3.0 Ocean Wave

3.1 Technology Overview

Ocean waves represent a form of renewable energy created by wind currents passing over open water. Since wind currents are generated by uneven solar heating, wave energy can be considered a concentrated form of solar energy. Incoming solar radiation levels on the order of 100 W/m2 are transferred into waves with power levels that can exceed 1,000 kW/m of wave crest length. The transfer of solar energy to waves is greatest in areas with the strongest wind currents (primarily between 30° and 60° latitude), near the equator with persistent trade winds and in high altitudes because of polar storms.

Waves are also efficient transporters of solar energy. Storm winds generally create irregular and complex waves. In deep water, after the storm winds die down, the storm waves can travel thousands of kilometers in the form of regular smooth waves, or swells, that retain much of the energy of the original storm waves. The energy in swells or waves dissipates after it reaches waters that are less than 200 meters deep. At 20-meter water depths, a wave's energy typically drops to about one-third of the level it had in deep water.

The total annual average wave energy[21] off the U.S. coastlines (including Alaska and Hawaii), calculated at a water depth of 60 meters, has been estimated (Bedard et al. 2005) at 2,100 terawatt-hours (TWh). The fraction of the total wave power that is economically recoverable in U.S. offshore regions has not been estimated, but it is significant even if only a small fraction of the 2,100 TWh/yr available is captured. (Currently, approximately 11,200 TWh/yr of primary energy is required to meet total U.S. electrical demand.)

Wave energy potential varies considerably in different parts of the world, and wave energy can't be harnessed effectively everywhere. Areas of the world rich in wave power include the western coasts of Scotland, northern Canada, southern Africa, Australia, *and the Northwest coast of the United States*. The estimated wave energy capacity available off the Oregon coast is approximately 14,000 MW (Bedar et al).

Wave energy offers several advantages over wind energy, including smoother power output, higher energy density, better demand matching, greater predictability, local manufacturing opportunities and reduced visual impact. Despite these advantages, wave energy technology is still pre-commercial, and it is too early to predict which technology or mix of technologies will prevail. EPRI has conducted cost-of-electricity assessments at specific locations and for certain devices such as Ocean Power Delivery's Pelamis device, which is pictured below. EPRI estimated the cost of electricity from a Pelamis device at 9 to16 cents/kWh. More accurate cost estimates are premature until further research and development addresses the

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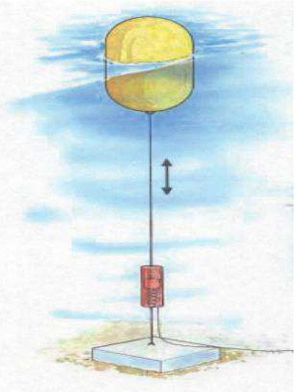
[21] The common measure of wave power is $P = (\rho g^2TH^2)/ 32\Pi$ watt per meter (W/m) of crest length (distance along an individual crest) where:
P = the density of seawater = 1,025 kg/m3,
G = acceleration due to gravity= 9.8 m/s/s,
T = period of wave (s), and
H = wave height (m).

technical and commercial barriers that must be resolved before wave energy is commercially competitive.

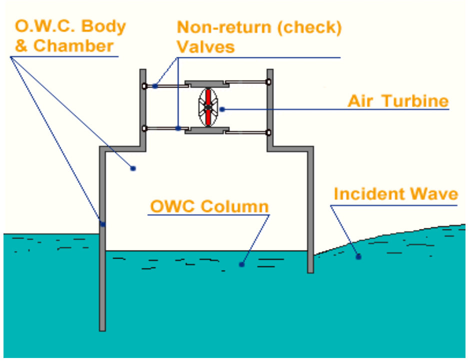
A variety of offshore wave-energy devices are undergoing field testing. These devices are generally classified as point absorbers, terminators, attenuators and overtopping devices. Some systems extract energy from surface waves. Others extract energy from pressure fluctuations below the water surface. Some systems are fixed in position and let waves pass by them, while others follow the waves and move with them. And some systems concentrate and focus waves to maximize electrical generation. Below are descriptions and commercial status of each type of wave energy conversion technology.



Point absorbers, (illustrated at left), are floating structures with components that move relative to each other due to wave action (e.g., a floating buoy inside a fixed cylinder). The relative motion drives electromechanical or hydraulic energy converters.

Commercial status*:* The Ocean Power Technologies (OPT) PowerBuoy demonstration unit, pictured at right, is rated at 40 kW and was installed in 2005 for testing offshore from Atlantic City, New Jersey. Tests are being conducted in the Pacific Ocean with a unit installed in 2004 and 2005 off the coast of the Marine Corps Base in Oahu, Hawaii. A commercial-scale PowerBuoy system is planned for the northern coast of Spain, with an initial wave park (multiple units) at a 1.25-MW rating. Initial operation is expected in 2007.

Point Absorber
(OPT Power Buoy)

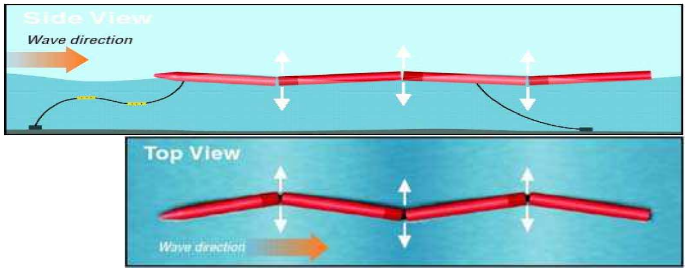


Terminator devices extend perpendicularly to the direction of wave travel and capture or reflect the power of the wave. These devices are typically onshore or near-shore; however, floating versions have been designed for offshore applications. In the oscillating water column (OWC), illustrated above, water enters through a subsurface opening into a chamber with air trapped above it. Wave action causes the captured water column to move up and down like a piston to force the air though an opening connected to a turbine.

Terminator
(Energetech Oscillating Water Column)

Commercial status: The full-scale, 500-kW prototype OWC, pictured above, was designed and built by Energetech and underwent testing in 2006 offshore at Port Kembla in Australia.

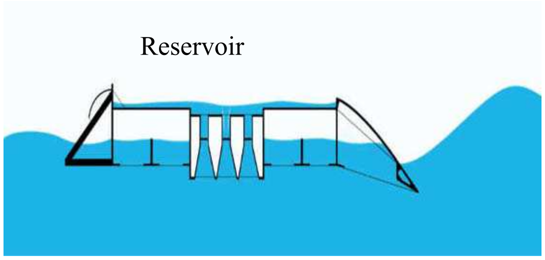
Attenuators, such as the one illustrated below, are long multi-segment floating structures oriented parallel to the direction of the waves. The differing heights of waves along the length of the device causes flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters.



Commercial status: A full-scale, four-segment production prototype, the Ocean Power Delivery (OPD) Pelamis, pictured below, is rated at 750 kW and was sea tested for 1,000 hours in 2004., This successful demonstration was followed in 2005 by the first order of a commercial wave energy conversion system from a consortium led by the Portuguese power company Enersis SA. The first stage, scheduled to be completed in 2006, consists of three Pelamis machines with a combined rating of 2.25 MW to be sited about 5 kilometers off the coast of northern Portugal. An expansion to more than 20-MW capacity is being considered. A Pelamis-powered 22.5-MW wave energy facility is also planned for Scotland, with the first phase targeted for 2006.

Attenuator
(OPD Pelamis)

Overtopping devices, such as the one illustrated at right, have reservoirs that are filled by incoming waves to levels above the average surrounding ocean. The water is then released, and gravity causes it to fall back toward the ocean surface. The energy of the falling water is used to turn hydro turbines. Specially built seagoing vessels can also capture the energy of offshore waves. These floating platforms create electricity by funneling waves through internal turbines and then back into the sea.



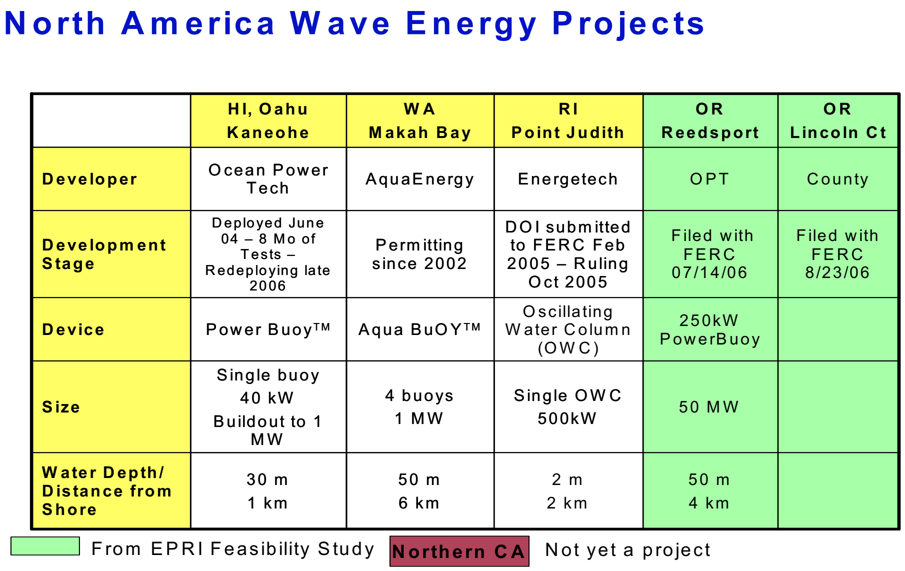
Overtopping
(Wave Dragon)

Commercial status: In March 2003, the 237-ton Wave Dragon prototype, pictured at left, was towed to the Danish Wave Energy Test Station in Nissum Bredning. Sea tests were conducted in this location through January 2005 to determine hydraulic behavior, turbine strategy and power production to the grid in Denmark.

In April 2006, a modified prototype was deployed at a more energetic wave climate site, and testing will continue until the summer of 2007. There has been over a year of operating and maintenance on all sub-systems, components and materials used on the prototype. Future Wave Dragon development includes a 7-MW demonstration project off the coast of Wales

3.2 Opportunity Overview

The Northwest is actively engaged in exploring the potential of its wave energy resource.



North America Wave Energy Projects

	HI, Oahu Kaneohe	WA Makah Bay	RI Point Judith	OR Reedsport	OR Lincoln Ct
Developer	Ocean Power Tech	AquaEnergy	Energetech	OPT	County
Development Stage	Deployed June 04 – 8 Mo of Tests – Redeploying late 2006	Permitting since 2002	DOI submitted to FERC Feb 2005 – Ruling Oct 2005	Filed with FERC 07/14/06	Filed with FERC 8/23/06
Device	Power Buoy™	Aqua BuOY™	Oscillating Water Column (OWC)	250kW PowerBuoy	
Size	Single buoy 40 kW Buildout to 1 MW	4 buoys 1 MW	Single OWC 500kW	50 MW	
Water Depth/ Distance from Shore	30 m 1 km	50 m 6 km	2 m 2 km	50 m 4 km	

🟩 From EPRI Feasibility Study **Northern CA** Not yet a project

The table above indicates that the Northwest is pursuing three of the five North American wave energy conversion projects. Northwest stakeholders have conducted site feasibility studies and filed FERC site permits for sites near Makah Bay, Washington, and Reedsport, Oregon, and are currently evaluating alternative technologies for future deployment and testing.

Each of these projects is described below along with a brief overview of Oregon State University's commitment to becoming America's leading institution in wave energy research and development.

Makah Bay Project:

The AquaEnergy Group, Ltd., plans to develop and operate a wave energy project in the Pacific Ocean in Makah Bay, Clallam County, near the city of Neah Bay, Washington. The land portion of the project is on Makah Indian Nation property. Part, or all of the aquatic portion of the project is within Washington state waters, the Olympic Coast National Marine Sanctuary (OCNMS) and the Flattery Rocks National Wildlife Refuge.

The Makah Bay Project is supported by a consortium of public and private agencies, the Makah Indian Nation, Washington State University, Clallam County PUD, Clallam County

Economic Development Council, BPA, Battelle, Energy Northwest and Washington State Public Utility Districts Association. AcquaEnergy and the Makah Tribe are working together with Washington state's federal legislative delegation to strengthen governmental awareness of the Makah Plant.

The project involves the design and construstion of a pilot 1-MW offshore wave energy power plant. It is made up of four wave energy conversion buoys, called AquaBuoys (pictured at right), which are based on a heaving buoy principle. The portion of each buoy that is above water is similar in size to large navigational buoys used to mark shipping lanes and identify obstructions. Four AcquaBuoys will be placed 3.7 statute miles (3.2 nautical miles) west of Hobuck Beach in Makah Bay in water depths of approximately 150 feet. Energy will be transported to a small shore station via an anchored transmission cable which will run along the sea floor, except near shore, where it will be buried using a horizontal directional drilling (HDD) technique.

AquaEnergy is developing the entire project to conduct research, to produce electricity for Clallam County Public Utility District and to demonstrate the economic, environmental and tribal benefits of wave energy conversion power plants.

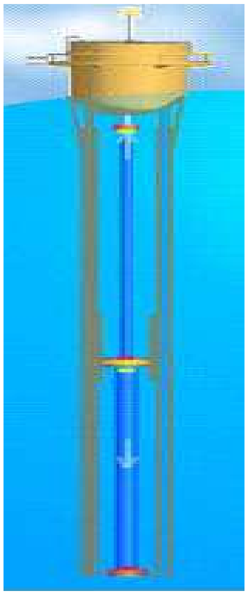
Additional elements of the Makah Bay wave energy plant include:

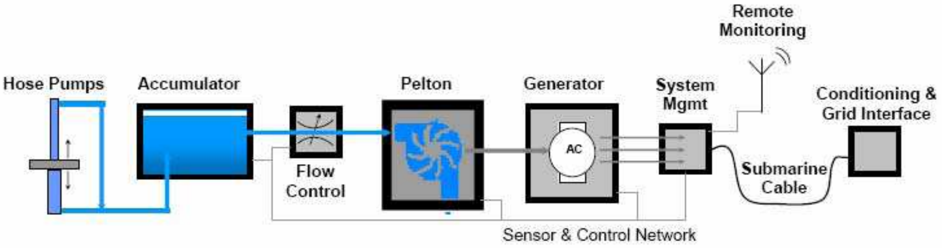
- Excellent wave energy potential (approximately 8.5 kw/ft or 28 kw/m wave front). The site has good wave energy content and consistent annual wave height;
- The Makah Bay site represents one of the better wave energy resources of sites evaluated in the 48 lower states;
- Sufficient water depths (at least 120 feet) reasonably close to shore;
- Nearby major utility electrical distribution lines;
- Participating land manager and electricty consumer in the Makah Indian Nation;
- Need for energy source on the west side of Clallam County PUD distribution service territory, and;
- Close to boating facilities of Neah Bay.

AquaEnergy is in the final stages of a three-year FERC Alternative Licensing Process involving the following public agency participants: FERC, National Oceanic and Atmospheric Administration (NOAA), Washington State Department of Natural Resources, Washington State Department of Ecology, Washington State Department of Fish and Wildlife, U.S. Coast Guard, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, Washington State Historical Preservations Office, Tribal Historical Preservation Office and Bureau of Indian Affairs.

An Environmental Assessment (EA) has already been completed by AquaEnergy consultant Davine Tarbell and Associates with a finding of no significant impact. AquaBuoy has also completed oceanography surveys, and samplings and surface measurement devices were deployed to determine wind and wave intensities over a period of several months. AquaBuoy intends to submit a FERC license application before the end of 2006, with the goal of making this project the nation's first fully operable offshore wave energy plant connected to a grid. This prototype plant will feature:

- A unique hose-pump power take-off system that uses only water as its hydraulic liquid;
- A point absorbing omni-directional wave energy converter;
- A non-toxic, environmentally friendly material composition that meets the Kyoto Protocol Standards;
- A low riding silhouette that conforms to aesthetic sensitivities;
- An offshore power plant configuration that avoids interference with marine traffic and fishing;
- An economic alternative to fossil fuel power plants; and,
- A green energy power plant with construction and components supplied locally.





Energy transfer takes place by converting the vertical component of wave motion into pressurized water flow by means of two-stroke hose pumps. Pumped water is directed into a conversion system consisting of a Pelton turbine driven generator. The buoy closest to shore will function as the collection buoy or hub, where the power cables from each AquaBuoy are connected to the sub-sea cable. The expected output from each buoy is 480-V AC current, with power levels between 0 and 250kW and with an estimated average output of 46kW. The Makah Bay pilot power plant is projected to deliver 1,500 MWh annually.

The AquaBuoy, illustrated above, consists of four elements:

- Buoy
- Acceleration tube
- Piston
- Hose-pump

The acceleration tube is a vertical, hollow cylinder rigidly mounted under the body of the buoy. The tube is open at both ends to allow unimpeded entry and exit of seawater in either direction. The piston, a broad, neutrally buoyant disk, is at the midpoint of the acceleration tube, When the buoy is at rest, the piston is held at the midpoint by the balanced tension of two hose pumps attached to opposite sides of the piston. They extend to the top and bottom of the acceleration tube, respectively.

The hose-pump is a steel reinforced rubber hose. When the hose is stretched, its internal volume is reduced, thereby acting as a pump. Pressurized sea water is subsequently expelled into a high-pressure accumulator, and, in turn, fed to a turbine which drives a generator.

Other AquaEnergy wave energy projects include:

- Figuera da Foz (Portugal), planned to be installed in 2008
- Ucluelet (British Columbia), planned to be installed in 2010

These three projects will have a combined power generation potential of 200 MW when at full capacity.

Reedsport Oregon Project

Oregon's first wave energy project will be located along the southern Oregon coast near the city of Reedsport. Ocean Power Technologies has filed a preliminary permit with FERC to develop a wave energy park.

The Reedsport site is a prime location for wave energy development because it has an excellent wave resource, an existing power substation with capacity for 50 MW, and a three-kilometer underwater effluent pipeline from a closed paper mill just north of Reedsport and at the mouth of the Umpqua River. This pipeline can be used to run underwater power cables from the wave park buoys to the Gardiner substation where the energy would enter into the grid.

New Jersey-based Ocean Power Technologies Inc. (OPT) has already applied for a permit from FERC to build and test the wave power installation. OPT intends to install its ocean-tested PowerBuoys pictured at left. The Reedsport OPT project would start with a 2-MW pilot-scale installation made up of 13 to14, 150-kW PowerBuoys. The second phase of the project would be commercial scale and produce up to 50 megawatts using the larger 500-kW version of the PowerBuoy which OPT is planning to develop. (Each time the power diameter is doubled, the power conversion device quadruples the amount of wave energy captured. Thus, wave energy has a very strong economy of scale similar to that for wind power).

Approval for the full-scale 50-MW wave power plant following completion of the initial program is expected to result in significant investment and creation of jobs in Oregon. Central Lincoln County Public Utility District supports the project and has said it would purchase power from the Reedsport wave park.

The first phase of this project, which BPA is proposing to fund at $100,000, includes deploying a wave energy conversion device, working with the marine industry to identify the components of a study plan and developing a permitting roadmap. The work plan for the first phase of the project consists of four tasks:

1. Perform an Environmental Assessment (EA) that must be completed before any prototype wave energy buoy is deployed in the ocean. An EA is a concise document that a federal agency prepares under the National Environmental Policy Act (NEPA) to provide sufficient evidence and analysis to determine whether a proposed agency action would require preparation of an environmental impact statement (EIS) or a finding of no significant impact.

2. Initiate a Marine Industry Outreach program to reach out and develop communication and consensus with other existing marine users on such topics as ideal wave park locations, operation and maintenance of wave devices, impacts on fishing and other marine issues.

3. Conduct a permitting study to identify all of the permitting agencies, data requirements and sequence of steps in filing with FERC. FERC will lead this effort since the permitting process for such projects has yet to be defined.

4. Data Acquisition: The ability to track and understand the dynamics of the energy delivered to the utility grid is an important component of the demonstration project. Central Lincoln PUD and OPT will develop a way to track the energy injected at the point of interconnection.

OPT is also planning a 1.5-MW project off the coast of Spain, a 2 to 5-MW project in France and a potential project in southwest England

Lincoln County Wave Park Project

Oregon is on the verge of developing the nation’s first commercial scale wave energy park. In an independent study conducted by EPRI, Oregon was identified as an ideal location for wave energy conversion based on its tremendous wave resource, coastal port infrastructure and transmission capacity. These factors, combined with Oregon State University’s world leading research on wave energy, the state’s highly capable manufacturing clusters and Oregonians’ long-term commitment to renewable energy make Oregon the complete candidate to lead the United States in development of the wave energy industry.

The Oregon State College of Engineering, the Oregon Department of Energy and EPRI are hoping to establish a national wave energy conversion research, development and demonstration center at one of several locations off the Lincoln County coast. (See Oregon State University’s National Wave Energy Research Center discussion below)

In August 2006, Lincoln County applied for a FERC preliminary permit for multiple wave plants situated in the open ocean in water depths between 1 and 70 meters, somewhere within the rectangular area bounded by Lincoln County’s northern and southern borders, the shoreline and the state’s jurisdictional three-mile territorial limit.

Lincoln County, together with Central Lincoln People's Utility District (CLPUD), has identified at least nine potential interconnections between the existing CLPUD near-shore substations on the power distribution grid and possible "wave energy park" locations just off the coast. A BPA substation in Toledo, Oregon, can distribute power beyond the county on the electrical grid. The project will comply with all interconnection requirements as specified by CLPUD and BPA. There also are possible interconnections with Pacific Power in the northern portion of Lincoln County.

Lincoln County will work closely with Oregon State University and other stakeholders to identify and deploy the most suitable wave energy conversion technologies from all of the available alternatives capable of generating commercially viable energy. Wave parks of various sizes will be explored.

Oregon State University's National Wave Energy Research Center

Oregon State University has been pushing for federal funding for a proposed National Wave Energy Research Center in Newport, Oregon. The OSU facility would likely be modeled after the European Marine Energy Center (EMEC) in the Orkney Islands off northern Scotland.

The EMEC facility includes four "plug-and-play" test berths at the 50-meter depth for wave energy device testing. Armored cables link each berth to a substation and an 11-kV transmission cable connecting to the national grid and to a data/communications center located in nearby Stromness.

The berths are pre-permitted, allowing wave energy device manufacturers to do full-scale grid-connected temporary installations of their devices without going through a full (and lengthy) permitting and siting process. (Ocean Power Delivery with its Pelamis wave energy device has benefited a great deal from use of the EMEC facility, as have several other wave energy companies). The EMEC facility also includes state-of-the-art onshore research laboratory facilities to enable research and development of wave energy conversion devices, longer-lasting marine materials and other related projects.

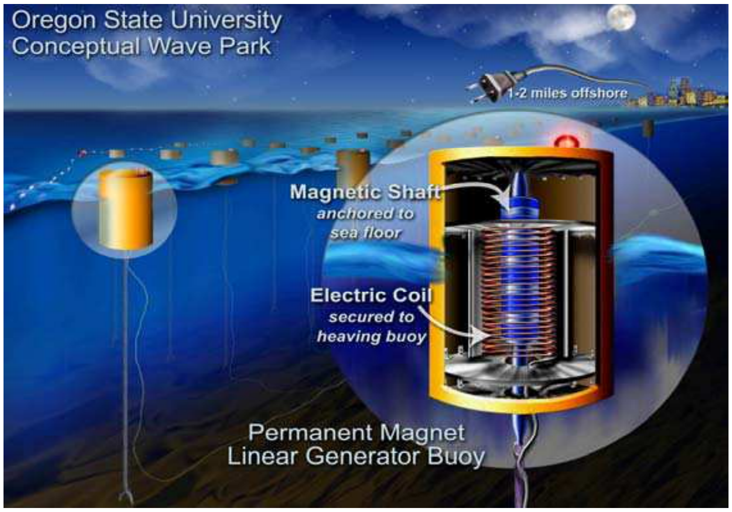
The Newport facility would create new local jobs, both in the construction phase and in daily operations, promote development and add to the state's goal of energy self sufficiency. It would receive direction and support from OSU and its Hatfield Marine Science Center in Newport, which is pictured below. In addition, OSU's College of Engineering, which has been doing cutting-edge research on wave energy conversion devices and is involved in the Reedsport project discussed above, is home to the Motor Systems Resource Facility, the highest-power energy systems laboratory at any university in the nation, and the O. H. Hinsdale Wave Research Laboratory. Both resources would be available for researchers working at the site.

Motor Systems Resource Facility

O. H. Hinsdale Wave Research Lab

Hatfield Marine Science Center

One of the OSU buoy devices on the drawing board is what engineers describe as a "permanent magnet linear generator." The 12-by15-foot long structure of the buoy is made of an impervious composite of plastic and fiberglass. A coil of copper wire within the buoy surrounds a neodymium magnet shaft, which is stationary and tethered to the ocean floor by a steel cable. As the buoy rises and falls on the waves, the coil moves up and down relative to the shaft, inducing voltage as it passes through the magnetic field. A power take-off cable carries the resulting electric current about 100 feet down to the seafloor where another cable transfers the power generated by many buoys to an onshore substation.



Each buoy is projected to generate 100 kilowatts of power, on average. A network of about 500 such buoys could power downtown Portland. Moreover, wave parks could address the state's energy imbalance. West of the Cascades, Oregon consumes about 1,000 megawatts more than it generates. By tapping about 5 percent of the coastline, wave energy could make up the difference without a need for new transmission lines.

The engineers' goal is to produce a device that is lean and streamlined and can withstand gale-force winds, monster storms and the vagaries of sea life. These vagaries can include anything from rafts of floating bull kelp to colonies of seals looking for a place to haul out. Engineers are now working on their fourth and fifth prototypes. They call their simplified approach to energy conversion "direct drive."

3.3 RD&D Challenges

Although many wave energy devices have been invented, only a small proportion have been tested and evaluated at sea in ocean waves rather than in artificial wave tanks. Many research and development goals remain, including cost reduction, efficiency and reliability improvements, identification of suitable sites, interconnection with the utility grid, and better understanding of the impacts of the technology on marine life and the shoreline. It is also essential to demonstrate the ability of the equipment to survive the salinity and pressure environments of the ocean as well as weather effects over the life of the facility.

Some environmental issues associated with permitting an ocean wave energy conversion facility include:

- Disturbance or destruction of marine life (including changes in the distribution and types of marine life near the shore);
- Possible threat to navigation from collisions due to the low profile of the wave energy devices above the water, making them undetectable either by direct sighting or by radar. Interference of mooring and anchorage lines with commercial and sport fishing is also possible;
- Degradation of scenic ocean front views from wave energy devices located near or on the shore and from onshore overhead electric transmission lines;
- Toxic releases from leaks or accidental spills of liquids used in those systems with working hydraulic fluids;
- Noise generation above and below the water surface.

Some of the mechanical and electrical issues associated with ocean wave devices include:

Survivability

Onshore devices do not experience conditions as severe as offshore devices, since waves break, and their power dissipates while traveling into shallow water. To date, most of the shoreline devices have been based on the concept of the Oscillating Water Column (OWC). However, even with shoreline devices, the turbine must be protected from over-speeding, which is caused by high wave power input or grid disconnection. This protection could be provided by an electronic feedback control system, which uses generator torque, valve position and air pressure in the turbine chamber as signal parameters.

The geometry and the dimension of onshore devices are important as well. Almost all wave devices are fairly large in order to capture as much energy as possible from the sea. However, after the OWC in Toftestallen, Norway, was destroyed by a large storm in 1988, later OWCs have become smaller with an inclined surface facing the wave direction. In addition, the materials for onshore devices should be carefully selected; e.g., reinforced sulfate-resistant concrete for structure work and corrosion-resistant steel for turbine blades.

The size of offshore devices is also critical in determining their performance. However, because of their size, the geometric design must allow them to survive through destructive waves and storms. For instance, Pelamis has flexible joints between its rigid units and can punch through strong waves.

Offshore devices may also require special seals to prevent sea water leaking into the device through joints or other openings. The material used should be flexible and inert; e.g., reinforced rubber membrane for heaving buoys. Inert polymers with high strength or anti-corrosion steels can be used in flexible structures, such as Pelamis.

Mooring

Since the offshore devices are floating, the mooring system requires careful design. It should be able to withstand fatigue and stress from the motion of the sea, while letting the devices move in an allowed range. So far, three mooring methods have been developed. The first type uses heavy blocks of concrete lying on the seabed. The second type requires holes to be drilled into the seabed and filled with concrete to moor the device. This method can resist quite strong waves. The last method, which is now under research, is the seabed surface suction.

Maintenance and Accessibility

As with any power station, breakdowns or malfunctions are always possible. Exposure of wave energy conversion devices to the marine environment and large storms increases the chances of failure. In addition, the probability of breakdown is greater during winter when access to the system may be restricted by bad weather. Any delays in access can lead to a loss of energy.

Maintenance of certain wave devices could be carried out by the use of small submarines (already in use in Japan). The advantage of submarine maintenance is that it can work independently of the wave climate on the sea surface. This makes it possible to plan a periodic maintenance procedure. Onshore devices are obviously easier to construct and maintain. In addition, the possibility of breakdowns due to large storms is less for onshore systems.

The transmission of electricity from an offshore wave power plant requires the use of flexible submarine power cables. The bending fatigue characteristics of these cables and their steel armoring must be well understood and adequately designed for the conditions at hand. There is also the potential for insulation leakage and breakdown. Relay protection systems can help with this problem, but obviously the design and choice of materials for submarine cables requires further research.

3.4 Sector Actors

EPRI reports - EPRI Ocean Energy Program is for the public benefit. All technical work is totally transparent and available at www.epri.com/oceanenergy

EPRI WP-001-US, WEC Device Performance Estimation Methodology
EPRI WP-002-US, WEC Economic Assessment Methodology
EPRI WP-003-HI, Hawaii Site Survey
EPRI WP-003-ME, Maine Site Survey
EPRI WP-003-OR, Oregon Site Survey
EPRI WP-003-WA, Washington Site Survey
EPRI WP-004-NA, TISEC Device Survey and Characterization
EPRI WP-005-US, System Design Methodology
EPRI WP-006-HI, Hawaii System Level Design Study
EPRI WP-006-ME, Maine System Level Design Study
EPRI WP-006-MA, Massachusetts System Level Design Study

EPRI WP-006-SFA, SF California System Level Design Study - Pelamis
EPRI WP-006-SFB, SF California System Level Design Study – Energetech
EPRI WP-007-US, Environmental Issues Study
EPRI WP-008-USA, Regulatory Issues Study
EPRI WP-009-US, Final Summary Report

A. European Marine Energy Center Test Facility - www.bwea.com/marine/facilities.html

The European Marine Energy Centre (EMEC), based in the Orkney Islands north of Scotland, is among the first of its type in the world and will provide a unique one-stop facility for the industry to test potential wave and tidal energy generators.

B. Oregon State University Ocean Wave Energy Research. http://eecs.oregonstate.edu/msrf/

Development & Demonstration Center (under development – OSU is establishing a U.S. marine energy research center on par with EMEC

C. Wavegen - http://www.wavegen.com/

Located in Inverness, Scotland, Wavegen owns and operates one of the most advanced marine renewable development test facilities in the world. Its technology is based on the Oscillating Water Column (OWC) technology. Wavegen developed and operates Limpet, the world's first commercial-scale wave energy device that generates wave energy for the grid.

D. Energy Systems Research Unit (ESRU) - http://www.esru.strath.ac.uk/

ESRU is a research group within the Department of Mechanical Engineering at the University of Strathclyde in Glasgow which was established in 1987 as a cross-discipline team concerned with new approaches to environment energy demand reduction and sustainable energy supply.

E. Companies involved in ocean wave RD&D include:

- AquaEnergy - http://www.aquaenergygroup.com
- Archimedes WaveSwing - http://www.waveswing.com
- Ocean Power Delivery Ltd. – http://www.oceanpd.com
- Ocean Power Technologies - http://www.oceanpowertechnologies.com
- Ocean Wave Energy Company - http://www.owec.com
- Sea Power International AB - http://www.seapower.se
- WaveDragon ApS - http://wavedragon.net
- Wavegen - http://www.wavegen.com/.
- WavePlane - http://www.waveplane.com

4.0 Tidal In-Stream Energy Conversion (TISEC)

4.1 Technology Overview

Tidal flows result when the gravitational forces of the sun and the moon move a mass of water with speed and direction. Because it is closer to the earth, the moon exerts roughly twice the tide raising force of the sun. The gravitational forces of the sun and moon create two "bulges" in the earth's oceans: one closest to the moon, and the other on the opposite side of the globe. These bulges result in two tides (high to low water sequences) each day.

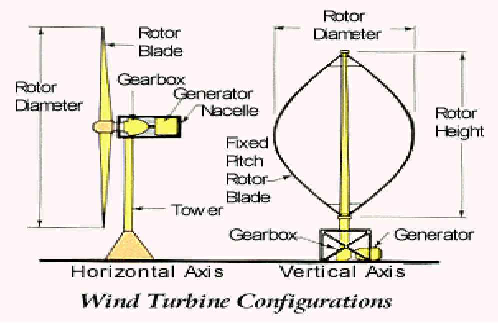
Electricity generation using tidal power is achieved by capturing the energy contained in a moving water mass due to tides. Two types of tidal energy can be extracted: the potential energy from the difference in height (or head) between high and low tides, and the kinetic energy of currents between ebbing and surging tides. The former method, which is pictured below and to the left, uses tidal barrages or dams across bays or estuaries. The latter method, illustrated below and to the right, employs submerged turbines to generate energy from in-stream tidal currents.

In-stream tidal technology is considered much more feasible than barrages or dams because of significantly lower construction costs, impacts on marine life, ecological disruptions and navigational problems.

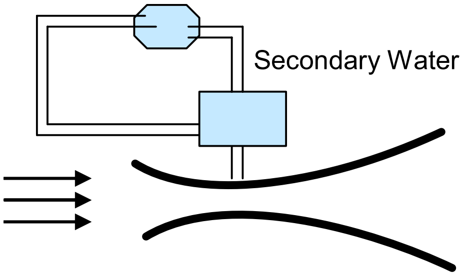
In-stream tidal technology generally employs submerged turbines that are similar in function to wind turbines, capturing energy through the processes of hydrodynamic, rather than aerodynamic, lift or drag.

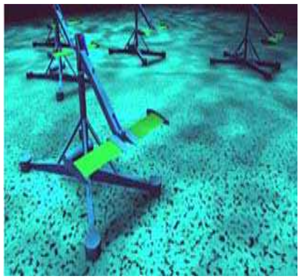
There are four basic types of in-stream tidal flow energy conversion devices: horizontal axis turbines, vertical axis turbines, venture devices and oscillatory devices. These devices are illustrated below.

Horizontal Axis Turbine **Vertical Axis Turbine**



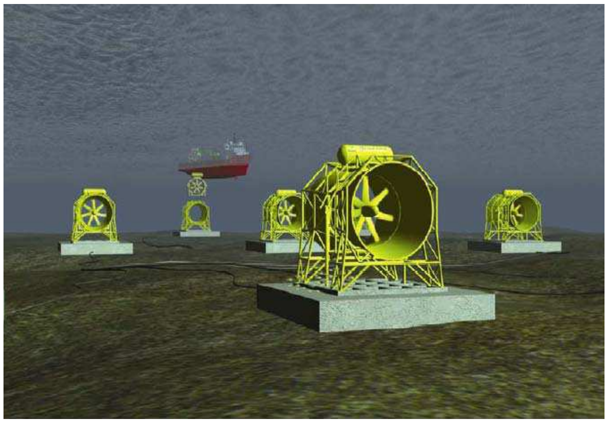
Venturi **Oscillatory**

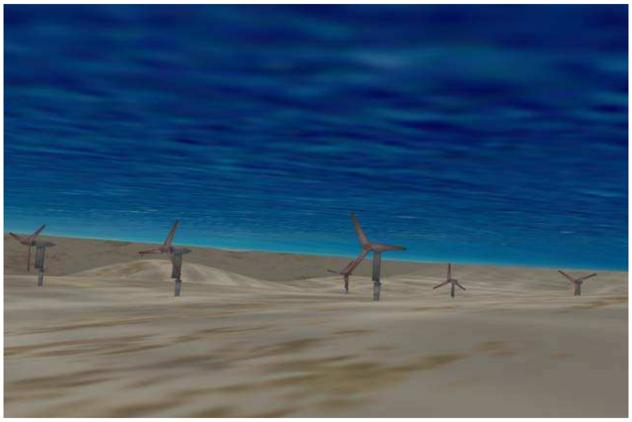




In-stream tidal flow devices have generators for converting kinetic energy into electricity, along with a means to transport electrical current to shore where it can be incorporated into the electrical grid.

Mechanisms such as posts, cables or anchors keep the turbines stationary relative to the currents with which they interact. In large areas with powerful currents, tidal flow devices may be installed in groups or clusters to create a “marine current facility” as shown below. Turbine spacing would be determined based on wake interactions and maintenance needs.





Tidal in-stream energy devices also have some inherent advantages over other renewable technologies such as wind and ocean wave. For example, wind and to a lesser extent wave technologies, depend on weather, whereas tides are based on the gravitational pull of the moon and the sun on the oceans. These forces follow a set pattern that can be predicted far into the future, allowing power production from tidal in-stream devices to be predicted with confidence. This predictability of tidal power will allow for easier integration within network planning.

The energy per second intercepted by an energy conversion device is a function of the frontal area of the device, the density of the water and the cube of the speed of the water. Since water is about 835 times denser than wind, the energy contained in a 12-mph water flow is approximately equal to that contained in an air mass moving at about 110 mph. This means that tidal turbines can produce the same amount of energy as wind turbines using much smaller and slower moving turbine blades.

In-stream tidal energy devices, which are generally submerged, also minimize the aesthetic issues that plague many energy infrastructure projects, from nuclear and coal to wind generation.

In spite of these advantages, in-stream tidal energy development worldwide is still in a pre-commercial state when compared to wind development. In fact, there are no commercially operating in-stream tidal turbines currently connected to any electric power transmission or distribution grid.[22]

However, a number of global market drivers are making tidal in-stream generation a more viable alternative to traditional energy sources:

- The worldwide demand for electricity is expected to double within the next 20 years, with the strongest growth in developing areas of Asia.
- The decommissioning of nuclear power stations and an increased reliance on natural gas resulting in concerns over security of supply and an increased push for renewables.
- Global warming and the introduction of emissions-trading schemes will enhance the economic viability of renewables.

In addition to these market drivers, the potential worldwide supply of untapped ocean current energy is enormous:

- The total worldwide power in ocean currents has been estimated to be about 5,000 GW, with power densities of up to 15 kW per square meter.
- India's minister of state for non-conventional energy sources estimated that over 15,000 MW of tidal power potential exists in the gulfs of Kachh and Cambay and in Gujarat and Durgaduani Creek in Sunderbans in West Bengal.
- It has been estimated that capturing just 1/1,000 of the available energy from the Gulf Stream would supply Florida with 35 percent of its electrical needs. The Gulf Stream

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[22] The only commercially operating tidal power plants are barrage designs: a 240-MW plant in France, a 20 MW plant in Nova Scotia and a .5-MW plant in Russia.

has 21,000 times more energy than Niagara Falls in a flow of water that is 50 times the total flow of all the world's freshwater rivers.

- The West Coast of North America has significant in-stream tidal resources, which could be tapped. For example, depending on the exact location, the annual average power density in Alaska's Bay of Fundy is between 5-10 kW per square meter, while Puget Sound and San Francisco Bay densities vary between 1-2 kW per square meter.[23]

In 2003, Brian Wilson,[24] the former United Kingdom DTI Energy Minister made the following statement: "Wave and tidal power have huge potential to supply a significant proportion of the country's [Britain] energy needs." Wilson also recognized the business opportunities presented by tidal and wave technologies:

> It is essential that we move from the research and development phase, which has been going on for many years, into commercial application. The potential for such devices in the UK is significant but it also important to remember that there is going to be a global demand for proven technologies and we are well placed to capture this market once they are operating successfully in the UK. Success in projects of this sort will further the commercial development of wave and tidal energy and could lead to the creation of a major industrial sector with export potential.

In 2005, EPRI addressed this question of the most promising in-stream tidal power technologies by evaluating the techno-economic feasibility of all known tidal in-stream energy conversion (TISEC) devices.[25] Seven states and provinces in North America participated in this collaborative study, including Alaska, Washington, California, Massachusetts, Maine, New Brunswick and Nova Scotia. In-kind funding was provided by state agencies, utilities within these states, and DOE through the National Renewable Energy Laboratory (NREL).

EPRI characterized the following eight in-stream turbines as acceptable for selection by the state/province advisors for application in pilot plant testing at several North American sites. Permitting, device selection, design and testing are already underway at several locations. (Highlights of the Puget Sound and San Francisco Bay tidal projects are summarized in section 4.2.)

1. The Gorlov Helical Turbine ("GHT"), pictured at left, is a cross-flow turbine with airfoil shaped blades that provide a reaction thrust that can rotate the device at twice the speed of the water flow. It is self-starting and can produce 1.5 kW of power from a water flow as low as three knots (1.5 m/sec). GHT output power is 110 volts, 60 Hz AC. The standard model GHT (1 meter in diameter and 2.5 meters in length) can be installed vertically or horizontally in multiple GHT arrays and in waters as shallow as four feet. Due to its axial symmetry, the GHT always rotates in

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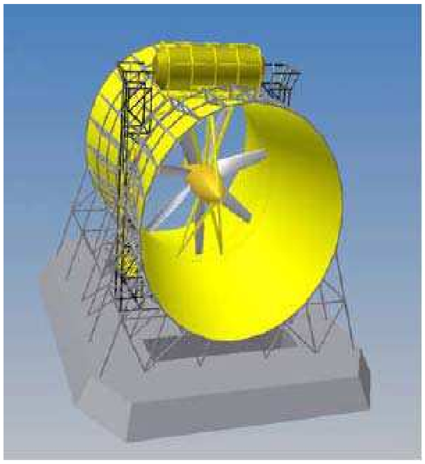
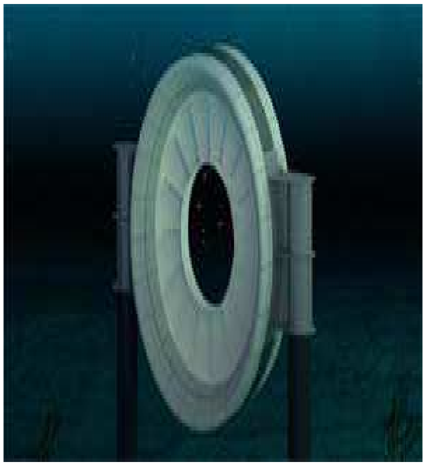
[23] EPRI presentation to International Energy Agency, Nov. 16, 2005
[24] Minister of State for Industry and Energy, DTI (Department of Trade & Industry UK)
[25] Survey & Characterization, Tidal In-Stream Energy Conversion (TISEC) Devices, EPRI-TP-004 NA

the same direction, even when tidal currents reverse direction.



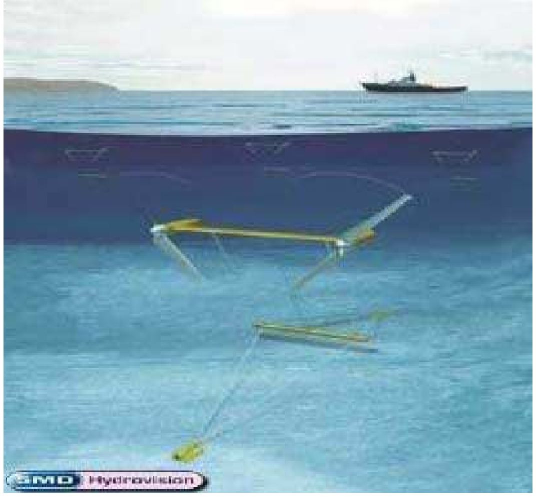
2. The Lunar Energy technology, known as the Rotech Tidal Turbine (RTT), illustrated at left, is a horizontal axis turbine located in a symmetrical duct. A fixed bi-directional duct, a patent pending blade and a hydraulic pump and motor all eliminate the need for yaw control, variable pitch blades and a mechanical gearbox, respectively. The RTT 2000 will be approximately 105 feet high and 100 feet long, weigh approximately 2,500 tons (mostly concrete and ballast) and produce 2 MW from a 6 knot (3.1 m/sec) tidal current. RTT output power is 11 kV, AC 50-60 Hz, three phase. Lunar anticipates that the turbine must be at a depth of at least 30 feet of water to allow unhindered navigation for all but the largest vessels. All electrical components are located in a hermetically sealed, nitrogen-filled airtight chamber without any dynamic rotary seals. The center cassette is intended to be removed for servicing every four years so that divers and remotely controlled vehicles will not be required during installation or servicing.

3. The Marine Current Turbine (MCT) SeaGen device, illustrated at left, has twin 18-meter diameter, open axial flow rotors mounted on wings on either side of the monopole support structure, which is set in a socket drilled in the seabed. Rotors have 180-degree pitch bi-directional flow control and drive induction generators at variable speed through three stage gearboxes. The entire wing and rotor assembly can be raised up the pile for maintenance. The MCT device will produce 2.5 MW in a 3-meter/sec flow with variable frequency AC at a nominal 600 volt and power conditioning and transformer output of 11 kV at 50-60 Hz.



4. The Open-Center Turbine, pictured at left, was developed by OpenHydro Inc. and features a fixed permanent magnet rim and an inner single-piece rotating disc. The technology is distinguished by its simplicity. No gearbox is needed thanks to the use of an encapsulated rim generator so that there is only one moving part – the turbine itself. There are no seals. The device features twin 15-meter diameter, counter-rotating turbines to offset torque and produces 1.52 MW in 5-knot (2.57 m/sec) flows. The output power is 11kV, 50-60 Hz, 3-phase. The device is mounted on the seabed and has been successfully tested in sea trials by the U.S. Navy under a cooperative research and development agreement.

5. The EXIM Tidal Turbine Power Plant (TTPP), pictured at left, is manufactured by Seapower and based on the Savonius turbine design, which is S-shaped if viewed from above. The dual vertical axis rotor, 1 meter in diameter by 3 meters high, will generate 44 kW in 2.4 m/sec water flow. Output power is 400 VAC, 50-60 Hz, three-phase induction generation.



6. SMD Hydrovision's (SMDH) TidEl system, pictured at left, consists of two horizontal-axis counter rotating rotors linked by a crossbeam and tethered to the seabed with mooring lines that orient the rotors downstream on flood and ebb tides. Each turbine is driven by an 18.5-meter diameter rotor with fixed pitch blades and housed in a buoyant pod. The pods contain high integrity seals, a planetary gearbox and an 11-kV, AC generator. The output power of the device is 11-kV, three-phase AC producing 1 MW at 2.3 m/sec water speed. Every two years, the unit, which floats when released from its mooring system, can be tugged to shore and swapped with a spare.

7. The Underwater Electric Kite (UEK), illustrated at left, is a twin fixed-pitch blade axial turbine that features a very high solidity turbine design and a 5.18-meter diameter augmentation ring that increases the internal velocity of the water flow to create a system with high efficiency. The device, which is rated at 400 kW in 3m/sec water flow is slack moored to the seabed so that it is oriented in the direction of flow. The mooring system allows the device to be floated to the surface for maintenance.

8. The Verdant Kinetic Hydro Power System (KHPS), illustrated below, is a three-bladed axial flow turbine incorporating a patented blade design, which is highly efficient over a large range of speeds. The turbine rotor drives a synchronous planetary speed increaser, which drives a grid-connected, three-phase induction generator. The gearbox and generator are mounted on a pylon assembly that has internal yaw

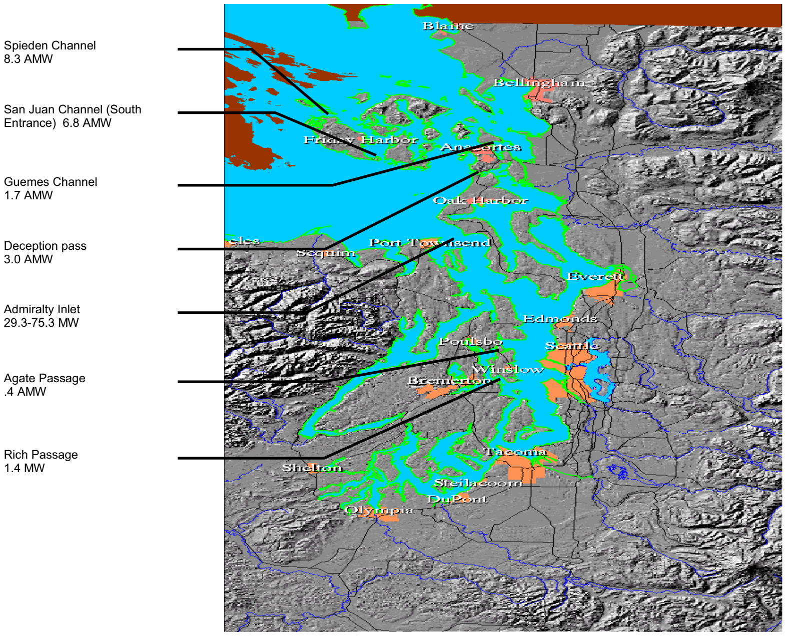
bearings, allowing the device to pivot in the direction of the tidal current. The turbine has a maintenance cycle of two years. A prototype being tested in New York City's East River has a 5-meter rotor diameter and is rated at 35.9 kW at 2.2 m/sec water speed.

Preliminary cost data on these technologies is proprietary and difficult to come by. However, Verdant Power estimated its pre-commercial production costs at $100,000 for the 40-kW machine illustrated above. These costs do not include mooring, cabling, integration and maintenance. As with the ocean wave technologies, much research and development remains to be done before reliable cost estimates become available.

4.2 Opportunity Overview

Although tidal in-stream energy technology is pre-commercial at this point, several pilot projects will be tested nationwide in the next few years. In 2005, EPRI conducted site feasibility and pilot studies at several North American locations in Maine, Massachusetts, New Brunswick, Nova Scotia, Alaska, Washington state and California. The three West Coast pilot projects identified in the study are summarized below.

- <u>Snohomish PUD Tidal Project</u> - EPRI identified the tidally active Puget Sound area as an exciting and sustainable energy source for meeting some of the Northwest's future generating needs. Puget Sound's proximity to large load centers means the electricity generated can be



connected directly to the local grid, eliminating the need to construct and maintain expensive transmission lines. In June 2006, Snohomish PUD filed preliminary study permit applications with FERC for seven tidal projects located in Admiralty Inlet, Agate Passage, Rich Passage, San Juan Channel, Spieden Channel, Guemes Channel and Deception Pass (see illustration above). Combined, these sites could provide as much as 100 average-megawatts of energy – or enough power for about 60,000 homes. FERC is expected to make a decision before the end of 2006. If granted, the FERC permits would not authorize construction, and Snohomish has not made any commitment to construct tidal facilities. Rather, the permits would allow the utility to apply for construction permits in the future if studies prove the sites are socially, environmentally and economically feasible. The PUD will only consider moving forward on tidal projects once it confirms the environmental and economic viability of the sites.

Pending FERC's approval of the preliminary study permits, Snohomish PUD anticipates commissioning EPRI to conduct the initial scoping and environmental studies. The overall objective of this work has been separated into four phases (see table below), with go-no-go decision milestones between each phase.

The objective of Phase I is to: (1) identify and select potential sites; (2) assess existing and near-term tidal flow power devices; (3) evaluate these devices for each site; (4) assess the environmental impacts of each site-device combination; (5) select a preferred site-device combination and make a recommendation, if appropriate, for a Phase II through Phase IV feasibility demonstration project; and (6) develop a detailed implementation plan for Phase II and a preliminary implementation plan for Phase III and IV.

The objective of Phase III is the installation of a prototype tidal flow power device at one of the sites with evaluation over one-to-two years. Snohomish PUD favors the modular design of newer tidal energy devices, in large part, because they allow for small test installations and can be easily removed should complications arise. An example of this technology is the turbine being tested by Verdant Power in New York's East River. Several manufacturers are developing similar technologies, and Snohomish PUD intends to evaluate each and tailor device selection to the requirements and specifications of each particular location.

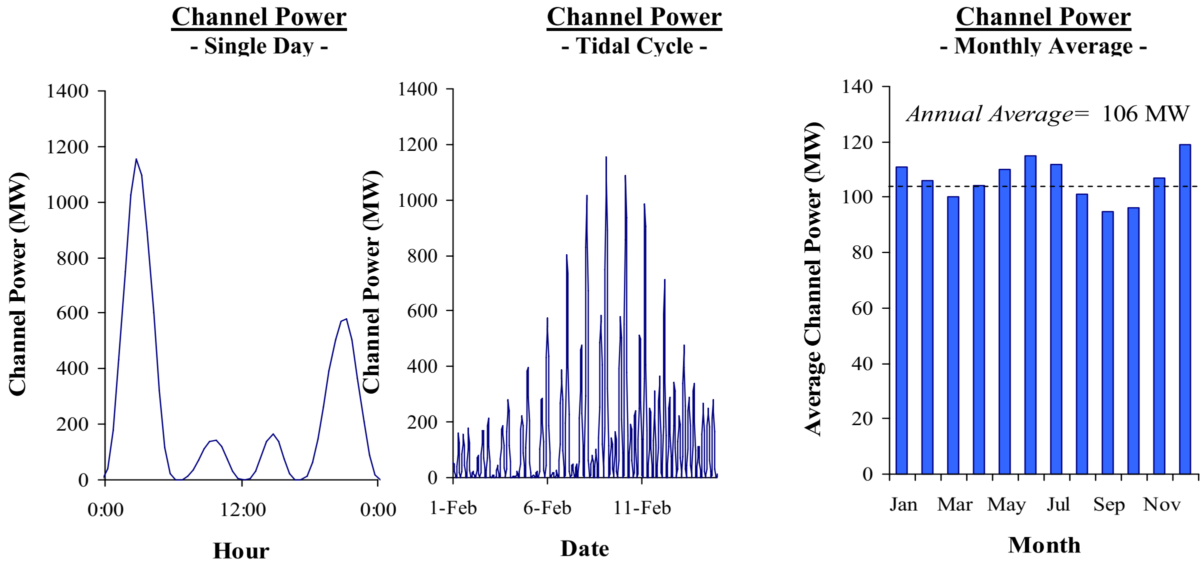
Snohomish anticipates that many obstacles will need to be overcome before construction can begin on a prototype tidal flow generation project. First, there are environmental concerns including impacts on marine mammals, fish and marine flora, as well as impacts to the shoreline and seabed from transmission cables. Second, social concerns from fishermen, commercial shipping traffic and recreational users of the waterways will need to be examined. Third, the permitting process, which is currently marked by a lack of coordination among various agencies and jurisdictions, must be understood and navigated.

BPA anticipates funding a portion of the Phase I costs. The exact amount has not yet been determined. This funding will enable Snohomish PUD to conduct a robust investigation of the various tidal energy sites.

- <u>Tacoma Narrows Tidal Project</u>: Tacoma Power is assessing the potential of installing a series of turbines near the Tacoma Narrows Bridge and has received a preliminary permit from FERC for a pilot project. In addition, scientists and regulatory experts at Devine Tarbell

& Associates have been working with Tacoma Power, EPRI, Verdant Power and other Northwest entities to evaluate the environmental and regulatory aspects of tidal energy at various sites in the Puget Sound area. Tacoma Narrows tidal resource performance data is provided below.

Tacoma Narrows Performance data

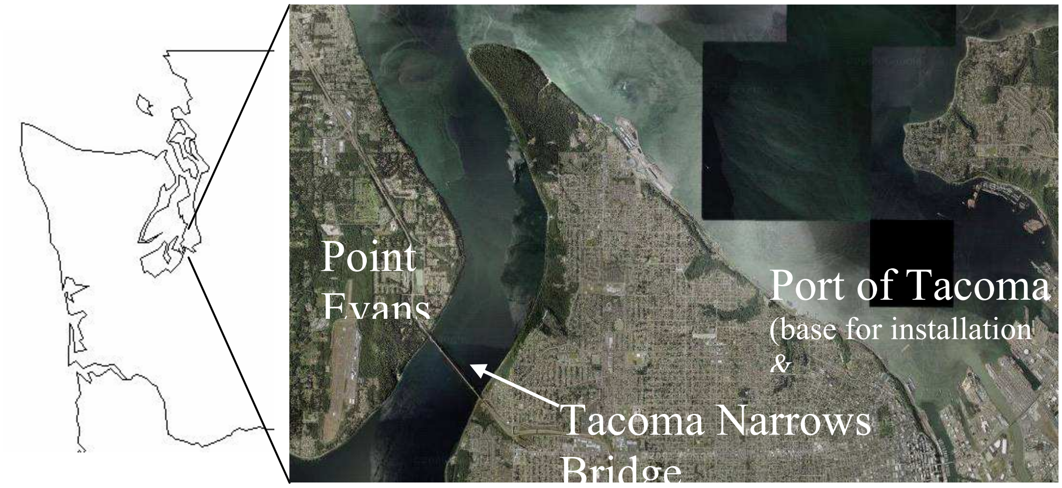


Channel Power - Single Day -

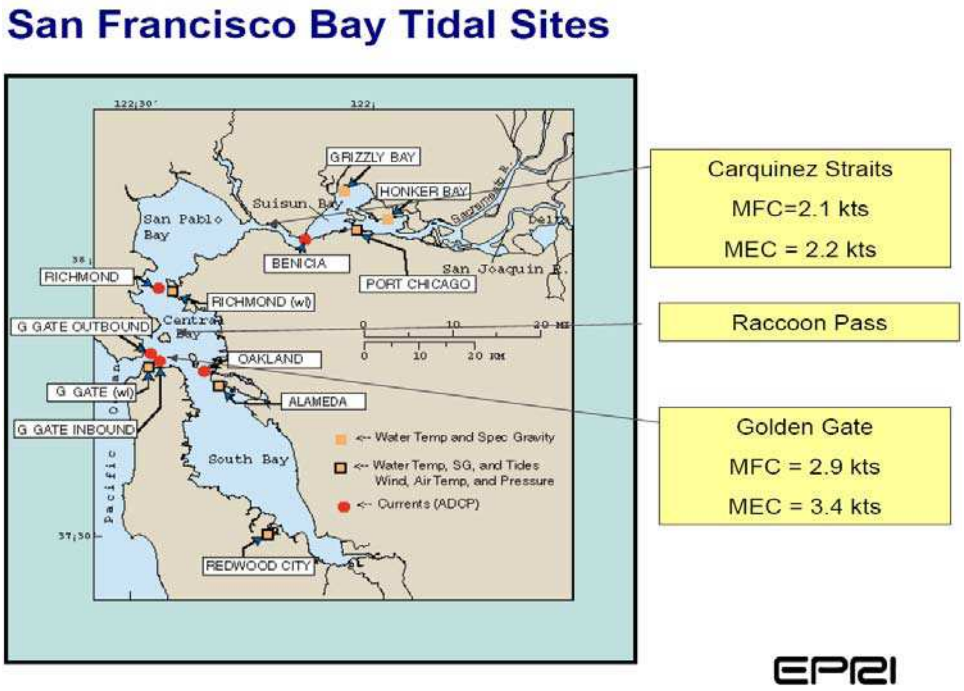
Channel Power - Tidal Cycle -

Channel Power - Monthly Average -

➡ Extraction Limit (15% Annual Average) = **16 MW**



- San Francisco Bay Tidal Project: The Golden Gate spans one mile. With two meters of tidal height at a velocity of 2 meters per second, up to 2.5 billion cubic meters of water races through the Golden Gate every six hours. It is estimated that in-stream tidal turbines at this strategic location could provide up to 1,500 megawatts of power.



4.3 RD&D Challenges

New technologies for generating in-stream tidal power offer many advantages. However the environment in which tidal turbines operate presents some daunting technical, environmental and regulatory challenges for both developers and the agencies responsible for regulating these devices.

A number of potential problems need to be addressed if in-stream tidal energy is to become viable. For example, tidal devices must be able to operate in the corrosive seawater environment. Mooring devices and turbines must be designed to withstand the forces imposed from high velocity and high density water flow; electrical equipment must be insulated from moisture of any kind; clearances must be maintained with surface shipping and commercial fishing; marine environments must be protected from seabed scouring and turbidity and leaking oils and fluids.

In addition, toxic agents in anti-fouling measures must be avoided or minimized; turbine operations must not impose unacceptable mortality rates on aquatic life; electric power quality and reliability must be maintained; and maintenance intervals must be kept to a minimum as the logistics of maintenance are likely to be complex and costly.

These challenges are exacerbated by the fact that tidal streams are a diffuse form of energy, requiring large numbers of energy devices spread over relatively large areas of seabed to produce significant mounts of energy.

4.4 Sector Actors

A. EPRI Reports - EPRI Ocean Energy Program is for the public benefit. All technical work is totally transparent and available at www.epri.com/oceanenergy.

EPRI TP-001-NA,	TISEC Resource/Device Performance Estimation Methodology
EPRI TP-002-NA,	TISEC Economic Assessment Methodology
EPRI TP-003-MA,	Massachusetts Site Survey
EPRI TP-003-ME,	Maine Site Survey
EPRI TP-003-NB,	New Brunswick Site Survey
EPRI TP-003-MA,	Nova Scotia Site Survey
EPRI TP-004-NA,	TISEC Device Survey and Characterization
EPRI TP-005-NA,	System Design Methodology
EPRI TP-006-AK,	Alaska System Level Design Study
EPRI TP-006-WA,	Washington System Level Design Study
EPRI TP-006-CA,	California System Level Design Study
EPRI TP-006-MA,	Massachusetts System Level Design Study
EPRI TP-006-ME,	Maine System Level Design Study
EPRI TP-006-NB,	New Brunswick System Level Design Study
EPRI TP-006-NS,	Nova Scotia System Level Design Study
EPRI TP-007-NA,	North America Environmental and Regulatory Issues
EPRI TP-008-NA,	Final Summary Report

B. European Marine Energy Center Test Facility - www.bwea.com/marine/facilities.html

The European Marine Energy Centre (EMEC), based in the Orkney Islands north of Scotland is among the first of its type in the world. It will provide a unique one-stop facility for the industry to test potential wave and tidal energy generators.

C. Oregon State University Ocean Wave Energy Research, Development & Demonstration Center (under development – OSU is establishing a U.S. marine energy research center on par with EMEC).

D. Companies Involved in In-Stream Tidal Energy Development

- Marine Current Turbines (MCT), www.marineturbines.com
- Blue Energy Canada, www.**blue**nergy.com
- The Engineering Business, www.engb.com
- SMD Hydrovision, www.smdhydrovision.com/products
- Verdant Power, www.verdantpower.com
- Rotech, www.rotech.co.uk
- Lunar Energy, www.lunarenergy.co.uk
- OpenHydro, www.openhydro.com
- Seapower, www.seapower.com.au
- Underwater Electric Kite, www.uekus.com