energy Technology Symp. (METS13) hosted by the 6th Annual Global Marine Renewable Energy Conf.*, Foundation for Ocean Renewables, Darnestown, MD, ⟨http://www.foroceanenergy.org/mets/2013-peer-reviewed-mets-papers/⟩ (Apr. 03, 2014).

VanZwieten, J. H., Jr., Oster, C. M., and Duerr, A. E. S. (2011). "Design and analysis of a rotor blade optimized for extracting energy from the Florida current." *Proc., ASME 2011 Int. Conf. on Ocean, Offshore, and Arctic Engineering*, American Society of Mechanical Engineers (ASME), New York.

Verdant Power. (2014). ⟨http://verdantpower.com/⟩ (Mar. 2014).

Vortex Hydro Energy. (2013). ⟨http://www.vortexhydroenergy.com/⟩ (Mar. 13, 2013).

Wang, D., Atlar, M., and Sampson, R. (2007). "An experimental investigation on cavitation, noise, and slipstream characteristics of ocean stream turbines." *J. Power Eng.*, 221(2), 219–231.

Wellinghoff, H. J., Pederson, J., and Morenoff, D. L. (2008). "Facilitating hydrokinetic energy development through regulatory innovation." *Energy Law J.*, 29(2), 397–420.

Yang, X., Haas, K. H., and Fritz, H. M. (2013). "Theoretical assessment of ocean current energy potential for the gulf stream system." *Marine Technol. Soc. J.*, 47(4), 101–112.

Yi, J. H., Lee, K. S., Park, J. S., and Park, W. S. (2009). "Structural health monitoring system for the Uldolmok tidal current power plant project." *Proc., ASME 28th Int. Conf. on Ocean*, Offshore and Arctic Engineering, Honolulu, HI.