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OFFSHORE HYDROKINETIC ENERGY CONVERSION FOR ONSHORE POWER GENERATION

Jack A. Jones
Principal Engineer
Mechanical Systems Division

Yi Chao
Principal Scientist
Earth Sciences Section

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

ABSTRACT

Design comparisons have been performed for a number of different tidal energy systems, including a fully submerged, horizontal-axis electro-turbine system, similar to Verdant Tidal Turbines in New York's East River, a platform-based Marine Current Turbine, now operating in Northern Ireland's Strangford Narrows, and the Rotech Lunar Energy system, to be installed off the South Korean Coast. A fourth type of tidal energy system studied is a novel JPL/Caltech hydraulic energy transfer system that uses submerged turbine blades which are mechanically attached to adjacent high-pressure pumps, instead of to adjacent electrical turbines. The generated high-pressure water streams are combined and transferred to an onshore hydroelectric plant by means of a closed-cycle pipeline. The hydraulic energy transfer system was found to be cost competitive, and it allows all electronics to be placed onshore, thus greatly reducing maintenance costs and corrosion problems. It also eliminates the expenses of conditioning and transferring multiple offshore power lines and of building offshore platforms embedded in the sea floor.

For time-dependent tidal energy, the pressurized hydraulic energy can be stored in an elevated onshore reservoir that can be used as per consumer energy demand, rather than as per tidal energy supply. This technology is a spinoff of a miniature ocean hydraulic energy transfer system that JPL is developing for the Office of Naval Research (ONR). The ONR device uses ocean temperature differences to provide pressurized hydraulic energy which supplies all electrical power for small submersibles. This type of hydraulic energy device is expected to allow submersibles to stay submerged for years. A three-month ocean endurance test is scheduled for late 2009.

Similar types of hydraulic energy transfer systems are potentially applicable to all types of hydrokinetic energy, including free-flowing rivers, ocean wave energy, and energy from ocean currents, such as the Gulf Stream. In each case, the corrosion-prone, submerged electrical turbines are replaced by all-mechanical water pumps without any electrical components, and the energy is hydraulically transferred to remote onshore hydroelectric plants by inexpensive pipes.

The submerged mechanical turbine blade/pump assemblies can be attached by long, small-diameter, flexible pressurized lines to the larger submerged, stationary pipe lines, thus allowing the submerged blade/pump assemblies to be lifted to the surface and serviced by boat. Check valves in the flexible lines allow damaged turbine blade/pump assemblies to be automatically taken off-line and later repaired or replaced as required.

1 INTRODUCTION

There are numerous ways to obtain non-carbon-emitting, renewable electrical power from both fresh water and salt water energy sources. The most common means is the use of hydroelectric dams, which accounts for about 75% of all renewable energy in the United States (Ref 1). *Hydroelectric power is, in fact, the least expensive electric power source that presently exists* (Table 1). Unfortunately, this particular type of energy source is almost completely utilized for all applicable rivers in the U.S., as well as for most of the rivers in the rest of the world.

One of the objectives of this paper is to briefly review other sources of energy that can be derived from either fresh water or seawater, and then to do a more detailed comparison of some of the major tidal turbine energy technologies, including a novel JPL/Caltech tidal turbine device that collects water energy offshore and converts it to electricity with an on-shore hydroelectric plant.

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Table 1. 2005 Costs for Various Energy Systems [21]

	Capacity Factor (%)	Capital Cost (1) ($/W)	Operating Cost (2) (cents/kWh)	CO2 (lbs per MWh)
Tidal In-stream Power Density				
>3.0kW/m2	29–46	1.7–2.0	4–7	None
1.5–3.0		2.1–2.4	4–11	None
<1.5kW/m2		3.3–4.0	6–12	None
Wind (class 3–6)	30–42	1.2–1.6	4.7–6.5	None
Solar Thermal Trough	33	3.3	18	None
Coal PC USC (1)	80	1.3	4.2	1760
Natural Gas @ $7/MM BTU (2)	80	0.5	6.4	860
Hydroelectric (3)	80	0.3	2.0	None

(1) 600 MW Plant, Pittsburgh #8 Coal
(2) GE 7 F machine or equivalent
(3) Excluding cost of dam [1]
http://www.oceanrenewable.com/wp-content/uploads/2008/03/7th-ewtec-paper-final-032907.pdf

2 OTHER SOURCES OF WATER ENERGY

2.1 OTEC

One type of energy that can be drawn from water is known as Ocean Thermal Energy Conversion (OTEC). It has long been known that warmer water resides near the surface of the ocean and that colder water resides near the bottom of the sea. The coldest ocean water in deep locations is about 4°C, which is the temperature of the highest density of water. Ocean surface temperatures vary tremendously around the globe and are usually seasonal. In tropical seas, the surface temperature water frequently lies between 24°C and 33°C and cools to 4°C to 9°C at depths below about 500 m.

Numerous operating cycles, usually employing the Rankine cycle have been developed for OTEC, with the first being proposed in France by d' Arsonval in 1881. Several prototypes were developed by French, American, and Japanese teams and were tested in Cuba, Brazil, Hawaii, and Japan until the mid 1980s (Ref 2).

The thermal efficiency of OTEC plants is only about 2–3% when power required for pumping lower cold water is included in the evaluation. The size and cost of these pipes is significant. For example, in a project for a 40-MW plant at Kahe Point, Hawaii, the insulated cold water pipe would be 3670-m long, 10–12-m in diameter, and extend to 1000-m depth. There were also environmental concerns due to the potential change in the oceanographic properties of seawater due to pumping, and thus OTEC has mostly been abandoned as a major source of electrical energy, except in niche areas, such as for the Department of Defense.

JPL has, in fact, recently found a niche application for OTEC in supplying energy to submersibles (Ref 3). The JPL OTEC device uses submersibles that travel upward to warm water and downward to cold water. The warm water melts a phase change material (PCM) inside external tubes causing expansion that compresses on liquid contained within a central tube inside the PCM (Fig 1). This high-pressure liquid is then hydraulically transferred to an adjacent high- pressure accumulator, where it is temporarily stored. The thermally produced high-pressure liquid is ultimately used to power a hydroelectric motor, thus creating electricity in a manner similar to a hydroelectric generator. The electricity then charges batteries, which are used for buoyancy control, sensors, and communications. The glider then travels back down to cold water, thus freezing and contracting the PCM, to complete the cycle by returning the low pressure oil back into the central PCM tubes. A fully integrated OTEC submersible is now being fabricated by JPL and the Scripps Institution of Oceanography for the Office of Naval Research (ONR), and it will be endurance-tested in the Pacific Ocean later in 2009.

2.2 Hydrokinetic Energy

Another class of water-derived energy is known as hydrokinetic energy, and this includes using water's kinetic motion energy, as opposed to potential energy (dams) or thermal energy (OTEC). Hydrokinetic energy includes waves, ocean currents, river currents, and ocean tides. It represents as much as 10% of all U.S. electrical power needs (Fig 2, Ref 4). The following sections will briefly discuss the various classes of hydrokinetic energy, with more detailed discussion of tidal energy later.

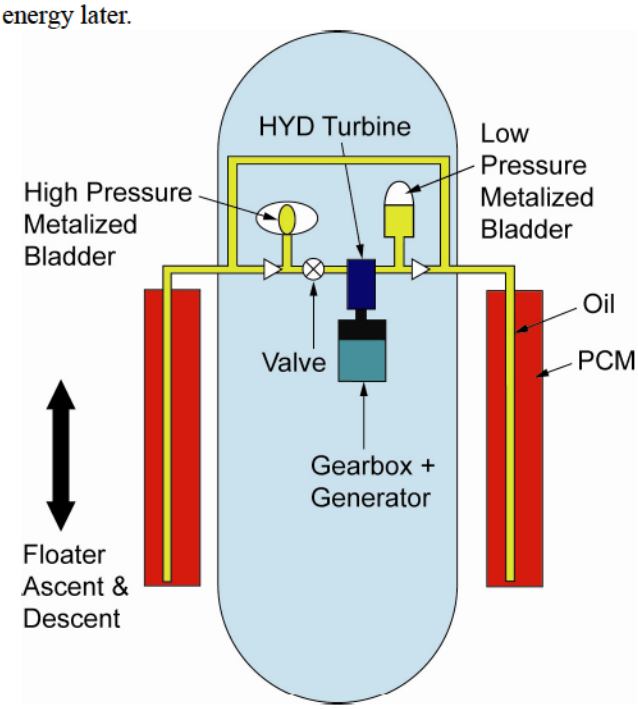

Figure 1. OTEC Floater with Adjacent Hydraulic Energy Transfer System

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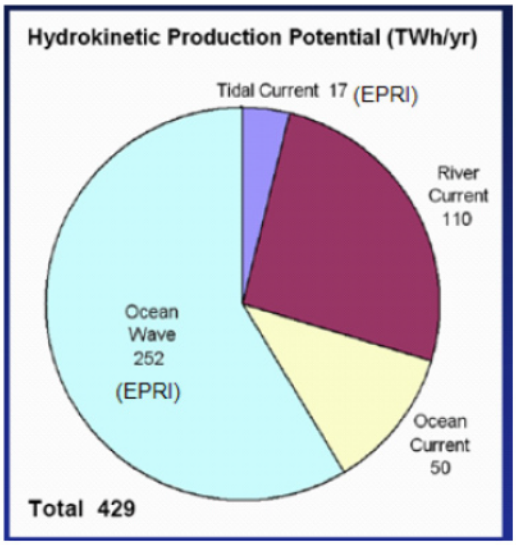

Figure 2. U.S. Hydrokinetic Production Potential

2.2.1 Ocean Wave Energy

Wave power devices extract energy directly from surface waves or from pressure fluctuations below the surface. Renewable energy analysts believe that worldwide, there is potential energy of up to 2700 GW, roughly equivalent to the total of all electric power produced on Earth (Ref 5,6). Practical limits are much lower, however, and wave-power rich areas are mostly limited to the Western coast of Scotland, Northern Canada, Southern Africa, Australia, Hawaii, and the northeast and northwest coasts of the United States (Fig 3, Ref 7).

There are many types of wave power devices, and over a thousand have been patented since the 1980s. Offshore systems are situated in deep water, typically more than 40-m deep. These devices tend to be very costly and often require expensive floating platforms. Furthermore, they usually require submerged electrical generators, which are prone to leakage and electrical corrosion.

2.2.2 Ocean Current Energy

The total worldwide power in major ocean currents has been estimated to be about 5000 GW (Ref 8), or about twice the sum of all electricity presently produced on Earth. Although ocean currents are slower than winds, water is about 835 times more dense than wind, so the energy densities are much higher than in wind. The relatively constant extractable energy density near the surface of the Florida Straits Current is located about 20–30 km offshore and in water that is 200–300-m deep (Fig 4, Ref 9). Capturing just 15% of the available energy from the fastest portions of the Gulf Stream would supply about 4530 MW, or about half of the electrical needs of Florida.

The total power is represented as:

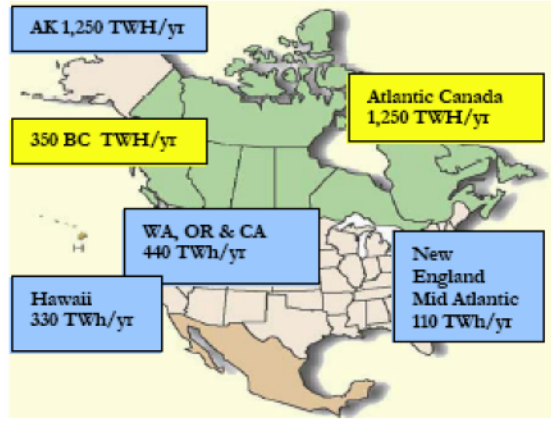

Figure 3. U.S. Wave Energy Potential

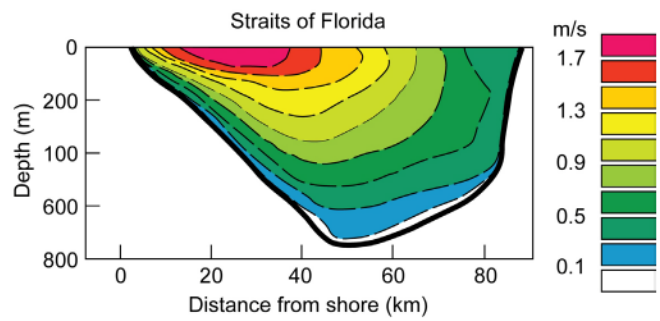

Figure 4. Gulf Stream Flow Velocities Near Southern Florida

(1) Available Power = $(1/2\rho V^3 A)(0.15) = 4530$ MW, where

ρ = 1025 kg/m^3
V = 1.7 m/sec
A = 100-m * 30,000-m = 3,000,000 m^2
0.15 = effective use factor estimated by the Electric Power Research Institute (EPRI)

Countries that are interested in pursuing the application of ocean current energy technologies include the European Union, Japan, and China. Ocean current energy is at an early stage of development, with only a small number of prototypes and demonstration units tested to date. One such technology involves submerged turbines. Energy can be extracted from ocean currents using submerged turbines that are similar in function to wind turbines, capturing energy through the processes of hydrodynamic, rather than aerodynamic, lift or drag. These turbines would have rotor blades, a generator for converting the rotational energy into electricity, and a means for transporting the electrical current to shore for incorporation into the electrical grid.

The cost of ocean current energy is still higher than conventional energy plants, but the costs are coming down. The primary technical challenges are:

- Prevention of marine growth build-up
- High maintenance costs of submerged electrical turbines
- Corrosion resistance

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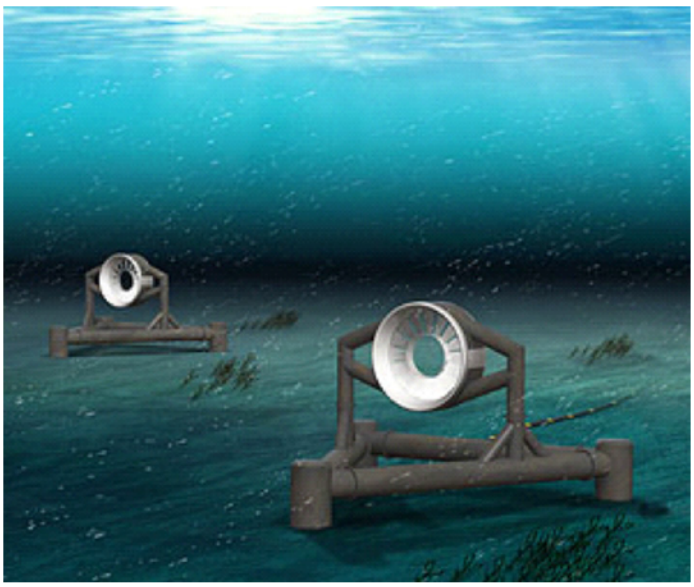

Figure 5A. Open Hydro Turbine

- High cost of submerged electrical cables
- Potential climate changes in downstream regions due to reduced ocean current flows.

2.2.3 River Current Energy

River current energy can be harvested in the same manner as ocean current energy, and can actually provide significantly more energy of about 12,500 MW (Ref 9). Even though most of American rivers with hydroelectric potential are already dammed, there is still significant energy in rivers such as the Mississippi, Colorado, Columbia, St. Lawrence, Missouri, Yukon, etc. One of the issues with river current energy is that the location of the submerged turbines must remain clear of boat traffic and, thus, must be clearly marked.

Table 2. Worldwide Tidal Areas

('–' indicates missing information, '?' indicates undecided information)

Country	Place	Mean Tidal Range (m)	Area of Basin (km²)	Maximum Capacity (MW)
Argentina	San Jose	5.9	–	6800
Australia	Secure Bay	10.9	–	?
Canada	Cobequid	12.4	240	5338
	Cumberland	10.9	90	1400
	Shepody	10.0	115	1800
	Passamaquoddy	5.5	–	?
India	Kutch	5.3	170	900
	Cambay	6.8	1970	7000
South Korea	Garolim	4.7	100	480
	Cheonsu	4.5	–	–
Mexico	Rio Colorado	6–7	–	?
	Tiburon	–	–	?
United Kingdom	River Severn	7.8	450	8640
	River Mersey	6.5	61	700
	Strangford Lough	–	–	–
	Conwy	5.2	5.5	33
United States	Passamaquoddy Bay, Maine	5.5	–	?
	Knik Arm, Alaska	7.5	–	2900
	Turnagain Arm, Alaska	7.5	–	6501
	Golden Gate, California	?	–	?
Russia	Mezen	9.1	2300	19200
	Tugur	–	–	8000
	Penzhinskaya Bay	6.0	20,500	87,000
South Africa	Mozambique Channel	?	?	?
New Zealand	Kaipara Harbour	2.10	947	200+

(from: http://en.wikipedia.org/wiki/Tidal_energy)

2.2.4 Ocean Tidal Flow Energy

Some of the oldest ocean energy technologies use tidal power. All coastal areas consistently experience two high and two low tides over a period of slightly greater than 24 hours. For those tidal differences to be harnessed into electricity, the difference between high and low tides is preferably at least five meters, or more than 16 feet. There are only about 40 sites on the Earth with tidal ranges of this magnitude. Some sites worldwide that look particularly promising are listed in Table 2 (Ref 10). Although these sites collectively could produce about 166 GW, there are typically strong peaks associated with several hours of high tidal flow followed by several hours of very low tidal flow. When the power is averaged out, these locations could potentially provide about 44 GW of power.

Currently, there is only one semi-operational tidal power plant in the United States. It is located in Manhattan's East River and is operated by Verdant Power. However, conditions are good for tidal power generation in the Alaskan Islands, the Pacific Northwest, and the Atlantic Northeast regions of the United States. Due primarily to the lack of U.S. investment research funds to date, ocean tidal energy is now dominated by other countries, especially in Europe.

3 TIDAL POWER TECHNOLOGIES

The cost of tidal turbines is generally much less than that of ocean current turbines, since tidal turbines are usually closer to shore and in shallower water. Some disadvantages of tidal power are the very large fluctuation of energy output per every 6-hour tidal period and the fact that the most common submerged electrical power generation systems are subject to corrosion with any leakage of the surrounding sea water.

There are many different types of tidal power technologies. A partial list of categories includes the following (Ref 11):

Barrage or dam. A barrage or dam is typically used to convert tidal energy into electricity by forcing the water through turbines, activating a generator. Gates and turbines are installed along the dam. When the tides produce adequate difference in the level of water on opposite sides of the dam, the gates are opened. The water then flows through the turbines. The turbines turn an electric generator to produce electricity. Small power plants using this technology are now functioning in France, Russia, and Canada. The dams have been criticized, however, for impeding boat traffic and sea life migration, as well as for resulting in silt accumulation behind the dams.

Tidal Fence. Tidal fences look like giant turnstiles. They can reach across channels between small islands or across

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straits between the mainland and island. The turnstiles spin via tidal currents typical of coastal waters. Some of these currents run at 5–8 knots and generate as much energy as winds of much higher velocity. Tidal fences also impede boat traffic, as well as sea life migration.

Open Hydro. An open hydro system uses a permanent magnet rotor in the rotating rim and stator coils in the cowling (Fig 5A, Ref 12). Open Hydro (www.openhydro.com) is the first developer to use the European Marine Energy Centre tidal stream field tests in Ireland's Orkney Islands. The 6-m diameter turbine shown in Fig 5 is rated at 250-kW capacity. High costs and maintenance problems have thus far impeded progress of this technology.

Horizontal Axis Tidal Turbines. These tidal turbines look like wind turbines. They are arrayed underwater in rows, as in some wind farms. The turbines function best where coastal currents run at between 3.6 and 4.9 knots, in currents of that speed, a 15-m diameter tidal turbine can generate as much energy as a 60-m diameter wind turbine. Ideal locations for tidal turbine farms are close to shore in water depths of 20–30 m. This type of tidal turbine generally does not impede sea life migration or result in silt buildup.

4 TYPES OF HORIZONTAL AXIS TIDAL TURBINES

Of all the environmentally-friendly tidal turbines, the horizontal axis designs are baselined for the most commercial tidal energy projects, and there are many types of horizontal axis tidal turbines in development today. The remainder of this paper will look at three submerged power generation horizontal axis tidal systems currently undergoing development and will compare these systems to a novel JPL/Caltech horizontal axis turbine system that creates electricity on-shore by means of an inexpensive hydroelectric plant.

4.1 Verdant Tidal Turbines

The first tidal generator actually attached to a commercial grid in the United States is operated by Verdant Power in New York City's East River. Verdant's Roosevelt Island Tidal Energy (RITE) Project was initiated in 2002 and has been operating on-grid intermittently since December 2006 (Ref 13). The project presently consists of six, 35-kW horizontal axis turbines (Fig 5B) that are fully bidirectional and have accumulated over 7000 hours of operation (2008).

A simple operational schematic of this type of horizontal blade tidal turbine system is shown in Fig 6. The tidal flow turns a blade at about 15 rpm, which is increased to about 1500 rpm by means of a gearbox. The higher rpm is then used to generate electricity by means of a submerged generator, and the energy is sent to shore with submerged power lines. The project has been plagued by a number of problems, including blades breaking off and salt water leakage into the generators. Reinforced turbines were installed in September 2008 and are currently being tested. The Verdant horizontal axis tidal turbine is basically similar to another device in Hammerfest,

Figure 5B. Verdant Tidal Turbine

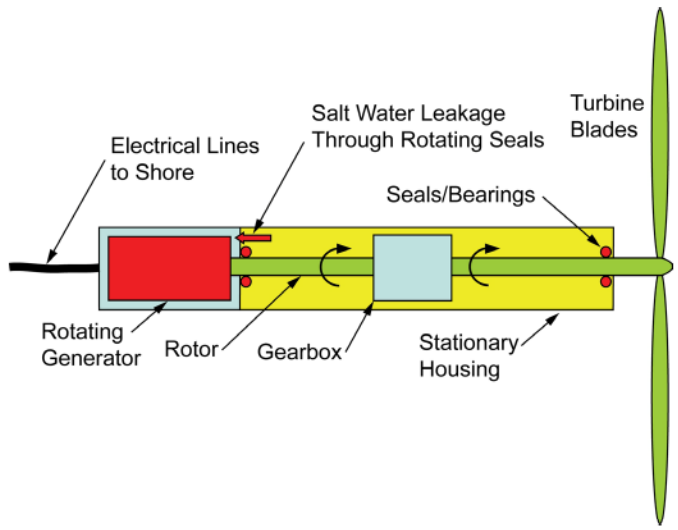

Figure 6. Typical Horizontal Axis Submerged Tidal Turbine

Norway that started supplying 300 kW in November 2003 (Ref 14).

The First Verdant prototype was very expensive, but Verdant expects the cost to come down to about $2400/kW installed (Ref 15). By comparison, a coal generator costs in the region of $1300/kW installed (Table 1), but that does not take into consideration the ongoing cost of fuel, as well as costs due to the impact on the environment and health.

4.2 Marine Current Turbines

UK based Marine Current Turbines (MCT) installed a double-bladed, horizontal-axis tidal turbine (Fig 7) in Strangford Lough in Northern Ireland in April 2008 (Ref 14). It fed 150 kW into the grid for the first time on July 17, 2008. In shallow waters, the turbines are suspended on a tower that

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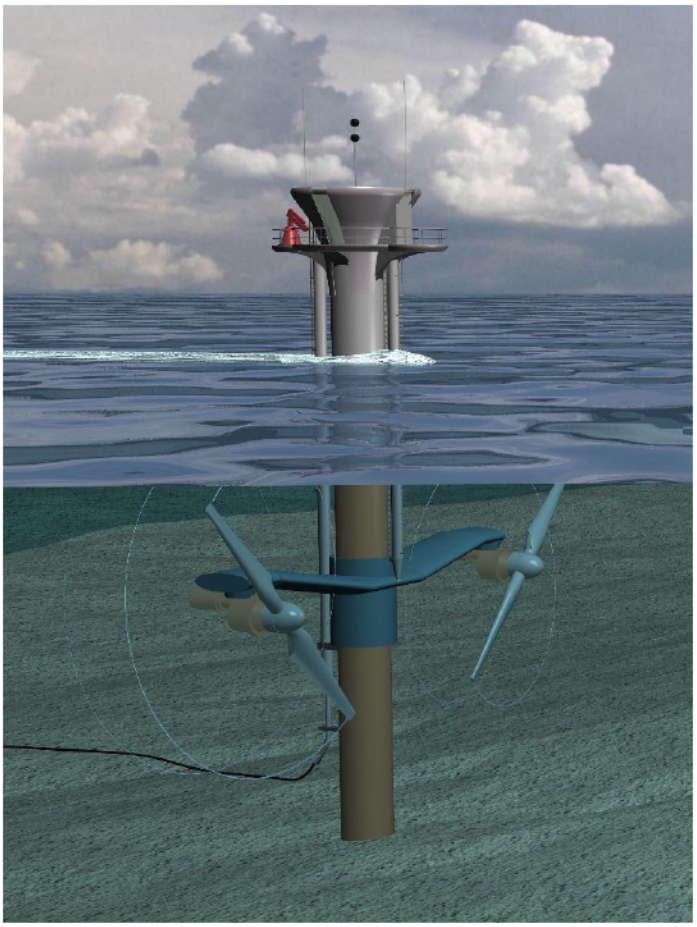

Figure 7. Marine Current Turbines

extends above the surface of the water and enables the turbines to be lifted above the water for maintenance purposes. The tower is reputed to be quite expensive and is a major cost driver for this type of device, although maintenance costs are considerably less without the need for specially-trained, high cost divers.

The MCT project uses two rotors that are 16-m in diameter, with each rotor producing 600 kW. The tidal flows in Strangford Lough are very strong, and average about 2.5 m/sec. The electricity produced is transferred by buried electrical cables to the shore, which is a distance of about 400-m.

4.3 Lunar Energy Rotech Tidal Turbine

UK-based Lunar Energy has developed a novel tidal turbine system that does not require expensive towers and is less susceptible to salt water corrosion of the electrical components. The horizontal axis turbine is positioned on a concrete base that is lowered to the sea floor (Fig 8). It provides a cowling that increases the tidal velocity by means of a "venturi effect" (Ref 16). The main power producing unit can be lifted out of the cowling and base, so that service can be performed on shore, instead of using expensive trained divers.

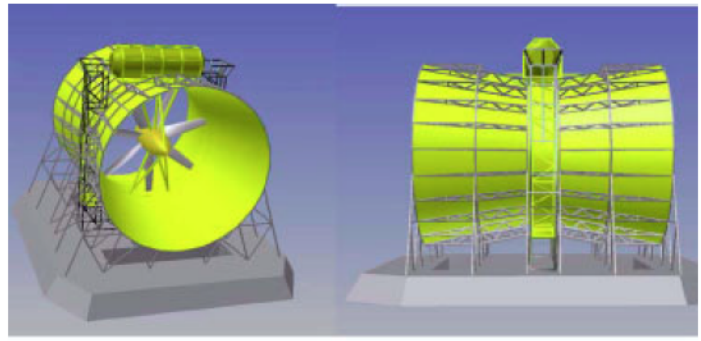

Figure 8. Rotech Lunar Energy tidal turbine

The most novel part of this device, however, is that the turbine blades are used to power a hydraulic pump, instead of a generator (Fig 9). The hydraulic pump generates a stream of high-pressure fluid that is transferred to a hydraulic generator on top of the turbine. The electricity produced is then transferred to shore by means of buried cables. The use of a hydraulic turbine interface means that the entire electrical generator system can be fully sealed from the outer seawater, and thus there is less danger of salt water intrusion and resulting corrosion of the electricity-producing generator itself.

Lunar Energy has announced an agreement with a South Korean utility company to create a 300-turbine field to produce 300 MW of energy off the coast of South Korea by 2015.

5 HYDRAULIC ONSHORE POWER CONVERSION

JPL has recently extended the adjacent hydraulic power generation concepts represented by the OTEC submersible device (Section 2.1) and by the Lunar Rotech tidal turbine (Section 4.3). For both of these systems, energy is converted from one form (heat or tidal flow) to high-pressure hydraulic energy, transferred to an adjacent region, and then ultimately converted to electric power. JPL has now revised the type of energy-transfer design so that the hydraulic power of multiple hydrokinetic energy sources can be combined, transferred to a remote shore by means of high-pressure pipes, and converted to electricity with an on-shore hydroelectric plant.

5.1 Tidal or River Currents

In the JPL/Caltech hydraulic tidal power generator design, turbine blades spin slowly due to the flow of a river, tidal flow, or ocean current (Fig 10). The rotor's rotational speed is increased through a gearbox, which then drives a high-pressure fluid pump. The high-pressure fluid, such as fresh water, is transported in small flexible lines to a common high-pressure pipe and then to an efficient, on-shore hydroelectric power plant. This all-mechanical design is less expensive, more efficient, and eliminates most corrosion and all submerged electrical components (Ref 17). It replaces expensive and dangerous submerged power cables and power-conditioning systems with simple pressurized tubes.

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Schematics of how the system operates in a closed cycle and in open cycle modes are shown in Figs 11 and 12, respectively. In the open cycle, the surrounding water is taken into the pump and is pressurized before being combined with other pressurized flows from the other turbines. The combined flow is sent to shore and generates power in a conventional hydroelectric plant. The exhausted fluid is then returned to the surrounding water supply. In the closed cycle design, the returning low-pressure main water flow is then separated to allow each individual flow to return to the separate turbine pumps. Fresh water with trace bio-inhibitors and corrosion inhibitors can be used for the closed cycle fluid. In general, the closed-cycle system is more ecologically friendly than the open-cycle system.

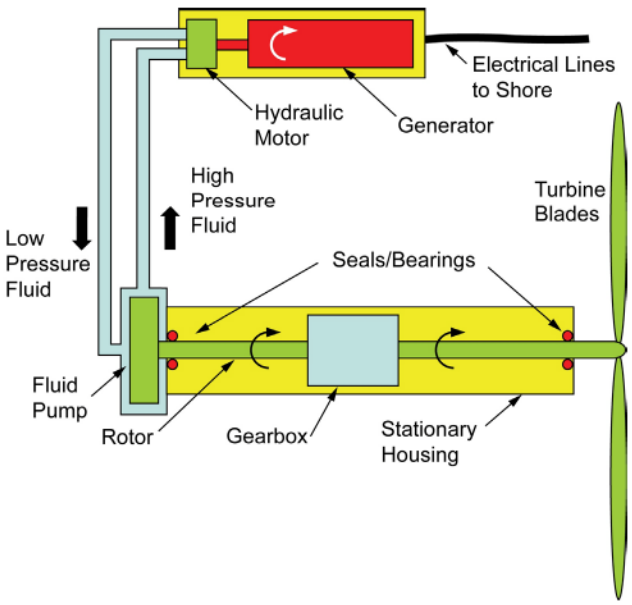

Figure 9. Rotech Lunar Energy operational schematic

Each high-pressure line and low-pressure line that connects to the main flow should preferably be flexible in order to allow for turbine motion relative to the main lines. Furthermore, each high-pressure line should preferably be connected by means of a check valve, so that if the water pump does not build up sufficient pressure, the flows from the other turbines will not backflow into the underperforming turbine. It is also important for the tidal system to be capable of handling reverse flows, as does the Lunar Energy Rotech system.

5.2 Gulf Stream Current

A schematic of how the system might look in a deep ocean current is shown in Fig 13. For this design, which could be used in the Gulf Stream, the cowlings for the turbines are buoyant and are anchored to heavy weights in the sea floor. Each high-pressure line could be connected to an above-surface platform (shown), where the high-pressure flow is converted to electricity by a hydroelectric plant on the platform. Alternately, the high-pressure fluid flow could be piped to shore, where it is converted to electricity in an on-shore hydroelectric plant.

JPL calculations have shown that high pressure pipes can also be employed for long-distance energy transfer. For a 100-MW plant that is about 10 km from shore, a pipe diameter of 1 m would be required for a 3000-psi flow, assuming a 10% pressure drop, which reduces total energy efficiency by a similar amount. Lower pressures and/or lower pressure drop losses would result in larger required pipe diameters. The cost of these pipes are clearly much more than the shorter, lower-pressure pipes required for tidal or river currents. For a Gulf Stream hydraulic energy transfer system, it is probably less expensive to use shorter and smaller pipes in conjunction with a hydroelectric plant that is stationed on an offshore platform. There are leakage and corrosion issues for buoyant turbine cowlings, however, and there are environmental concerns related to reduction of Gulf Stream velocities.

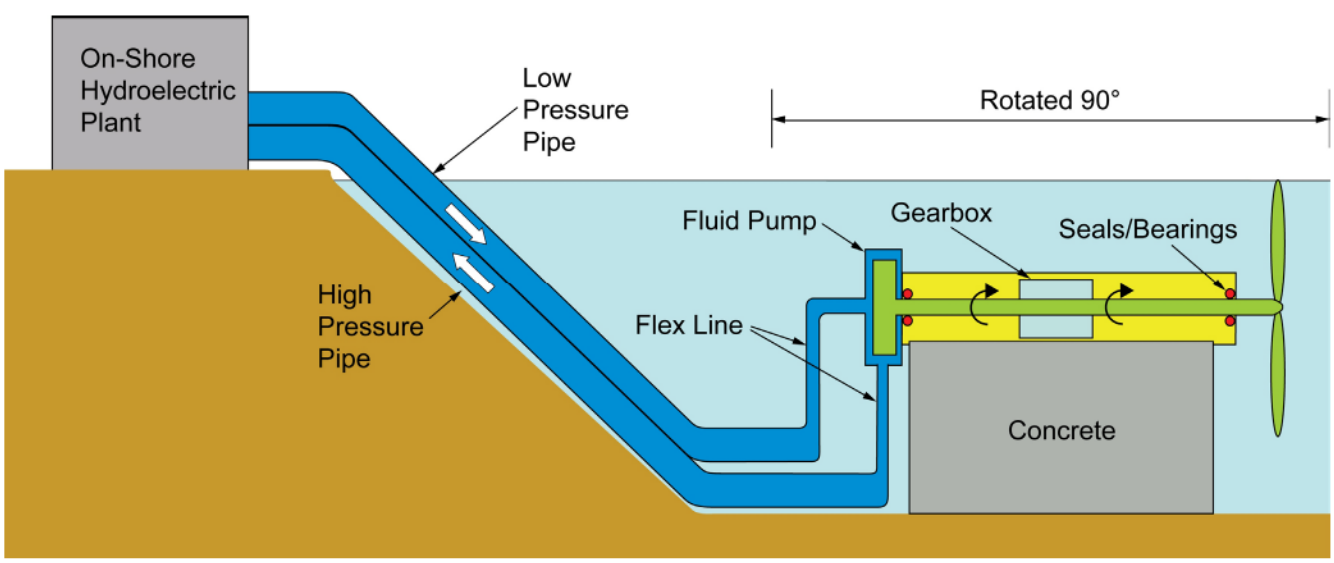

Figure 10. JPL/Caltech Hydraulic Tidal Power Generation Schematic

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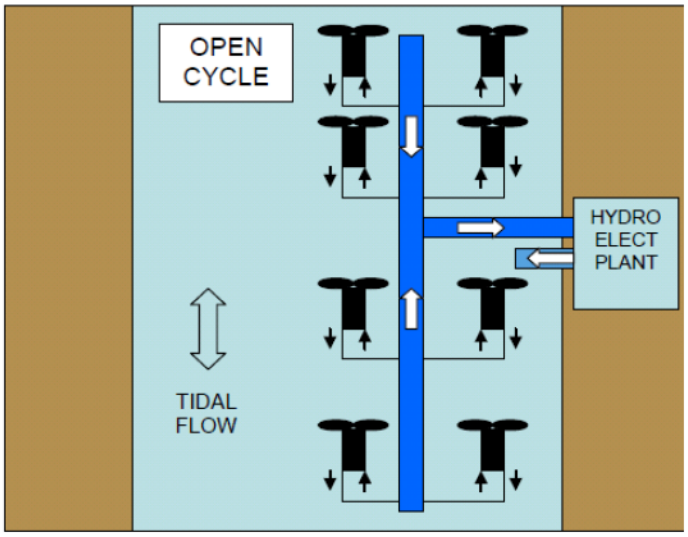

Figure 11. Hydraulic Power Generation Open Cycle (Top View)

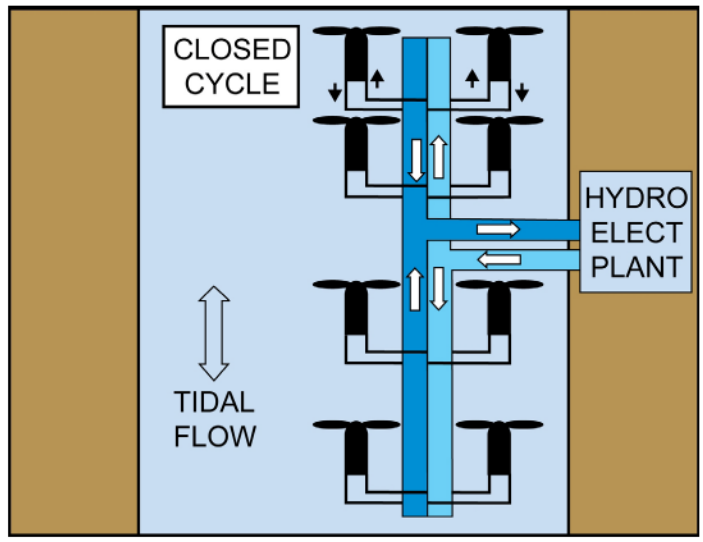

Figure 12. Hydraulic Power Generation Closed Cycle (Top View)

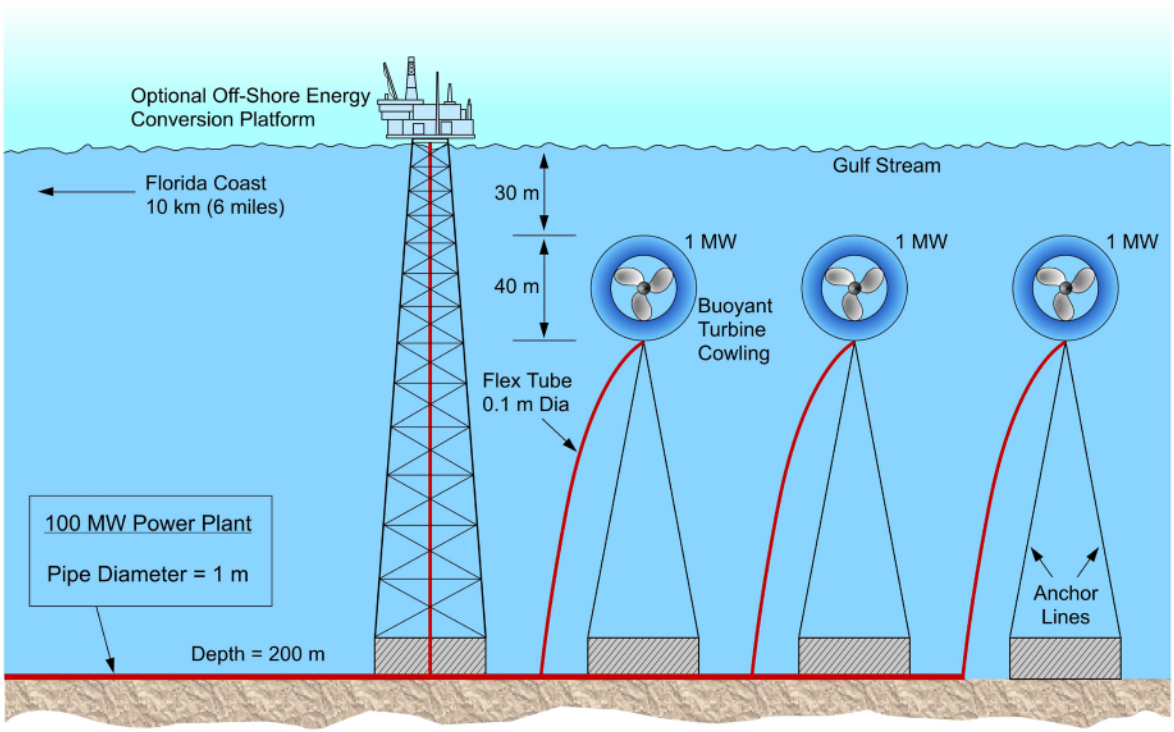

Figure 13. Hydraulic Power Generation for the Gulf Stream

5.3 Pumped Energy Storage

A schematic of how the tidal system might look for a hilly area, such as San Francisco, is shown in Fig 14. This system is shown as open-cycle, but could also be closed-cycle if desired. An optional elevated reservoir is shown, in which the pressurized water can be stored to even out the electrical supply, since tidal flows are necessarily very time-dependent, and will produce no power during tidal ebbs. An open-cycle salt water pump storage facility has been operating in Okinawa, Japan since 1999 (Ref 18). This facility is an open-cycle system which it employs standard electromechanical pumps, not tidal-powered pumps.

5.4 Pipe Costs for 10-MW River or Tidal Current Hydraulic Transfer System

Preliminary costing has been performed for the pipes required for a 10-MW hydroelectric plant placed in an area

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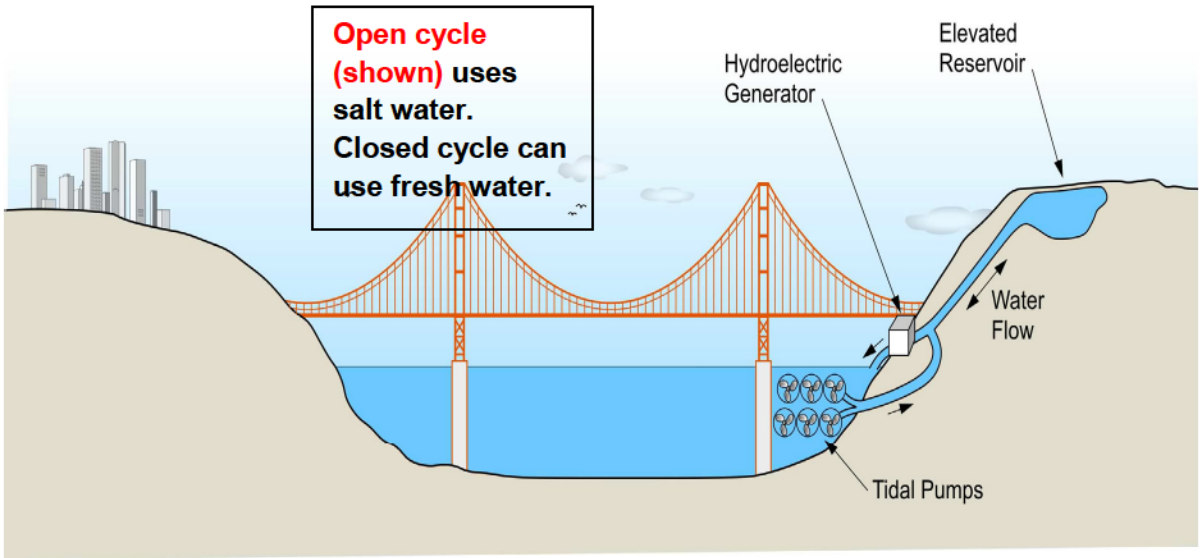

Figure 14. San Francisco Bay Tidal Power with Optional Pumped Storage

similar to the Marine Current Turbines location in the Strangford Lough in Northern Ireland (Ref 14). For the 2.5-m/sec average tidal current, each of 20 turbines would be 16 m in diameter and be configured similar to Fig 15. The long length of parallel tubes would be 45-cm I.D. by 800-m long reinforced fiberglass pipes (RFP) for both the high-pressure (500 psig) and low-pressure (50 psig) lines. The shorter length to shore would be 70-cm I.D. by 500-m long. Total pipe cost has been estimated as approximately $200/m (Ref 19) for the high-pressure lines and $50/m for the low-pressure lines, for a total cost of $275,000 or $27.50 per kW. This is about 1% of the total estimated cost for the typical tidal turbines (Table 1).

Primary assembly of the pipes could be on-shore and floated out to the appropriate location at null tide. The entire assembly including the tidal powered pumps themselves must be weighted down with inexpensive reinforced concrete (Ref 20) to protect the components from strong tidal forces. The cost of turbine pump assemblies has been costed as equal to or less than turbine generator assemblies, and thus total costs are expected to be equivalent to or less than Verdant-type or MCT-type tidal turbines which further require expensive pilings.

The hydraulic on-shore energy system is also expected to be less expensive and more efficient than the Lunar Energy type of adjunct hydraulic energy transfer due to cost and efficiency improvements associated with a much larger on-shore power generation system. Costs of the on-shore hydroelectric power plants are lower than any other electric power system, as previously shown in Table 1, and thus total fabrication and maintenance costs of the on-shore hydraulic energy transfer system should be lower than other comparable tidal energy systems.

6 CONCLUDING REMARKS

There are many means of providing non-carbon-emitting electrical power from both fresh water and salt water energy sources. By far, the least expensive is conventional hydroelectric power, which is nearly fully utilized in the United States, as well as worldwide. Other potential sources of water energy are hydrokinetic energy, such as from tides, river currents, ocean currents, and waves. Combined, these new energy sources could provide up to about 10% of present U.S. electrical energy needs. Devices that are under development to harvest these energy sources are relatively expensive and are often subject to corrosion of submerged electric power-generation equipment. The novel JPL/Caltech water hydraulic energy transfer system described in this paper appears to be a low-cost means of converting offshore hydrokinetic energy to pressurized hydraulic energy, which is then converted to electricity ***onshore*** by an inexpensive hydroelectric plant. With the hydraulic energy transfer system, the submerged electrical generator components are replaced by non-electrical pumps, and thus all submerged electrical components are completely eliminated. The pipe fabrication costs are expected to be only about 1% of total fabrication costs, and installation should be relatively inexpensive, since most of the fabrication is performed on-shore. Although installation and maintenance costs appear low, confirmation requires actual in situ testing.

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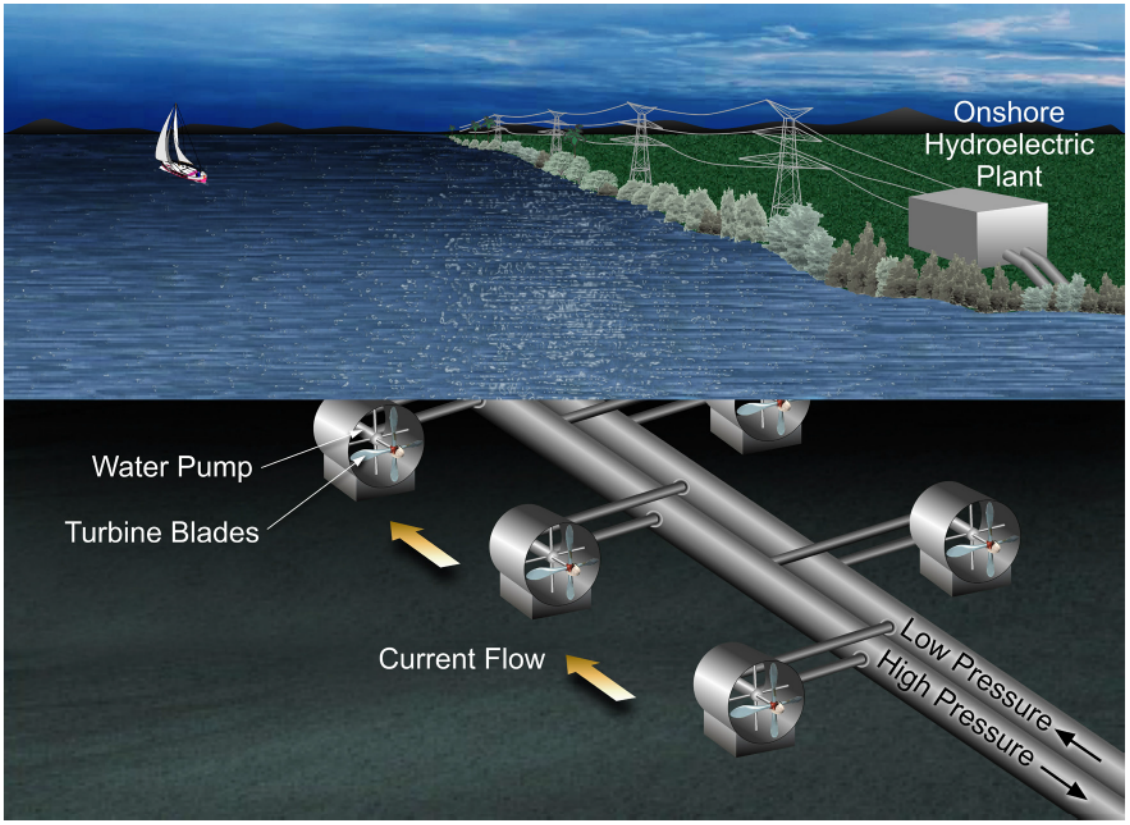

Figure 15. Hydraulic Energy Transfer System

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