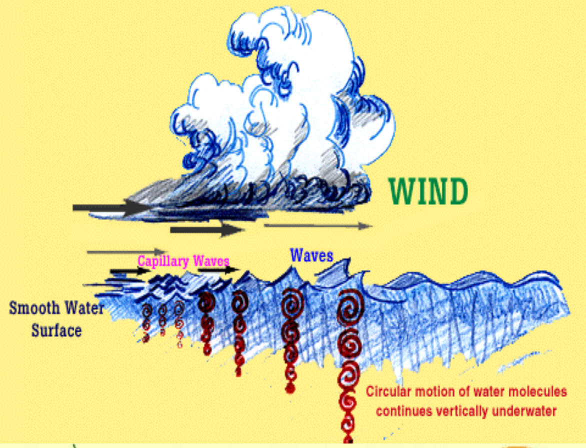
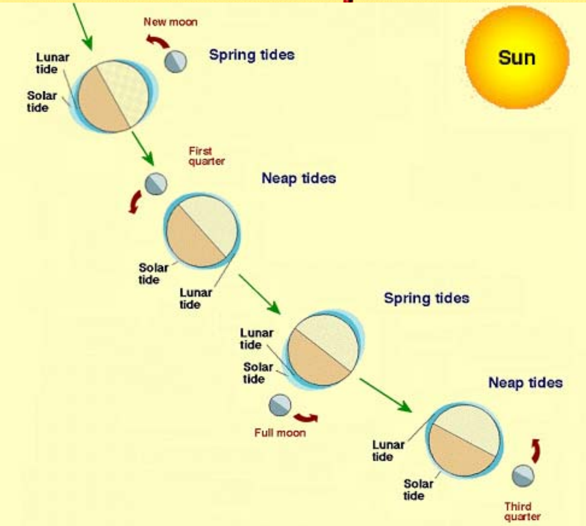
ELECTRIC POWER
RESEARCH INSTITUTE

Primer: Power from Ocean Waves and Tides





This primer is intended to inform the general public about the possibility of adding ocean wave and tidal power to our portfolio of energy supply options. We have investigated the possibility of many renewables resources such as solar, wind, geothermal, and biomass. Ocean wave and tidal energy are probably the last of the large natural resources not yet investigated for producing electricity in the

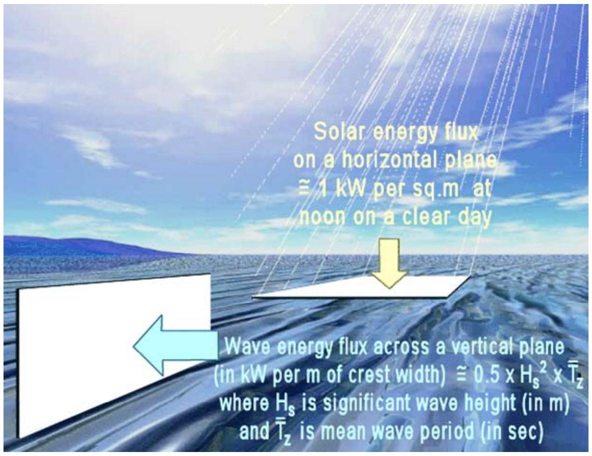
The United States has significant ocean wave and tidal energy resources. The technology to convert those resources to electricity, though in its infancy, is here today. This is a renewable resource that can be converted—cleanly and emission free—to electricity. Given proper care in design, siting, deployment, operation, and maintenance, ocean wave and tidal power could be among the most environmentally benign electricity-generation technologies yet developed.

The natural power of the ocean has inspired awe since the dawn of mankind. Mariners and others who deal with the forces of the sea have learned to understand the potentially destructive powers of ocean waves, as well as the regularity and predictability of the tides. Ocean waves and tides contain large amounts of kinetic energy that is derived from the winds and gravitational pull of the sun-earth-moon system. Even though early civilizations developed devices to convert waves and tides into mechanical energy, the technology to cost-effectively convert ocean waves and tidal flow into electrical energy is still in its early stages. Waves are created by wind blowing over a length of ocean as depicted below. Tidal changes in sea level occur as the Earth rotates beneath the elliptical ocean envelope that is produced by solar and lunar gravitational forces, as depicted here. Wave energy, although variable, can be predicted days in advance. Tidal power, also variable, can be predicted into the indefinite future. This predictability is important to electrical grid dispatchers who must balance the changing demand with the supply.

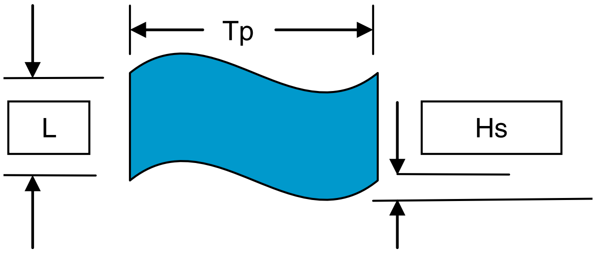
Wave and Tidal Power

The wave power (P_{wave}) (in watts-per-unit wave-crest length [L] in meters) is a function of the dominant wave period (Tp) in seconds and the square of the significant wave height (Hs) in meters squared, as illustrated on the next page.

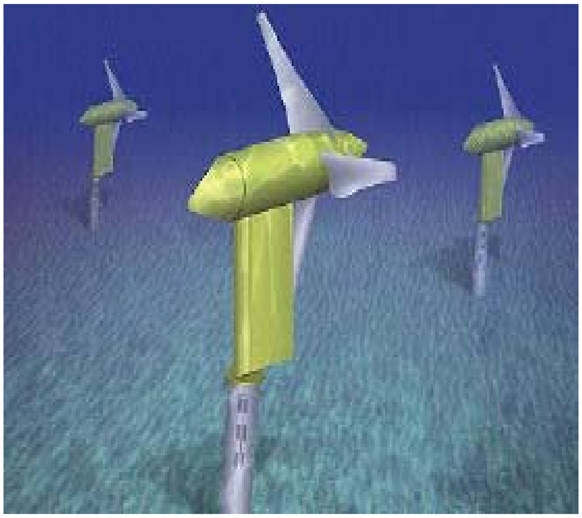
The tidal current power (P_{flow}) (in watts-per-unit cross-sectional area [A] in meters squared) is a function of the density of the water (seawater is 1,024 Kg/m^3) and the cube of the speed of the water (V) in meters per second, as illustrated on the next page.



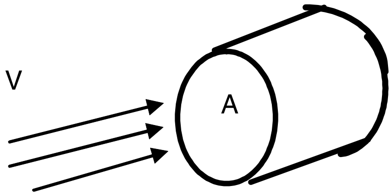
$$(P/L)_{wave} = 0.42\ Hs^2\ Tp$$



Wave Power



$$(P/A)_{flow} = 0.5\ \text{density}\ V^3$$



Tidal Current Power

As an example, the annual average wave power flux in deep water off the coast of northern California is on the order of 30 kW/m and the annual depth-average power density of the tidal flows under the Golden Gate bridge is on the order of 3 kW/m^2.

The Use of the Metric System and K, M, G, and T

The metric system uses the prefixes kilo (k), mega (M), giga (G) and tera (T) to indicate that a quantity is a thousand times (k), a million times (M) , a billion (G) times, or a trillion (T) times greater than a watt. Therefore, a kilowatt is one thousand times greater than a watt, a megawatt is one million times greater than a watt, a gigawatt is one billon times greater than a watt. and a terawatt is a trillion times greater than a watt.

The Difference Between Watts and Watt Hours (Power and Energy)

Power is a term that indicates rate; it is the rate at which energy is generated. Energy is a term that indicates quantity. Generating or consuming electricity at a rate of 1 watt of power for 1 hour is equal to 1 watt-hour of energy. Using an analogy familiar to us all, the rate of water, in gallons per minute, coming out of a garden hose is analogous to electrical power in watts. Filling a bucket at 1 gallon per minute for 10 minutes results in a quantity of 10 gallons of water in the bucket. Likewise, for electricity, generating 1 watt of power and for 1,000 hours generates 1,000 watt-hours (or 1 kWh) of electrical energy. To keep ten 100-watt light bulb on for 1 hour , for example, consumes 1000-watt hours or 1 kilowatt-hour of electrical energy

Rate in Gallons per Minute, Electrical Analog is Power in Watts

Quantity in Gallons, Electrical Analog is Energy in Watt-Hours

How Much Electrical Power is Used by a Typical U.S. home?

Since most people cannot relate to watts and watt hours in terms of everyday experiences, we are frequently asked to explain what it means to add new wave or tidal generation in a measure that people understand. We use the number of U.S. homes served by a power source as that measure.

The average U.S. home uses electrical power at the average rate of 1,300 watts (or 1.3 kW). Therefore, in a 30-day month, that average U.S. home consumes 936,000 watt-hours (or 936 kWh). If that home is paying an average of 6 cents per kWh, their electricity bill for that month is $56.16.

Capacity Factor, Rated Power, and Average Power

Notice that the discussion in the previous paragraph was in terms of average power. Average power, however, is not the conventional way of describing the size of an electricity generation power plant. The conventional way is in terms of the rated or maximum power. For a wave or tidal power plant, the rated power can be generated only at times of maximum wave height or maximum tidal-current velocity. The average power is considerably less that the rated power. For wave and tidal plants (and wind plants), the average power is typically between 30% and 40% of the rated power. The term used to describe this “derating to average” is “capacity factor,” and it is defined as the actual yearly electrical energy output of a generation plant divided by the electrical energy produced if the plant were continuously operated at rated power during the entire year.

How Many Homes are Served by a 100-MW (Rated Power) Wave or Tidal Generation Plant?

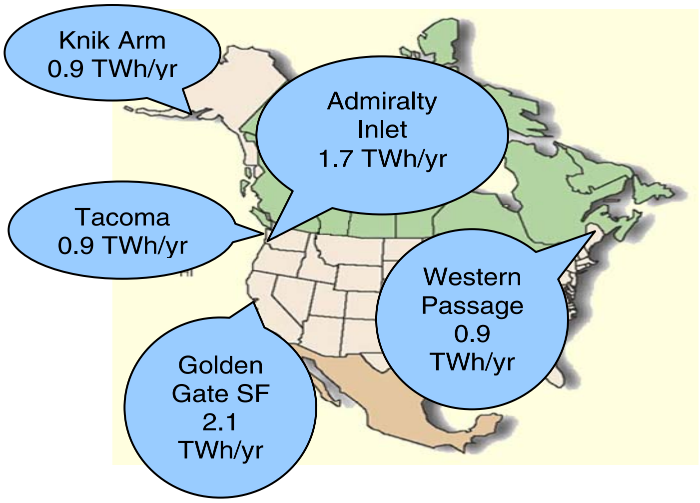
If a 100-MW wave or tidal generation power plant were to operate at its rated capacity over an entire year, it would produce 876,000 MWh, or 876 gigawatt-hours (876 GWh) of energy (100 MW * 8760 hours in a year). But as discussed previously, it will produce a lesser amount. If the generation plant operates at a 36% capacity factor, it will produce 135,360 MWh or ,alternately stated, it will average 36 MW of power production in a year (100 MW * 36%).

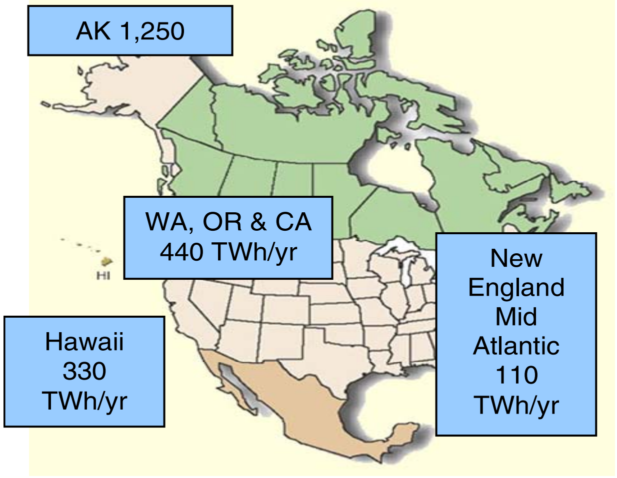
How many houses would the wave or tidal generation power plant serve? Using the average of 1.3 kW power consumed per US home, it would power 30,000 homes (36,000 kW/1.3 kW per home). Therefore, a 100-MW wave generator operating at 36% capacity factor produces the equivalent amount of energy in a year that 30,000 houses consume in a year.

The U.S. Wave and Tidal Resource Is Significant

The U.S. wave and tidal energy resource potential that could be credibly harnessed is about 400 TWh/yr, or about 10% of 2004 national energy demand.

Electric Power Research (EPRI) has studied the U.S. wave energy resource and found it to be about 2,100 TWh/yr divided regionally, as shown in the figures on the next page. Assuming an extraction of 15% wave-to-mechanical energy (which is limited by device spacing, device absorption, and sea space constraints), typical power train efficiencies of 90% and a plant availability of 90%, the electricity produced is about 260 TWh/yr, or equal to an average power of 30,000 MW (or a rated capacity of about 90,000 MW). This amount is approximately equal to the total 2004 energy generation from conventional hydro power (which is about 6.5% of the total 2004 U.S. electricity supply). EPRI has studied the North American tidal energy potential at selected sites shown below. The tidal energy resource at those U.S. tidal sites alone is 19.6 TWh/yr. Assuming an extraction of 15% tidal kinetic energy to mechanical energy, typical power train efficiencies of 90%, and a plant availability of 90%, the yearly electricity produced at the U.S. sites below is about 270 MW (average power, rated capacity is about 700 MW). EPRI estimates that the total tidal and river in-stream potential is on the order of 140 TWh/yr or about 3.5% of 2004 national electricity supply.





How Is Ocean Wave Energy Converted to Electricity?

Wave energy extraction is complex, and many device designs have been proposed. The device technology, is introduced here in terms of physical arrangements and energy conversion mechanisms, such as:

- Distance from shore—Wave energy devices may convert wave power at the shoreline, near the shore (defined as shallow water where the depth is less than one half of the wavelength), or offshore.
- Bottom mounted or floating—Wave energy devices may be either bottom mounted or floating.

Wave energy devices can be classified by the type of displacement and the reaction system employed. Various hydraulic or pneumatic power take-off systems are used, and, in some cases, the mechanical motion of the displacer is converted directly to electrical power (direct-drive).

Four of the best known device concepts are introduced below and the principles of operation are illustrated in the figures that follow.

Point Absorber

This is a bottom-mounted or floating structure that absorbs energy in all directions. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors. The illustration shows a floating buoy; however, it could be a bottom-standing device with an upper floater element as well. Pressure differences on the top of the float (created by surface wave action) set the upper floater into motion.

Oscillating Water Column (OWC)

At the shoreline, this could be a cave with a blow hole and an air turbine/generator in the blow hole. Near or offshore, this is a partially submerged chamber with air trapped above a column of water. As waves enter and exit the chamber, the water column moves up and down and acts like a piston on the air, pushing it back and forth. A column of air, contained above the water level, is compressed and decompressed by this movement to generate an alternating stream of high-velocity air in an exit blow hole. The air is channeled through a turbine/generator to produce electricity.

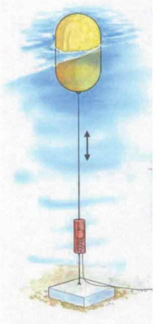
Overtopping Terminator

This is a floating reservoir structure with a ramp, over which the waves topple, and hydro turbines/generators through which the water returns to the sea. As shown in the illustration, a floating structure moves at or near the water surface, typically with reflecting arms to focus the wave energy. It has both a ramp and a reservoir so that as waves arrive, they overtop the ramp and are restrained in the reservoir. The head of collected water turns the turbines as it flows back out to sea, and the turbines are coupled to generators to produce electricity.

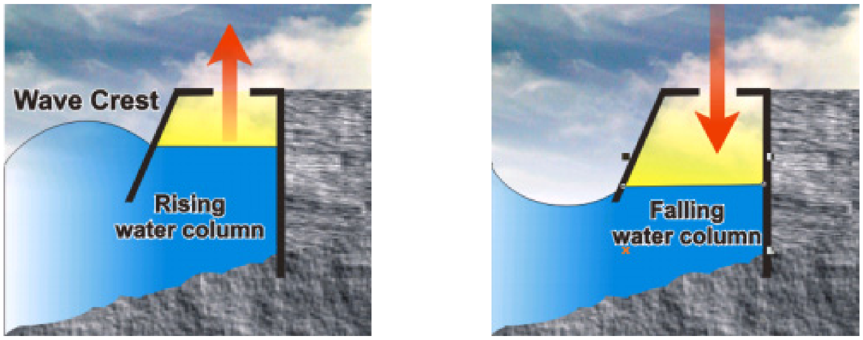
Attenuator

One example of the attenuator principle is a long floating structure that is oriented parallel to the direction of the waves. Sometimes, this is called a linear absorber. The structure is composed of multiple sections that rotate in pitch and yaw relative to each other. That motion is used to pressurize a hydraulic piston arrangement and turn a hydraulic turbine/generator to produce electricity. The figure illustrates a freely floating hinged-contour attenuator device. The four sections move relative to each other, and this motion is converted at each hinge point into electricity by a hydraulic power converter system.

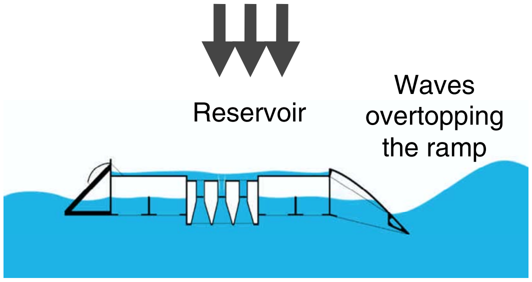
Examples of machines using each of the four concepts are shown on the next page.



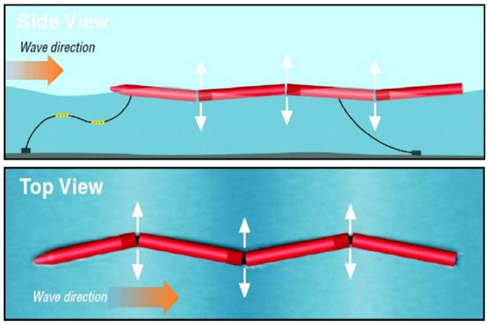
Point Absorber



Oscillating Water Column (OWC)



Overtopping



Attenuator

PowerBuoy, Courtesy of Ocean Power Technology

OWC, Courtesy of Energetech

WaveDragon, Courtesy of WaveDragon

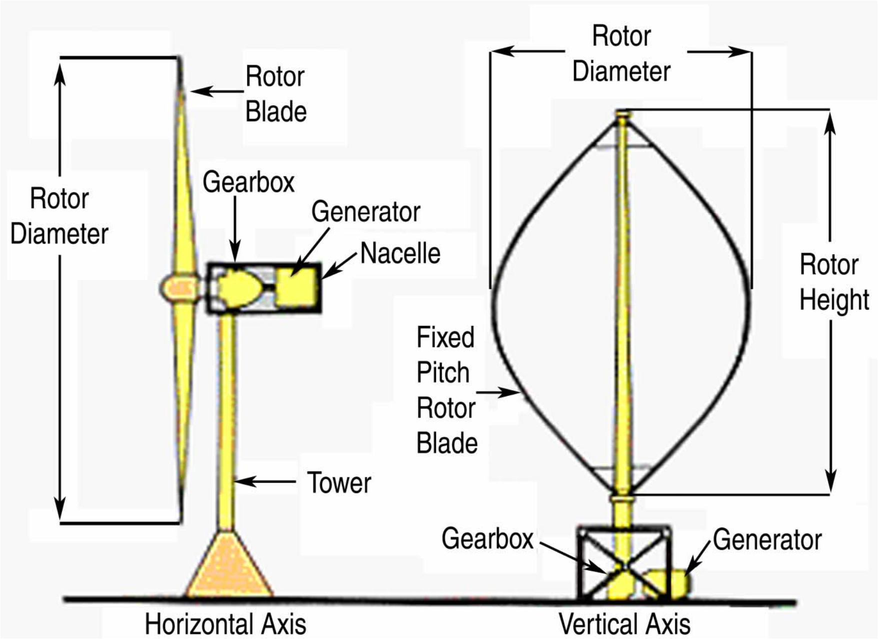
Pelamis, Courtesy of Ocean Power Delivery

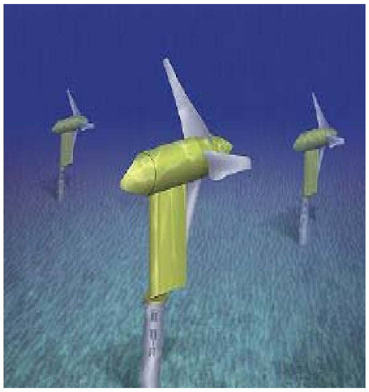
How Is Ocean Tidal Energy Converted to Electricity?

Tidal energy extraction is complex, and many device designs have been proposed. These designs are introduced here in terms of their physical arrangements and energy conversion mechanisms. Water turbines, like wind turbines, are generally grouped into two types:

- Vertical-axis turbines, in which the axis of rotation is vertical with respect to the ground (and roughly perpendicular to the water stream)
- Horizontal-axis turbines, in which the axis of rotation is horizontal with respect to the ground (and roughly parallel to the water stream)

The first figure below illustrates the two types of turbines and typical subsystems for an electricity generation application. Examples of machines using each of the two designs are shown below.





Horizontal-Axis Turbine, Courtesy of Verdant Power

Courtesy of Verdant Power

Vertical-Axis Turbine, Courtesy of GCK

Contact Information

For more information, contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com).

1015267 June 2007

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

Printed on recycled paper in the United States of America