Introduction to Hydropower

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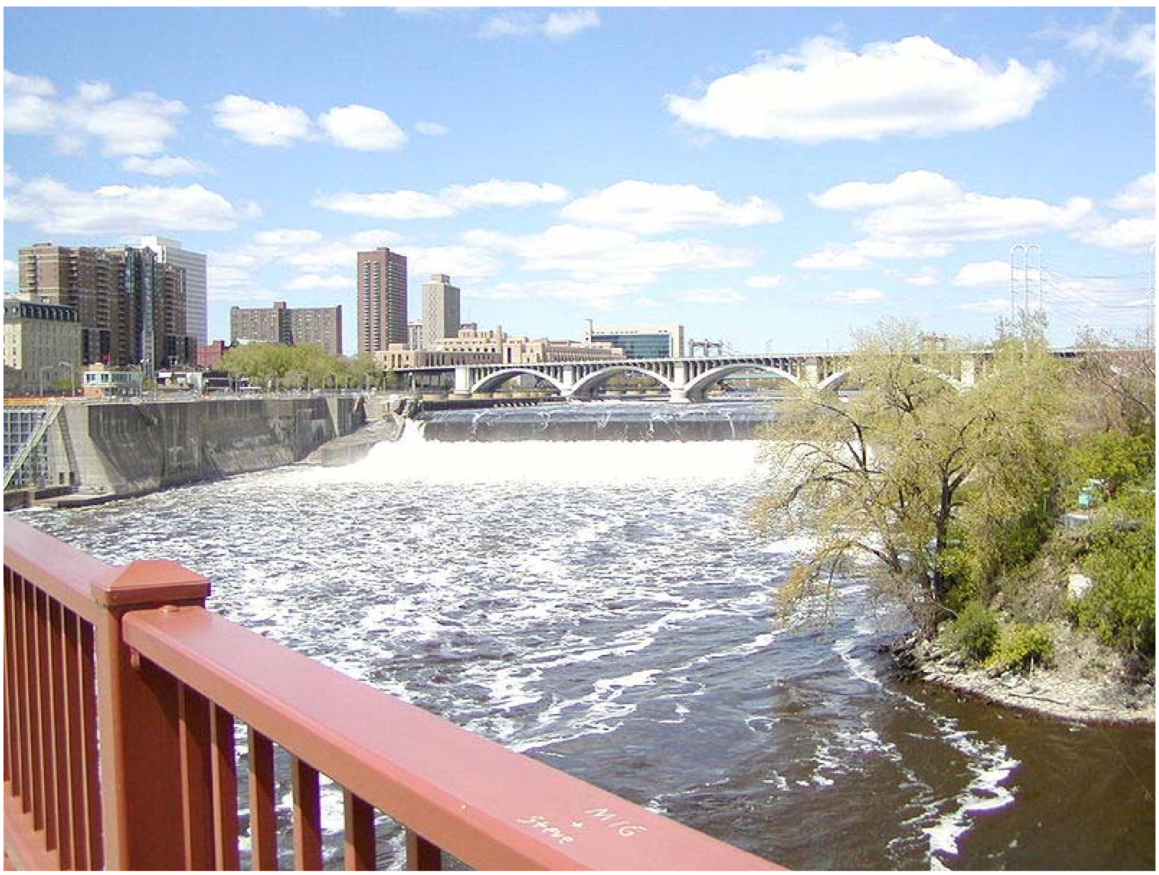
Chapter- 1

Introduction to Hydropower



Saint Anthony Falls, United States.

Hydropower, **hydraulic power** or **water power** is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the widespread availability of commercial electric power, hydropower was used for irrigation, and operation of various machines, such as watermills, textile machines, sawmills, dock cranes, and domestic lifts.

Another method used a trompe to produce compressed air from falling water, which could then be used to power other machinery at a distance from the water.

In hydrology, hydropower is manifested in the force of the water on the riverbed and banks of a river. It is particularly powerful when the river is in flood. The force of the water results in the removal of sediment and other materials from the riverbed and banks of the river, causing erosion and other alterations.

History

Early uses of waterpower date back to Mesopotamia and ancient Egypt, where irrigation has been used since the 6th millennium BC and water clocks had been used since the early 2nd millennium BC. Other early examples of water power include the Qanat system in ancient Persia and the Turpan water system in ancient China.

Waterwheels and mills

Hydropower has been used for hundreds of years. In India, water wheels and watermills were built; in Imperial Rome, water powered mills produced flour from grain, and were also used for sawing timber and stone; in China, watermills were widely used since the Han Dynasty. The power of a wave of water released from a tank was used for extraction of metal ores in a method known as hushing. The method was first used at the Dolaucothi gold mine in Wales from 75 AD onwards, but had been developed in Spain at such mines as Las Medulas. Hushing was also widely used in Britain in the Medieval and later periods to extract lead and tin ores. It later evolved into hydraulic mining when used during the California gold rush.

In China and the rest of the Far East, hydraulically operated "pot wheel" pumps raised water into irrigation canals. At the beginning of the Industrial revolution in Britain, water was the main source of power for new inventions such as Richard Arkwright's water frame. Although the use of water power gave way to steam power in many of the larger mills and factories, it was still used during the 18th and 19th centuries for many smaller operations, such as driving the bellows in small blast furnaces (e.g. the Dyfi Furnace) and gristmills, such as those built at Saint Anthony Falls, utilizing the 50-foot (15 m) drop in the Mississippi River.

In the 1830s, at the peak of the canal-building era, hydropower was used to transport barge traffic up and down steep hills using inclined plane railroads.

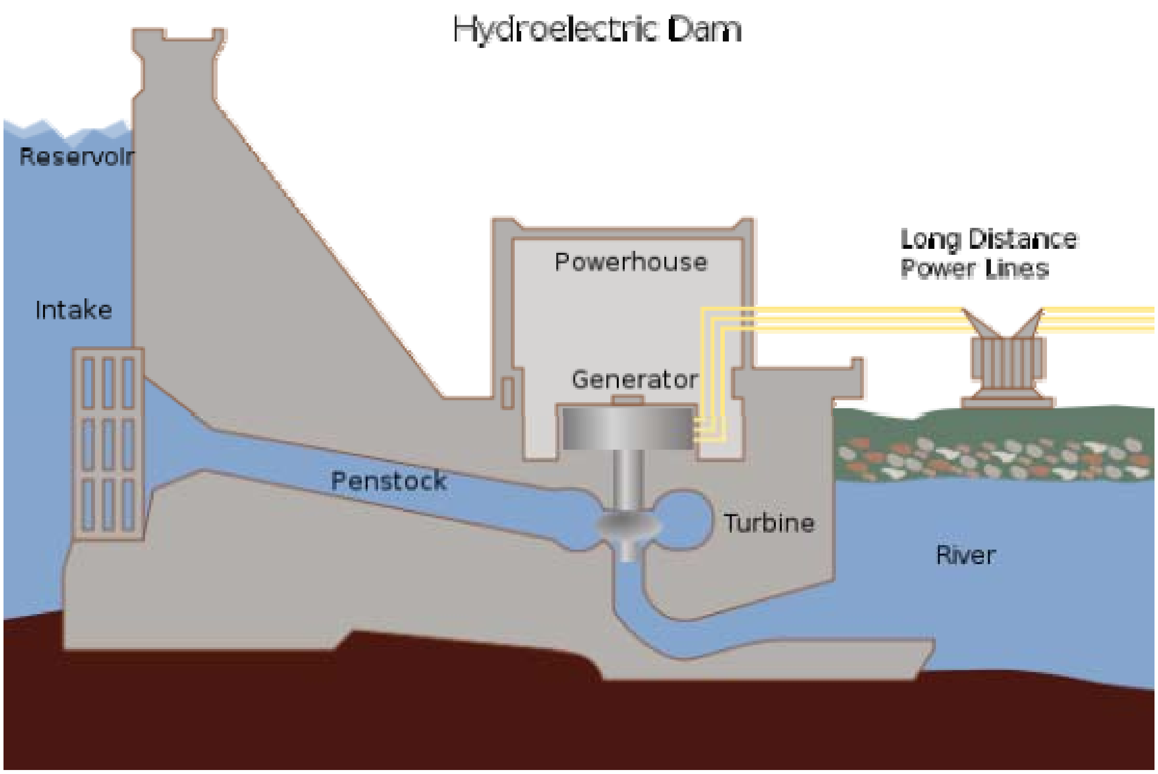
Hydraulic power pipes

Hydraulic power networks also existed, using pipes carrying pressurized liquid to transmit mechanical power from a power source, such as a pump, to end users. These were extensive in Victorian cities in the United Kingdom. A hydraulic power network was also in use in Geneva, Switzerland. The world famous Jet d'Eau was originally the only over pressure valve of this network.

Modern usage

There are several forms of water power currently in use or development. Some are purely mechanical but many primarily generate electricity. Broad categories include:

Hydroelectricity



A conventional dammed-hydro facility (hydroelectric dam) is the most common type of hydroelectric power generation.

- Conventional hydroelectric, referring to hydroelectric dams.
- Run-of-the-river hydroelectricity, which captures the kinetic energy in rivers or streams, without the use of dams.
- Pumped-storage hydroelectricity, to pump up water, and use its head to generate in times of demand.
- Tidal power, which captures energy from the tides in horizontal direction.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.

Marine energy

A Pelamis wave device under test at the European Marine Energy Centre (EMEC), Orkney, Scotland.

- Marine current power, which captures the kinetic energy from marine currents.
- Osmotic power, which channels river water into a container separated from sea water by a semi-permeable membrane.
- Ocean thermal energy, which exploits the temperature difference between deep and shallow waters.
- Tidal power, which captures energy from the tides in horizontal direction. Also a popular form of hydroelectric power generation.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.
- Wave power, the use ocean surface waves to generate power.

Calculating the amount of available power

A hydropower resource can be measured according to the amount of available power, or energy per unit time. In large reservoirs, the available power is generally only a function of the hydraulic head and rate of fluid flow. In a reservoir, the head is the height of water in the reservoir relative to its height after discharge. Each unit of water can do an amount of work equal to its weight times the head.

The amount of energy, E, released when an object of mass m drops a height h in a gravitational field of strength g is given by

$$E = mgh$$

The energy available to hydroelectric dams is the energy that can be liberated by lowering water in a controlled way. In these situations, the power is related to the mass flow rate.

$$\frac{E}{t} = \frac{m}{t} gh$$

Substituting *P* for $^{E}\!/_{t}$ and expressing $^{m}\!/_{t}$ in terms of the volume of liquid moved per unit time (the rate of fluid flow, φ) and the density of water, we arrive at the usual form of this expression:

$$P = \rho \phi g h$$

or

A simple formula for approximating electric power production at a hydroelectric plant is:

P = hrgk

where P is Power in kilowatts, h is height in meters, r is flow rate in cubic meters per second, g is acceleration due to gravity of 9.8 m/s2, and k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher with larger and more modern turbines.

Some hydropower systems such as water wheels can draw power from the flow of a body of water without necessarily changing its height. In this case, the available power is the kinetic energy of the flowing water.

$$P = \frac{1}{2} \rho \phi v^2$$

where *v* is the speed of the water, or with

$$\phi = A v$$

where *A* is the area through which the water passes, also

$$P = \frac{1}{2} \rho A v^3$$

Over-shot water wheels can efficiently capture both types of energy.

Chapter- 2

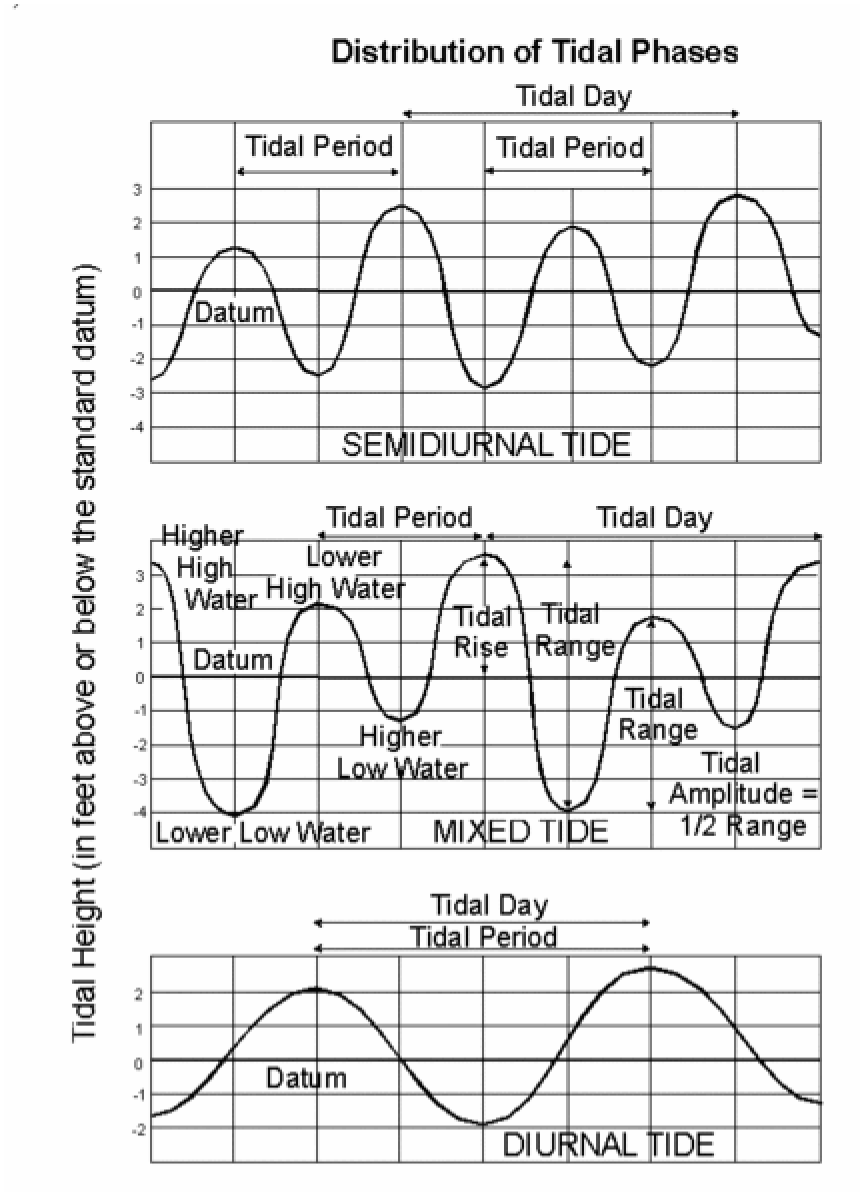
Tidal Power

Tidal power, also called **tidal energy**, is a form of hydropower that converts the energy of tides into electricity or other useful forms of power. The first large-scale tidal power plant (the Rance Tidal Power Station) started operation in 1966.

Although not yet widely used, tidal power has potential for future electricity generation. Tides are more predictable than wind energy and solar power. Among sources of renewable energy, tidal power has traditionally suffered from relatively high cost and limited availability of sites with sufficiently high tidal ranges or flow velocities, thus constricting its total availability. However, many recent technological developments and improvements, both in design (e.g. dynamic tidal power, tidal lagoons) and turbine technology (e.g. new axial turbines, crossflow turbines), indicate that the total availability of tidal power may be much higher than previously assumed, and that economic and environmental costs may be brought down to competitive levels.

Historically, tide mills have been used, both in Europe and on the Atlantic coast of North America. The earliest occurrences date from the Middle Ages, or even from Roman times.

Generation of tidal energy



Variation of tides over a day

Tidal power is the only form of energy which derives directly from the relative motions of the Earth–Moon system, and to a lesser extent from the Earth–Sun system. Tidal forces produced by the Moon and Sun, in combination with Earth's rotation, are responsible for the generation of the tides. Other sources of energy originate directly or indirectly from the Sun, including fossil fuels, conventional hydroelectric, wind, biofuels, wave power and solar. Nuclear energy makes use of Earth's mineral deposits of fissile elements, while geothermal power uses the Earth's internal heat which comes from a combination of residual heat from planetary accretion (about 20%) and heat produced through radioactive decay (80%).

Tidal energy is extracted from the relative motion of large bodies of water. Periodic changes of water levels, and associated tidal currents, are due to the gravitational attraction of the Sun and Moon. Magnitude of the tide at a location is the result of the changing positions of the Moon and Sun relative to the Earth, the effects of Earth rotation, and the local geography of the sea floor and coastlines.

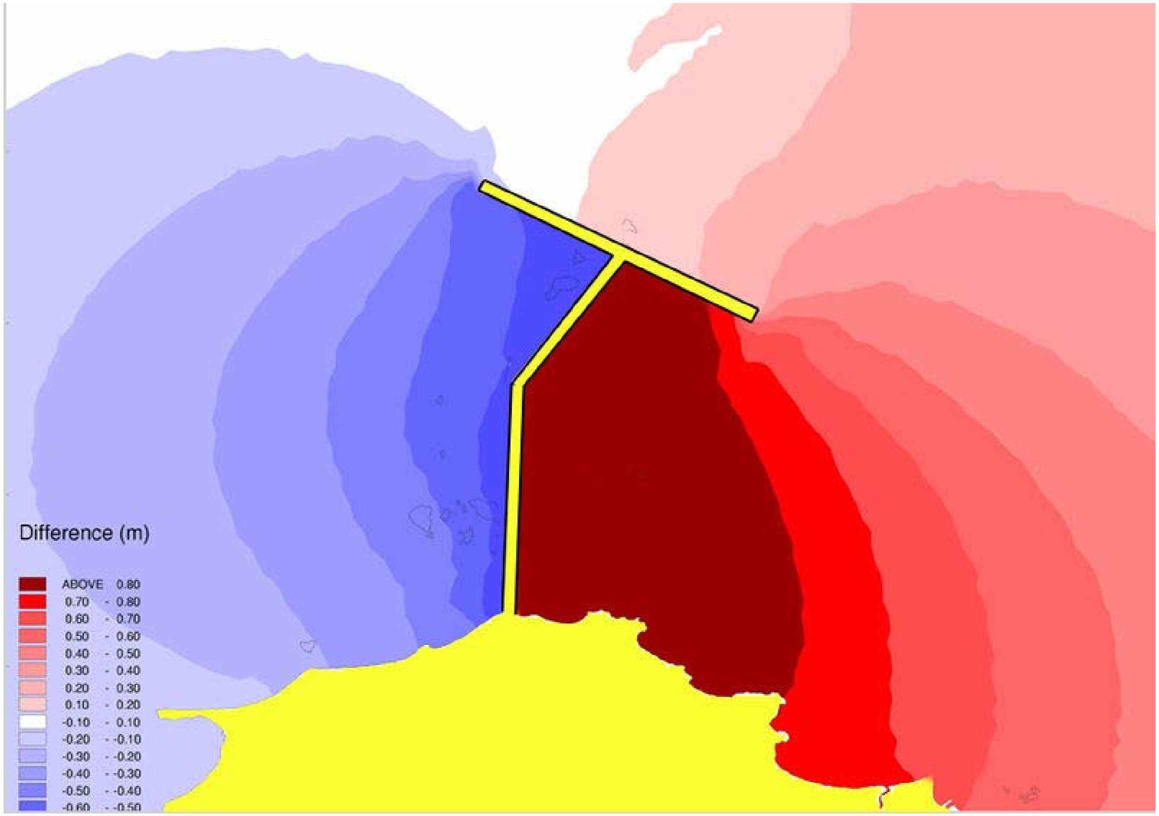
Because the Earth's tides are ultimately due to gravitational interaction with the Moon and Sun and the Earth's rotation, tidal power is practically inexhaustible and classified as a renewable energy resource.

A tidal generator uses this phenomenon to generate electricity. Greater tidal variation or tidal current velocities can dramatically increase the potential for tidal electricity generation.

The movement of the tides causes a continual loss of mechanical energy in the Earth–Moon system due to pumping of water through the natural restrictions around coastlines, and consequent viscous dissipation at the seabed and in turbulence. This loss of energy has caused the rotation of the Earth to slow in the 4.5 billion years since formation. During the last 620 million years the period of rotation has increased from 21.9 hours to the 24 hours we see now; in this period the Earth has lost 17% of its rotational energy. While tidal power may take additional energy from the system, increasing the rate of slowdown, the effect would be noticeable over millions of years only, thus being negligible.

Generating methods

The world's first commercial-scale and grid-connected tidal stream generator – SeaGen – in Strangford Lough. The strong wake shows the power in the tidal current.



Top-down view of a DTP dam. Blue and dark red colors indicate low and high tides, respectively.

Tidal power can be classified into three generating methods:

Tidal stream generator

Tidal stream generators (or TSGs) make use of the kinetic energy of moving water to power turbines, in a similar way to wind turbines that use moving air. This method is gaining in popularity because of the lower cost and lower ecological impact compared to tidal barrages.

Tidal barrage

Tidal barrages make use of the potential energy in the difference in height (or *head*) between high and low tides. Barrages are essentially dams across the full width of a tidal estuary, and suffer from very high civil infrastructure costs, a worldwide shortage of viable sites and environmental issues.

Dynamic tidal power

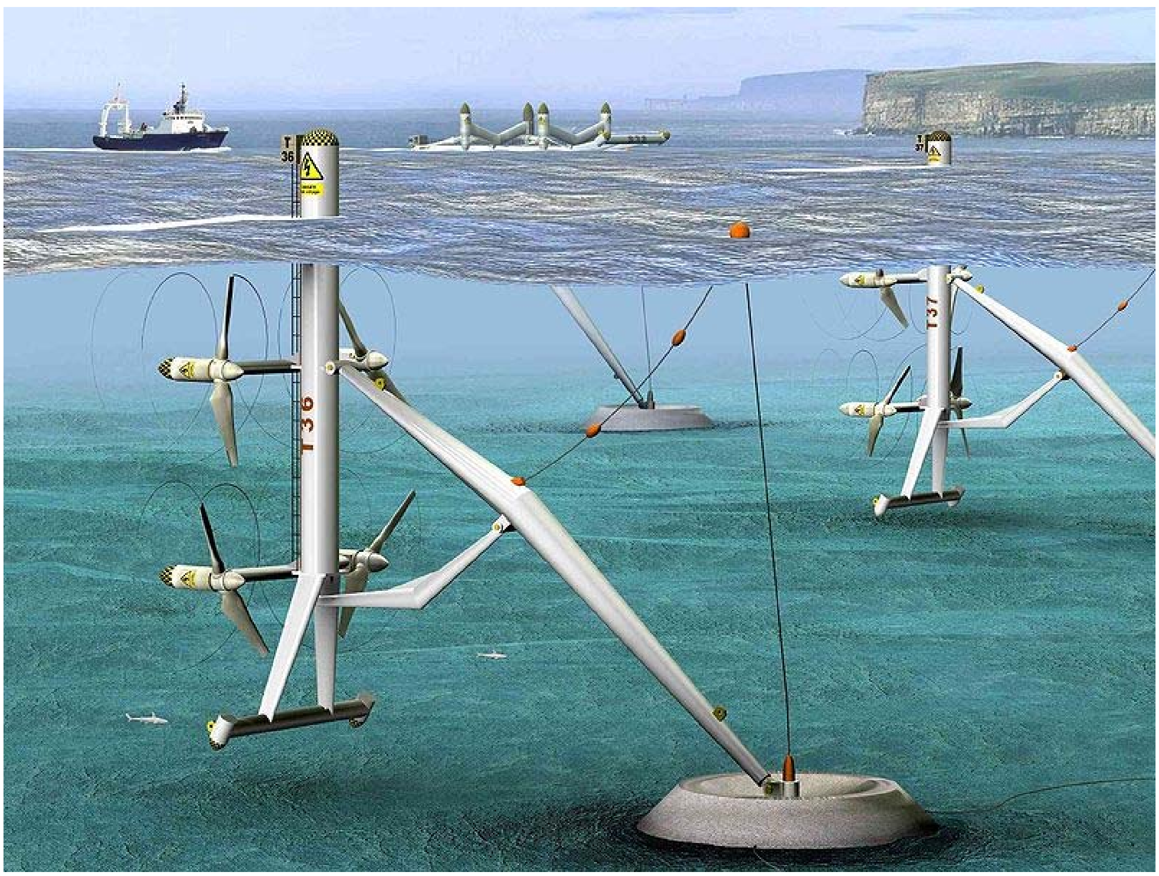
Dynamic tidal power (or DTP) exploits an interaction between potential and kinetic energies in tidal flows. It proposes that (for example: 30–50 km length) dams be built from coasts straight out into the sea or ocean, without enclosing an area. Tidal phase differences are introduced by the presence and dimensions of the dam, which is not negligible in size compared to the local tidal wavelength. This leads to hydraulic head differences across the dam. Turbines in the dam are used to convert power (6–15 GW per dam). In shallow coastal seas featuring strong coast-parallel oscillating tidal currents such as found in the UK, China and Korea, a significant water level differential (of at least 2–3 meters) would appear across the dam.

Current and future tidal power schemes

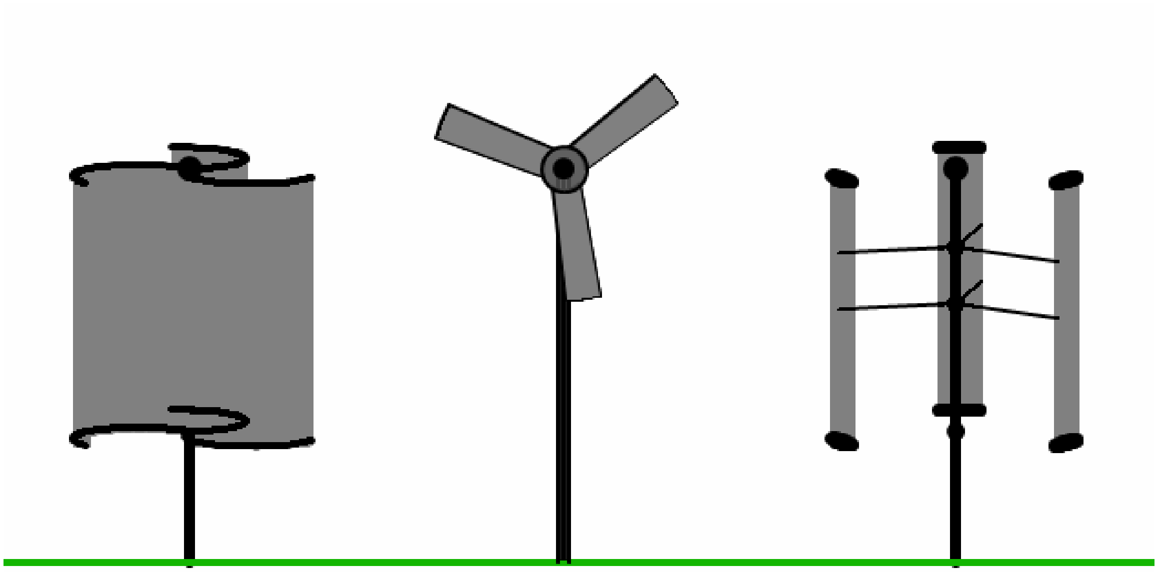
- The first tidal power station was the Rance tidal power plant built over a period of 6 years from 1960 to 1966 at La Rance, France. It has 240 MW installed capacity.
- The first tidal power site in North America is the Annapolis Royal Generating Station, Annapolis Royal, Nova Scotia, which opened in 1984 on an inlet of the Bay of Fundy. It has 20 MW installed capacity.
- The first in-stream tidal current generator in North America (Race Rocks Tidal Power Demonstration Project) was installed at Race Rocks on southern Vancouver Island in September 2006. The next phase in the development of this tidal current generator will be in Nova Scotia.
- A small project was built by the Soviet Union at Kislaya Guba on the Barents Sea. It has 0.4 MW installed capacity. In 2006 it was upgraded with a 1.2MW experimental advanced orthogonal turbine.
- Jindo Uldolmok Tidal Power Plant in South Korea is a tidal stream generation scheme planned to be expanded progressively to 90 MW of capacity by 2013. The first 1 MW was installed in May 2009.
- A 1.2 MW SeaGen system became operational in late 2008 on Strangford Lough in Northern Ireland.
- The Jiangxia Tidal Power Station near the mouth of the Yalu River in China is operational, with current installed capacity of 3.2 MW. It may be expanded.
- 254 MW Sihwa Lake Tidal Power Plant in South Korea is under construction and planned to be completed by the end of 2010.
- The contract for an 812 MW tidal barrage near Ganghwa Island north-west of Incheon has been signed by Daewoo. Completion is planned for 2015.
- A 1,320 MW barrage built around islands west of Incheon is proposed by the Korean government, with projected construction start in 2017.
- Other South Korean projects include barrages planned for Garorim Bay, Ansanman, and Swaseongho, and tidal generation associated with the Saemangeum reclamation project. The barrages are all in the multiple-hundred megawatts range.
- Estimates for new tidal barrages in England give the potential generation at 5.6GW mean power.

Country	Place	Mean tidal range (m)	Area of basin (km²)	Maximum capacity (MW)
United Kingdom	River Severn	7.8	450	8,640
Russia	Penzhinskaya Bay	6.0	20,500	87,000

Tidal stream generator



Artist's impression of tidal turbines on a different type of support structure.



Most tidal turbines closely resembles a wind turbine, more commonly the HAWT-type.

A **tidal stream generator** (**TSG**) is a machine that extracts energy from moving masses of water, or tides. These machines function very much like underwater wind turbines, hence are also sometimes referred to as **tidal turbines**.

TSGs are the cheapest and the least ecologically damaging among the three main forms of tidal power generation.

Similarity to wind turbines

Tidal stream generators draw energy from currents in much the same way as wind turbines.

As a relatively new technology, though first conceived in the 1970s during the oil crisis, the potential for power generation by an individual tidal turbine can be greater than that of similarly rated wind energy turbine. The higher density of water relative to air (water is about 800 times the density of air) means that a single generator can provide significant power at low tidal flow velocities compared with similar wind speed. Given that power varies with the density of medium and the cube of velocity, it is simple to see that water speeds of nearly one-tenth of the speed of wind provide the same power for the same size of turbine system; however this limits the application in practice to places where the tide moves at speeds of at least 2 knots (1 m/s) even close to neap tides. Furthermore, at higher speeds in a flow between 2 to 3 metres per second in seawater a tidal turbine can typically access four times as much energy per rotor swept area as a similarly rated power wind turbine.

Types of tidal stream generators

Since tidal stream generators are an immature technology, no standard technology has yet emerged as the clear winner, but a large variety of designs are being experimented with, some very close to large scale deployment. Several prototypes have shown promise with many companies making bold claims, some of which are yet to be independently verified, but they have not operated commercially for extended periods to establish performances and rates of return on investments.

The European Marine Energy Centre categorises them under four heads although a number of other approaches are also being tried.

Axial turbines

Evopod - A semi-submerged floating approach tested in Strangford Lough.

These are close in concept to traditional windmills operating under the sea and have the most prototypes currently operating. These include:

Kvalsund, south of Hammerfest, Norway. Although still a prototype, a turbine with a reported capacity of 300 kW was connected to the grid on 13 November 2003.

A 300 kW Periodflow marine current propeller type turbine — Seaflow — was installed by Marine Current Turbines off the coast of Lynmouth, Devon, England, in 2003. The

11m diameter turbine generator was fitted to a steel pile which was driven into the seabed. As a prototype, it was connected to a dump load, not to the grid.

Since April 2007 Verdant Power has been running a prototype project in the East River between Queens and Roosevelt Island in New York City; it was the first major tidal-power project in the United States. The strong currents pose challenges to the design: the blades of the 2006 and 2007 prototypes broke off, and new reinforced turbines were installed in September 2008.

Following the Seaflow trial, a fullsize prototype, called SeaGen, was installed by Marine Current Turbines in Strangford Lough in Northern Ireland in April 2008. The turbine began to generate at full power of just over 1.2 MW in December 2008 and is reported to have fed 150 kW into the grid for the first time on 17 July 2008, and has now contributed more than a gigawatt hour to consumers in Northern Ireland. It is currently the only commercial scale device to have been installed anywhere in the world. SeaGen is made up of two axial flow rotors, each of which drive a generator. The turbines are capable of generating electricity on both the ebb and flood tides because the rotor blades can pitch through 180˚.

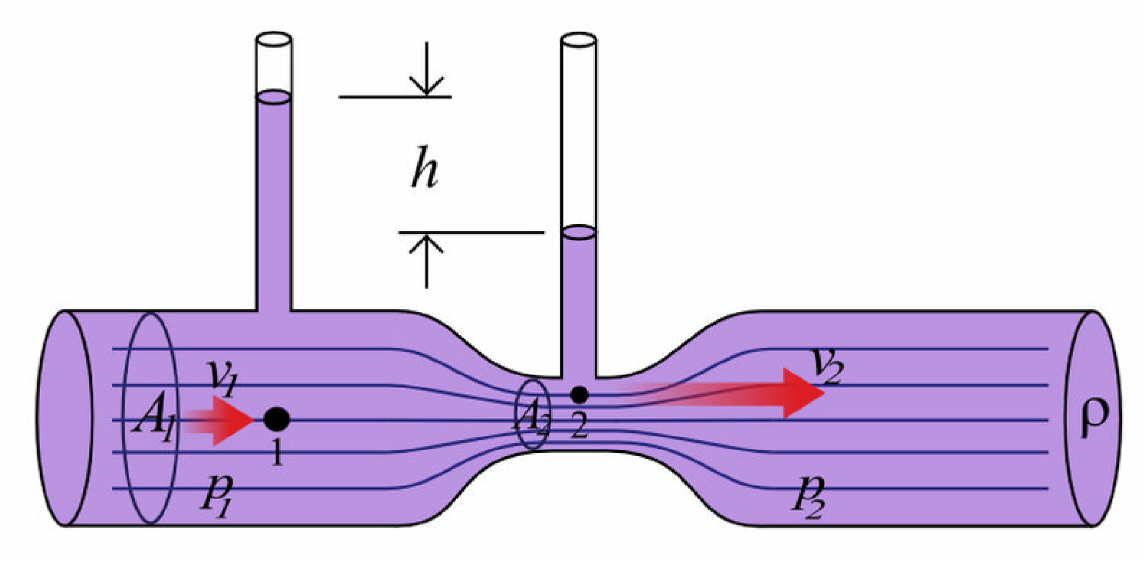
OpenHydro, an Irish company exploiting the Open-Centre Turbine developed in the U.S., has a prototype being tested at the European Marine Energy Centre (EMEC), in Orkney, Scotland.

A prototype semi-submerged floating tethered tidal turbine called Evopod has been tested since June 2008 in Strangford Lough, Northern Ireland at 1/10th scale. The company developing it is called Ocean Flow Energy Ltd, and they are based in the UK. The advanced hull form maintains optimum heading into the tidal stream and it is designed to operate in the peak flow of the water column.

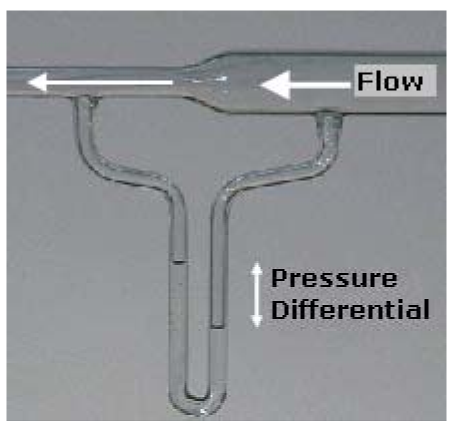
Tenax Energy of Australia is proposing to put 450 turbines off the coast of the Australian city Darwin, in the Clarence Strait. The turbines feature a rotor section that is approximately 15 metres in diameter with a gravity base which is slighter larger than this to support the structure. The turbines will operate in deep water well below shipping channels. Each turbine is forecast to produce energy for between 300 and 400 homes.

Tidalstream have commissioned a scaled-down Triton 3 turbine in the Thames. It can be floated out to site, installed without cranes, jack-ups or divers, and then ballasted into operating position. At full scale the Triton 3 in 30-50m deep water has a 3MW capacity, and the Triton 6 in 60-80m water has a capacity of up to 10MW, depending on the flow. Both platforms have man-access capability both in the operating position and in the float-out maintenance position.

Venturi effect



The pressure at "1" is higher than at "2" because the fluid speed at "1" is lower than at "2".



A flow of air through a venturi meter, showing the columns connected in a U-shape (a manometer) and partially filled with water. The meter is "read" as a differential pressure head in cm or inches of water.

The **Venturi effect** is the reduction in fluid pressure that results when a fluid flows through a constricted section of pipe. The Venturi effect is named after Giovanni Battista Venturi (1746–1822), an Italian physicist.

Background

According to the laws governing fluid dynamics, a fluid's velocity must *increase* as it passes through a constriction to satisfy the conservation of mass, while its pressure must *decrease* to satisfy the conservation of energy. Thus any gain in kinetic energy a fluid may accrue due to its increased velocity through a constriction is negated by a drop in pressure. An equation for the drop in pressure due to the Venturi effect may be derived from a combination of Bernoulli's principle and the continuity equation.

The limiting case of the Venturi effect is when a fluid reaches the state of choked flow, where the fluid velocity approaches the local speed of sound. In choked flow the mass flow rate will not increase with a further decrease in the downstream pressure environment.

However, mass flow rate for a compressible fluid can increase with increased upstream pressure, which will increase the density of the fluid through the constriction (though the velocity will remain constant). This is the principle of operation of a de Laval nozzle.

Referring to the diagram to the right, using Bernoulli's equation in the special case of incompressible flows (such as the flow of water or other liquid, or low speed flow of gas), the theoretical pressure drop ($p_1 - p_2$) at the constriction would be given by:

$$\frac{\rho}{2}(v_2^2 - v_1^2)$$

where ρ is the density of the fluid, v_1 is the (slower) fluid velocity where the pipe is wider, v_2 is the (faster) fluid velocity where the pipe is narrower (as seen in the figure). This assumes the flowing fluid (or other substance) is not significantly compressible - even though pressure varies, the density is assumed to remain approximately constant.

Experimental apparatus

Venturi tube demonstration apparatus built out of PVC pipe and operated with a vacuum pump

Venturi tubes

The simplest apparatus, as shown in the photograph and diagram, is a tubular setup known as a Venturi tube or simply a venturi. Fluid flows through a length of pipe of varying diameter. To avoid undue drag, a Venturi tube typically has an entry cone of 30 degrees and an exit cone of 5 degrees. To account for the assumption of an inviscid fluid a coefficient of discharge is often introduced, which generally has a value of 0.98.

Orifice plate

Venturi tubes are more expensive to construct than a simple orifice plate which uses the same principle as a tubular scheme, but the orifice plate causes significantly more permanent energy loss.

Instrumentation and Measurement

Venturis are used in industrial and in scientific laboratories for measuring the flow of liquids.

Flow rate

A venturi can be used to measure the volumetric flow rate *Q*.

Since

$$\begin{cases} Q = v_1 A_1 = v_2 A_2 \\ p_1 - p_2 = \frac{\varrho}{2}(v_2^2 - v_1^2), \end{cases}$$

then

$$Q = A_1 \sqrt{\frac{2(p_1 - p_2)}{\rho\left(\left(\frac{A_1}{A_2}\right)^2 - 1\right)}} = A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho\left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}}.$$

A venturi can also be used to mix a liquid with a gas. If a pump forces the liquid through a tube connected to a system consisting of a venturi to increase the liquid speed (the diameter decreases), a short piece of tube with a small hole in it, and last a venturi that decreases speed (so the pipe gets wider again), the gas will be sucked in through the small hole because of changes in pressure. At the end of the system, a mixture of liquid and gas will appear.

Differential Pressure

As fluid flows through a venturi, the expansion and compression of the fluids cause the pressure inside the venturi to change. This principle can be used in metrology for gauges calibrated for differential pressures. This type of pressure measurement may be more convenient, for example, to measure fuel or combustion pressures in jet or rocket engines.

This uses a shroud to increase the flow rate through the turbine. These can be mounted horizontally or vertically.

The Australian company Tidal Energy Pty Ltd undertook successful commercial trials of highly efficient shrouded tidal turbines on the Gold Coast, Queensland in 2002. Tidal Energy has commenced a rollout of their shrouded turbine for a remote Australian community in northern Australia where there are some of the fastest flows ever recorded (11 m/s, 21 knots) – two small turbines will provide 3.5 MW. Another larger 5 meter diameter turbine, capable of 800 kW in 4 m/s of flow, is planned for deployment as a tidal powered desalination showcase near Brisbane Australia in October 2008. Another device, the Hydro Venturi, is to be tested in San Francisco Bay.

Vertical and horizontal axis crossflow turbines

Invented by Georges Darreius in 1923 and Patented in 1929, these turbines that can be deployed either vertically or horizontally.

The Gorlov turbine is a variant of the Darrieus design featuring a helical design which is being commercially piloted on a large scale in S. Korea, starting with a 1MW plant that started in May 2009 and expanding to 90MW by 2013. Neptune Renewable Energy has developed Proteus which can be used to form an array in mainly estuarine conditions.

In late April 2008, Ocean Renewable Power Company, LLC (ORPC) successfully completed the testing of its proprietary turbine-generator unit (TGU) prototype at ORPC's Cobscook Bay and Western Passage tidal sites near Eastport, Maine. The TGU is the core of the OCGen technology and utilizes advanced design cross-flow (ADCF) turbines to drive a permanent magnet generator located between the turbines and mounted on the same shaft. ORPC has developed TGU designs that can be used for generating power from river, tidal and deep water ocean currents.

Trials in the Strait of Messina, Italy, started in 2001 of the Kobold concept.

Oscillating devices

Oscillating devices do not have a rotating component, instead making use of aerofoil sections which are pushed sideways by the flow. Oscillating stream power extraction was proven with the omni- or bi-directional Wing'd Pump windmill. During 2003 a 150 kW oscillating hydroplane device, the Stingray, was tested off the Scottish coast. The Stingray uses hydrofoils to create oscillation, which allows it to create hydraulic power. This hydraulic power is then used to power a hydraulic motor, which then turns a generator.

Pulse Tidal operate an oscillating hydrofoil device in the Humber estuary. Having secured funding from the EU, they are developing a commercial scale device to be commissioned 2012.

The bioSTREAM tidal power conversion system, uses the biomimicry of swimming species, such as shark, tuna, and mackerel using their highly efficient Thunniform mode propulsion. It is produced by Australian company BioPower Systems.

A 2 kW prototype relying on the use of two oscillating hydrofoils in a tandem configuration has been developed at Laval University and tested successfully near Quebec City, Canada, in 2009. A hydrodynamic efficiency of 40% has been achieved during the field tests.

Commercial plans

RWE's npower announced that it is in partnership with Marine Current Turbines to build a tidal farm of SeaGen turbines off the coast of Anglesey in Wales, near the Skerries.

In November 2007, British company Lunar Energy announced that, in conjunction with E.ON, they would be building the world's first deep-sea tidal energy farm off the coast of Pembrokshire in Wales. It will provide electricity for 5,000 homes. Eight underwater turbines, each 25 metres long and 15 metres high, are to be installed on the sea bottom off St David's peninsula. Construction is due to start in the summer of 2008 and the proposed tidal energy turbines, described as "a wind farm under the sea", should be operational by 2010.

British Columbia Tidal Energy Corp. plans to deploy at least three 1.2 MW turbines in the Campbell River or in the surrounding coastline of British Columbia by 2009.

An organisation named *Alderney Renewable Energy Ltd* is planning to use tidal turbines to extract power from the notoriously strong tidal races around Alderney in the Channel Islands. It is estimated that up to 3 GW could be extracted. This would not only supply the island's needs but also leave a considerable surplus for export.

Nova Scotia Power has selected OpenHydro's turbine for a tidal energy demonstration project in the Bay of Fundy, Nova Scotia, Canada and Alderney Renewable Energy Ltd for the supply of tidal turbines in the Channel Islands. Open Hydro

Pulse Tidal are designing a commercial device with seven other companies who are expert in their fields. The consortium was awarded an €8 million EU grant to develop the first device, which will be deployed in 2012 and generate enough power for 1,000 homes. Pulse is in a good position to scale up production because the supply chain is already in place.

Energy calculations

Turbine power

Various turbine designs have varying efficiencies and therefore varying power output. If the efficiency of the turbine "ξ" is known the equation below can be used to determine the power output of a turbine.

The energy available from these kinetic systems can be expressed as:

$$P = \frac{\xi \rho A V^3}{2}$$

where:

ξ = the turbine efficiency
P = the power generated (in watts)
ρ = the density of the water (seawater is 1025 kg/m^3)
A = the sweep area of the turbine (in m^2)

V = the velocity of the flow

Relative to an open turbine in free stream, depending on the geometry of the shroud shrouded turbines are capable of as much as 3 to 4 times the power of the same turbine rotor in open flow. .

Resource assessment

While initial assessments of the available energy in a channel have focus on calculations using the kinetic energy flux model, the limitations of tidal power generation are significantly more complicated. For example, the maximum physical possible energy extraction from a strait connecting two large basins is given to within 10% by:

$$P = 0.22\,\rho\, g\, \Delta H_{\max}\, Q_{\max}$$

where

ρ = the density of the water (seawater is 1025 kg/m³)
g = gravitational acceleration (9.81 m/s^2)
ΔH_{max} = maximum differential water surface elevation across the channel
Q_{max}= maximum volumetric flow rate though the channel.

Potential sites

As with wind power, selection of location is critical for the tidal turbine. Tidal stream systems need to be located in areas with fast currents where natural flows are concentrated between obstructions, for example at the entrances to bays and rivers, around rocky points, headlands, or between islands or other land masses. The following potential sites are under serious consideration:

- Pembrokeshire in Wales
- River Severn between Wales and England
- Cook Strait in New Zealand
- Kaipara Harbour in New Zealand
- Bay of Fundy in Canada.
- East River in the USA
- Golden Gate in the San Francisco Bay
- Piscataqua River in New Hampshire
- The Race of Alderney and The Swinge in the Channel Islands
- The Sound of Islay, between Islay and Jura in Scotland
- Pentland Firth between Caithness and the Orkney Islands, Scotland
- Humboldt County, California in the United States

Modern advances in turbine technology may eventually see large amounts of power generated from the ocean, especially tidal currents using the tidal stream designs but also from the major thermal current systems such as the Gulf Stream, which is covered by the more general term marine current power. Tidal stream turbines may be arrayed in high-velocity areas where natural tidal current flows are concentrated such as the west and east coasts of Canada, the Strait of Gibraltar, the Bosporus, and numerous sites in Southeast Asia and Australia. Such flows occur almost anywhere where there are entrances to bays and rivers, or between land masses where water currents are concentrated.

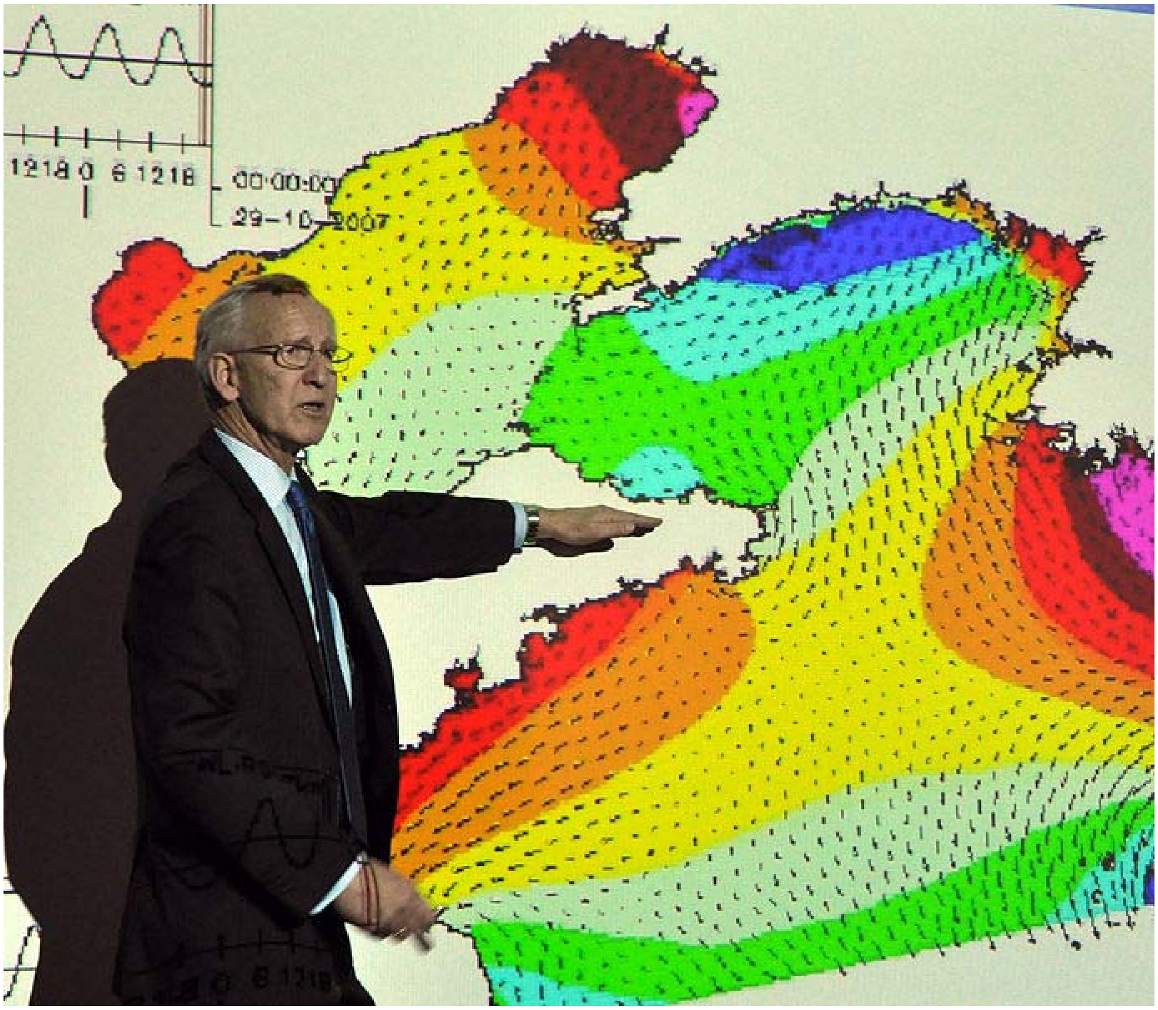
Environmental impacts

Very little direct research or observation of tidal stream systems exists. Most direct observations consist of releasing tagged fish upstream of the device(s) and direct observation of mortality or impact on the fish.

One study of the Roosevelt Island Tidal Energy (RITE, Verdant Power) project in the East River (New York City), utilized 24 split beam hydroacoustic sensors (scientific echosounder) to detect and track the movement of fish both upstream and downstream of each of six turbines. The results suggested (1) very few fish using this portion of the river, (2) those fish which did use this area were not using the portion of the river which would subject them to blade strikes, and (3) no evidence of fish traveling through blade areas.

Work is currently being conducted by the Northwest National Marine Renewable Energy Center (NNMREC)to explore and establish tools and protocols for assessment of physical and biological conditions and monitor environmental changes associated with tidal energy development.

Dynamic tidal power



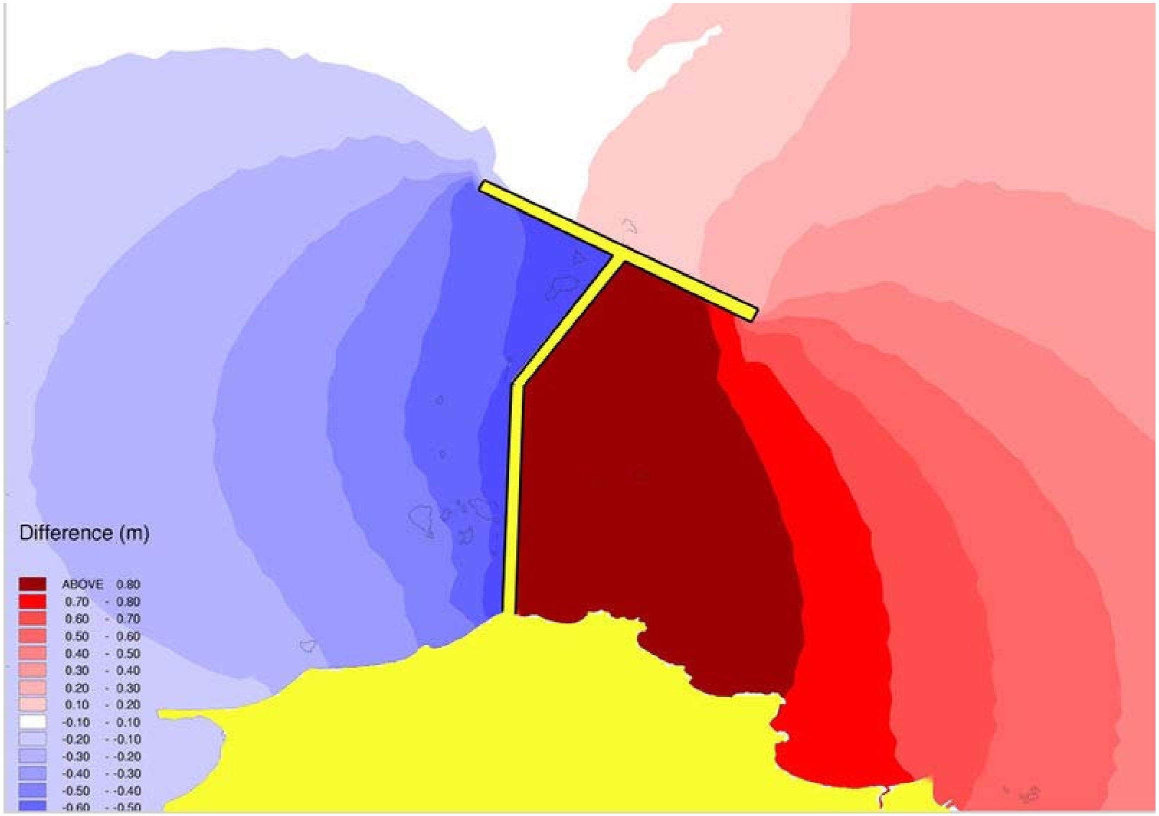
Co-inventor Kees Hulsbergen presenting the principles of DTP at Tsinghua University in Beijing, in February 2010.

Dynamic tidal power or **DTP** is the newest technique of tidal power generation. It involves creating large dam-like structure extending from the coast straight to the ocean, with a perpendicular barrier at the far end, forming a large 'T' shape.

This long T-dam interferes with coast-parallel oscillating tidal waves which run along the coasts of continental shelves, containing powerful hydraulic currents (common in *e.g.* China, Korea, and the UK).

The concept was invented and patented in 1997 by Dutch coastal engineers Kees Hulsbergen and Rob Steijn.

Description



Top-down view of a DTP dam. Blue and dark red colors indicate low and high tides, respectively.

A DTP dam is a long dam of 30 to 60 km which is built perpendicular to the coast, running straight out into the ocean, without enclosing an area. The horizontal acceleration of the tides is blocked by the dam. In many coastal areas the main tidal movement runs parallel to the coast: the entire mass of the ocean water accelerates in one direction, and later in the day back the other way. A DTP dam is long enough to exert an influence on the horizontal tidal movement, which generates a water level differential (head) over both sides of the dam. The head can be converted into power using a long series of conventional low-head turbines installed in the dam.

Benefits

A single dam can accommodate over 8 GW (8000 MW) of installed capacity, with a capacity factor of about 30%, for an estimated annual power production of each dam of about 23 billion kWh (83 PJ/yr). To put this number in perspective, an average European person consumes about 6800 kWh per year, so one DTP dam could supply energy for about 3.4 million Europeans. If two dams are installed at the right distance from one another (about 200 km apart), they can complement one another to level the output (one dam is at full output when the other is not generating power). Dynamic tidal power doesn't require a very high natural tidal range, so more sites are available and the total availability of power is very high in countries with suitable conditions, such as Korea, China, and the UK (the total amount of available power in China is estimated at 80 - 150 GW).

Technological development

No DTP dam has ever been built, although all of the technologies required to build a DTP dam are available. Various mathematical and physical models have been conducted to model and predict the 'head' or water level differential over a dynamic tidal power dam. The interaction between tides and long dams has been observed and recorded in large engineering projects, such as the Delta Works and the Afsluitdijk in the Netherlands. The interaction of tidal currents with natural peninsulas is also well-known, and such data is used to calibrate numerical models of tides. Formulas for the calculation of added mass were applied to develop an analytical model of DTP. Observed water level differentials closely match current analytical and numerical models. Water level differential generated over a DTP dam can now be predicted with a useful degree of accuracy.

Some of the key elements required include:

- Bi-directional turbines (capable of generating power in both directions) for low head, high-volume environments. Operational units exist for seawater applications, reaching an efficiency of over 75%.
- Dam construction methods. This could be achieved by modular floating caissons (concrete building blocks). These caissons would be manufactured on shore and subsequently floated to the dam location.

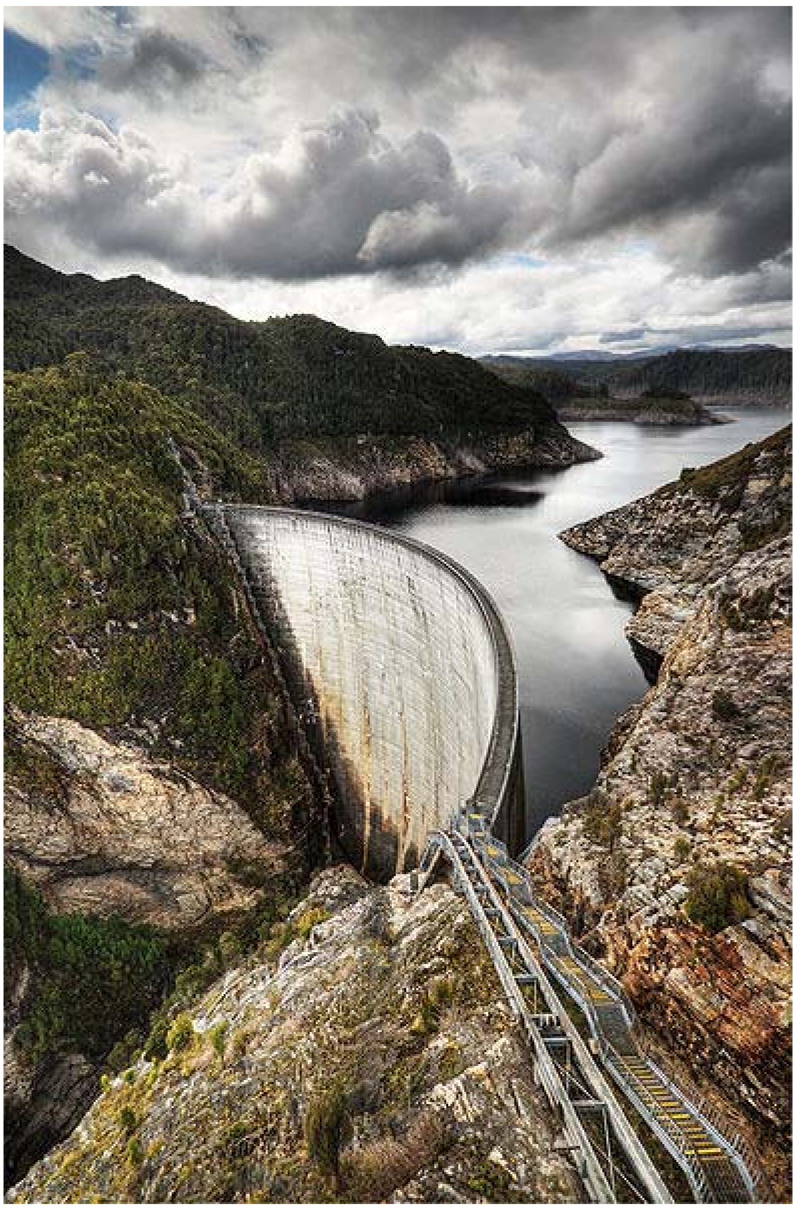
Challenges

A major challenge is that a demonstration project would yield almost no power, even at a dam length of 1 km or so, because the power generation capacity increases as the square of the dam length (both head and volume increase in a more or less linear manner for increased dam length, resulting in a quadratic increase in power generation). Economic viability is estimated to be reached for dam lengths of about 30 km.

Other concerns include: shipping routes, marine ecology, sediments, and storm surges.

Chapter- 3

Hydroelectricity



The Gordon Dam in Tasmania is a large conventional dammed-hydro facility, with an installed capacity of up to 430 MW.

Hydroelectricity is the term referring to electricity generated by hydropower; the production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy. Once a hydroelectric complex is constructed, the project produces no direct waste, and has a considerably lower output level of the greenhouse gas carbon dioxide (CO_2) than fossil fuel powered energy plants. Worldwide, an installed capacity of 777 GWe supplied 2998 TWh of hydroelectricity in 2006. This was approximately 20% of the world's electricity, and accounted for about 88% of electricity from renewable sources.

History

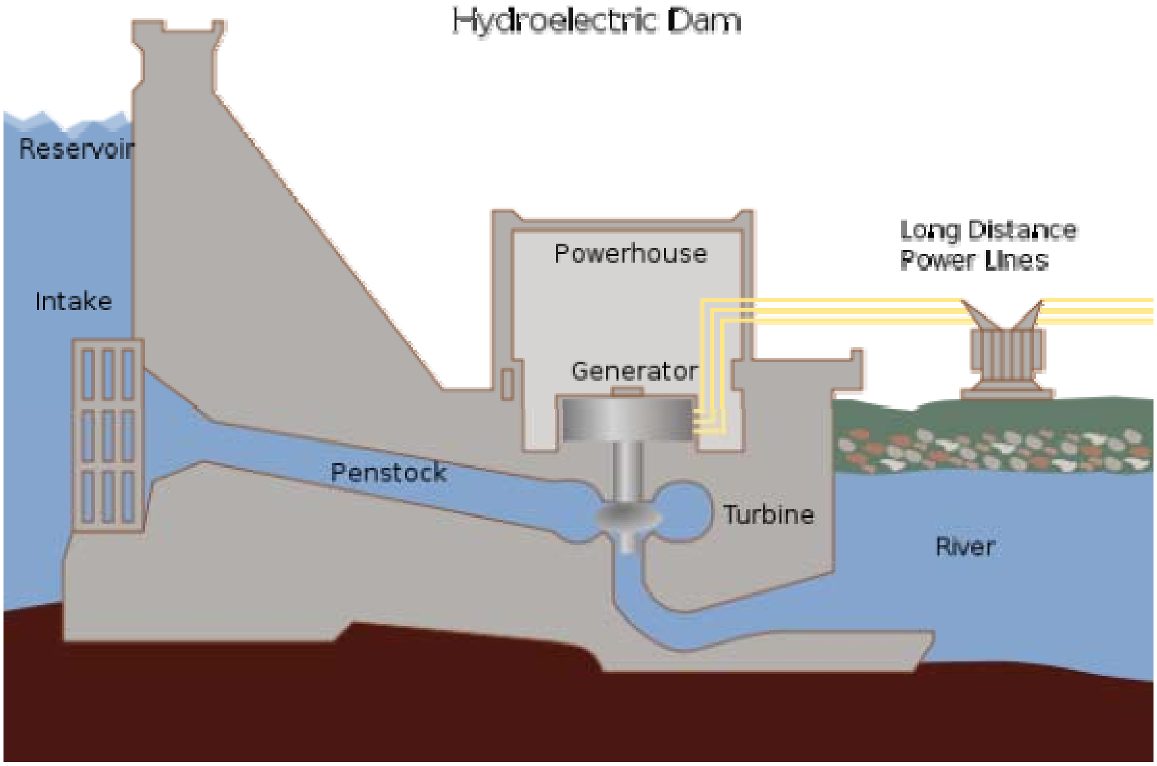
Hydropower has been used since ancient times to grind flour and perform other tasks. In the mid-1770s, a French engineer Bernard Forest de Bélidor published *Architecture Hydraulique* which described vertical- and horizontal-axis hydraulic machines. By the late 19th century, the electrical generator was developed and could now be coupled with hydraulics. The growing demand for the Industrial Revolution would drive development as well. In 1878, the world's first house to be powered with hydroelectricity was Cragside in Northumberland, England. The old Schoelkopf Power Station No. 1 near Niagara Falls in the U.S. side began to produce electricity in 1881. The first Edison hydroelectric power plant - the Vulcan Street Plant - began operating September 30, 1882, in Appleton, Wisconsin, with an output of about 12.5 kilowatts. By 1886 there was about 45 hydroelectric power plants in the U.S. and Canada. By 1889, there were 200 in the U.S.

At the beginning of the 20th century, a large number of small hydroelectric power plants were being constructed by commercial companies in the mountains that surrounded metropolitan areas. By 1920 as 40% of the power produced in the United States was hydroelectric, the Federal Power Act was enacted into law. The Act created the Federal Power Commission who's main purpose was to regulate hydroelectric power plants on federal land and water. As the power plants became larger, their associated dams developed additional purposes to include flood control, irrigation and navigation. Federal funding became necessary for large-scale development and federally owned corporations like the Tennessee Valley Authority (1933) and the Bonneville Power Administration (1937) were created. Additionally, the Bureau of Reclamation which had began a series of western U.S. irrigation projects in the early 20th century was now constructing large hydroelectric projects such as the 1928 Boulder Canyon Project Act. The U.S. Army Corps of Engineers was also involved in hydroelectric development, completing the Bonneville Dam in 1937 and being recognized by the Flood Control Act of 1936 as the premier federal flood control agency.

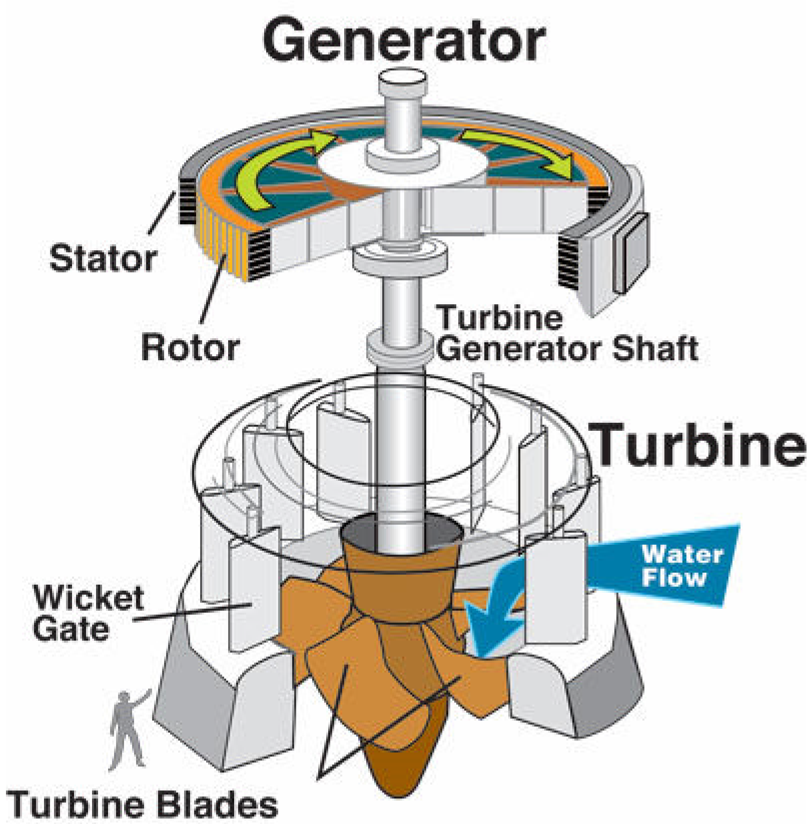
Hydroelectric power plants continued to become larger throughout the 20th century. After the Hoover Dam's initial 1,345 MW power plant became the world's largest hydroelectric power plant in 1936 it was soon eclipsed by the 6809 MW Grand Coulee Dam in 1942. Brazil's and Paraguay's Itaipu Dam opened in 1984 as the largest, producing 14,000 MW but was surpassed in 2008 by the Three Gorges Dam in China with a production capacity of 22,500 MW. Hydroelectricity would eventually supply countries like Norway, Democratic Republic of the Congo, Paraguay and Brazil with over 85% of their electricity. The United States currently has over 2,000 hydroelectric power plants which supply 49% of its renewable electricity.

Generating methods

Turbine row at Los Nihuiles Power Station in Mendoza, Argentina



Cross section of a conventional hydroelectric dam.



A typical turbine and generator

Conventional

Most hydroelectric power comes from the potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. To deliver water to a turbine while maintaining pressure arising from the head, a large pipe called a penstock may be used.

Pumped-storage

This method produces electricity to supply high peak demands by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine. Pumped-storage schemes currently provide the most commercially important means of large-scale grid energy storage and improve the daily capacity factor of the generation system.

Run-of-the-river

Run-of-the-river hydroelectric stations are those with smaller reservoir capacities, thus making it impossible to store water.

Tide

A tidal power plant makes use of the daily rise and fall of water due to tides; such sources are highly predictable, and if conditions permit construction of reservoirs, can also be dispatchable to generate power during high demand periods. Less common types of hydro schemes use water's kinetic energy or undammed sources such as undershot waterwheels.

Sizes and capacities of hydroelectric facilities

Large and specialized industrial facilities

The Three Gorges Dam, is the largest operating hydroelectric power stations at an installed capacity of 22,500 MW.

Although no official definition exist for the capacity range of large hydroelectric power stations, facilities from over a few hundred megawatts to more than 10 GW is generally considered large hydroelectric facilities. Currently, only three facilities over 10 GW (10,000 MW) are in operation worldwide; Three Gorges Dam at 22.5 GW, Itaipu Dam at 14 GW, and Guri Dam at 10.2 GW. Large-scale hydroelectric power stations are more commonly seen as the largest power producing facilities in the world, with some hydroelectric facilities capable of generating more than double the installed capacities of the current largest nuclear power stations.

While many hydroelectric projects supply public electricity networks, some are created to serve specific industrial enterprises. Dedicated hydroelectric projects are often built to provide the substantial amounts of electricity needed for aluminium electrolytic plants, for example. The Grand Coulee Dam switched to support Alcoa aluminium in Bellingham, Washington, United States for American World War II airplanes before it was allowed to provide irrigation and power to citizens (in addition to aluminium power) after the war. In Suriname, the Brokopondo Reservoir was constructed to provide electricity for the Alcoa aluminium industry. New Zealand's Manapouri Power Station was constructed to supply electricity to the aluminium smelter at Tiwai Point.

The construction of these large hydroelectric facilities and the changes it makes to the environment, are often too at very large scales, creating just as much damage to the environment as at helps it by being a renewable resource. Many specialized organizations, such as the International Hydropower Association, look into these matters on a global scale.

Small

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. This may be stretched to 25 MW and 30 MW in Canada and the United States. Small-scale hydroelectricity production grew by 28% during 2008 from 2005, raising the total world small-hydro capacity to 85 GW. Over 70% of this was in China (65 GW), followed by Japan (3.5 GW), the United States (3 GW), and India (2 GW).

Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production.

Micro

A micro-hydro facility in Vietnam.

Micro hydro is a term used for hydroelectric power installations that typically produce up to 100 KW of power. These installations can provide power to an isolated home or small community, or are sometimes connected to electric power networks. There are many of these installations around the world, particularly in developing nations as they can provide an economical source of energy without purchase of fuel. Micro hydro systems complement photovoltaic solar energy systems because in many areas, water flow, and thus available hydro power, is highest in the winter when solar energy is at a minimum.

Pico

Pico hydro is a term used for hydroelectric power generation of under 5 KW. It is useful in small, remote communities that require only a small amount of electricity. For example, to power one or two fluorescent light bulbs and a TV or radio for a few homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 1 m (3 ft). Pico-hydro setups typically are run-of-the-river, meaning that dams are not used, but rather pipes divert some of the flow, drop this down a gradient, and through the turbine before being exhausted back to the stream.

Calculating the amount of available power

A simple formula for approximating electric power production at a hydroelectric plant is: $P = \rho h r g k$, where

- P is Power in watts,
- ρ is the density of water (~1000 kg/m^3),
- h is height in meters,
- r is flow rate in cubic meters per second,
- g is acceleration due to gravity of 9.8 m/s^2,
- k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher (that is, closer to 1) with larger and more modern turbines.

Annual electric energy production depends on the available water supply. In some installations the water flow rate can vary by a factor of 10:1 over the course of a year.

Advantages and disadvantages of hydroelectricity

Advantages

The Ffestiniog Power Station can generate 360 MW of electricity within 60 seconds of the demand arising.

Economics

The major advantage of hydroelectricity is elimination of the cost of fuel. The cost of operating a hydroelectric plant is nearly immune to increases in the cost of fossil fuels such as oil, natural gas or coal, and no imports are needed.

Hydroelectric plants also tend to have longer economic lives than fuel-fired generation, with some plants now in service which were built 50 to 100 years ago. Operating labor cost is also usually low, as plants are automated and have few personnel on site during normal operation.

Where a dam serves multiple purposes, a hydroelectric plant may be added with relatively low construction cost, providing a useful revenue stream to offset the costs of dam operation. It has been calculated that the sale of electricity from the Three Gorges Dam will cover the construction costs after 5 to 8 years of full generation.

CO2 emissions

Since hydroelectric dams do not burn fossil fuels, they do not directly produce carbon dioxide. While some carbon dioxide is produced during manufacture and construction of the project, this is a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation. One measurement of greenhouse gas related and other externality comparison between energy sources can be found in the ExternE project by the Paul Scherrer Institut and the University of Stuttgart which was funded by the European Commission. According to this project, hydroelectricity produces the least amount of greenhouse gases and externality of any energy source. Coming in second place was wind, third was nuclear energy, and fourth was solar photovoltaic. The extremely positive greenhouse gas impact of hydroelectricity is found especially in temperate climates. The above study was for local energy in Europe; presumably similar conditions prevail in North America and Northern Asia, which all see a regular, natural freeze/thaw cycle (with associated seasonal plant decay and regrowth).

Other uses of the reservoir

Reservoirs created by hydroelectric schemes often provide facilities for water sports, and become tourist attractions themselves. In some countries, aquaculture in reservoirs is common. Multi-use dams installed for irrigation support agriculture with a relatively constant water supply. Large hydro dams can control floods, which would otherwise affect people living downstream of the project.

Disadvantages

Ecosystem damage and loss of land

Hydroelectric power stations that uses dams would submerge large areas of land due to the requirement of a reservoir.

Large reservoirs required for the operation of hydroelectric power stations result in submersion of extensive areas upstream of the dams, destroying biologically rich and productive lowland and riverine valley forests, marshland and grasslands. The loss of land is often exacerbated by the fact that reservoirs cause habitat fragmentation of surrounding areas.

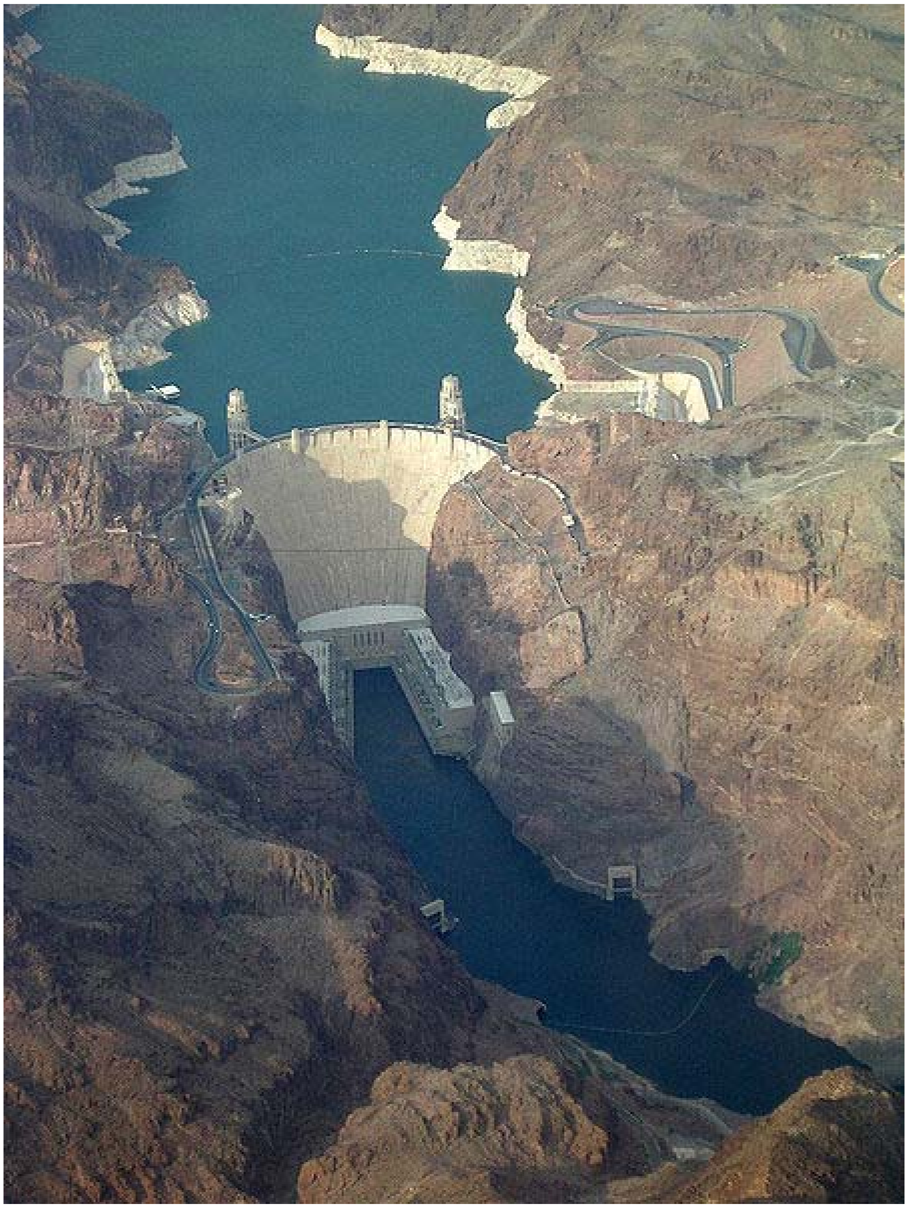
Hydroelectric projects can be disruptive to surrounding aquatic ecosystems both upstream and downstream of the plant site. For instance, studies have shown that dams along the Atlantic and Pacific coasts of North America have reduced salmon populations by preventing access to spawning grounds upstream, even though most dams in salmon habitat have fish ladders installed. Salmon spawn are also harmed on their migration to sea when they must pass through turbines. This has led to some areas transporting smolt downstream by barge during parts of the year. In some cases dams, such as the Marmot Dam, have been demolished due to the high impact on fish. Turbine and power-plant designs that are easier on aquatic life are an active area of research. Mitigation measures such as fish ladders may be required at new projects or as a condition of re-licensing of existing projects.

Generation of hydroelectric power changes the downstream river environment. Water exiting a turbine usually contains very little suspended sediment, which can lead to scouring of river beds and loss of riverbanks. Since turbine gates are often opened intermittently, rapid or even daily fluctuations in river flow are observed. For example, in the Grand Canyon, the daily cyclic flow variation caused by Glen Canyon Dam was found to be contributing to erosion of sand bars. Dissolved oxygen content of the water may change from pre-construction conditions. Depending on the location, water exiting from turbines is typically much warmer than the pre-dam water, which can change aquatic faunal populations, including endangered species, and prevent natural freezing processes from occurring. Some hydroelectric projects also use canals to divert a river at a shallower gradient to increase the head of the scheme. In some cases, the entire river may be diverted leaving a dry riverbed. Examples include the Tekapo and Pukaki Rivers in New Zealand.

Flow shortage

Changes in the amount of river flow will correlate with the amount of energy produced by a dam. Lower river flows because of drought, climate change or upstream dams and diversions will reduce the amount of live storage in a reservoir therefore reducing the amount of water that can be used for hydroelectricity. The result of diminished river flow can be power shortages in areas that depend heavily on hydroelectric power.

Methane emissions (from reservoirs)



The Hoover Dam in United States is a large conventional dammed-hydro facility, with an installed capacity of up to 2,080 MW.

Lower positive impacts are found in the tropical regions, as it has been noted that the reservoirs of power plants in tropical regions may produce substantial amounts of methane. This is due to plant material in flooded areas decaying in an anaerobic environment, and forming methane, a very potent greenhouse gas. According to the World Commission on Dams report, where the reservoir is large compared to the generating capacity (less than 100 watts per square metre of surface area) and no clearing of the forests in the area was undertaken prior to impoundment of the reservoir, greenhouse gas emissions from the reservoir may be higher than those of a conventional oil-fired thermal generation plant. Although these emissions represent carbon already in the biosphere, not fossil deposits that had been sequestered from the carbon cycle, there is a greater amount of methane due to anaerobic decay, causing greater damage than would otherwise have occurred had the forest decayed naturally.

In boreal reservoirs of Canada and Northern Europe, however, greenhouse gas emissions are typically only 2% to 8% of any kind of conventional fossil-fuel thermal generation. A new class of underwater logging operation that targets drowned forests can mitigate the effect of forest decay.

In 2007, International Rivers accused hydropower firms for cheating with fake carbon credits under the Clean Development Mechanism, for hydropower projects already finished or under construction at the moment they applied to join the CDM. These carbon credits – of hydropower projects under the CDM in developing countries – can be sold to companies and governments in rich countries, in order to comply with the Kyoto protocol.

Relocation

Another disadvantage of hydroelectric dams is the need to relocate the people living where the reservoirs are planned. In February 2008, it was estimated that 40-80 million people worldwide had been physically displaced as a direct result of dam construction. In many cases, no amount of compensation can replace ancestral and cultural attachments to places that have spiritual value to the displaced population. Additionally, historically and culturally important sites can be flooded and lost.

Such problems have arisen at the Aswan Dam in Egypt between 1960 and 1980, the Three Gorges Dam in China, the Clyde Dam in New Zealand, and the Ilisu Dam in Turkey.

Failure hazard

Because large conventional dammed-hydro facilities hold back large volumes of water, a failure due to poor construction, terrorism, or other causes can be catastrophic to downriver settlements and infrastructure. Dam failures have been some of the largest man-made disasters in history. Also, good design and construction are not an adequate guarantee of safety. Dams are tempting industrial targets for wartime attack, sabotage and terrorism, such as Operation Chastise in World War II.

The Banqiao Dam failure in Southern China directly resulted in the deaths of 26,000 people, and another 145,000 from epidemics. Millions were left homeless. Also, the creation of a dam in a geologically inappropriate location may cause disasters like the one of the Vajont Dam in Italy, where almost 2000 people died, in 1963.

Smaller dams and micro hydro facilities create less risk, but can form continuing hazards even after they have been decommissioned. For example, the small Kelly Barnes Dam failed in 1967, causing 39 deaths with the Toccoa Flood, ten years after its power plant was decommissioned in 1957.

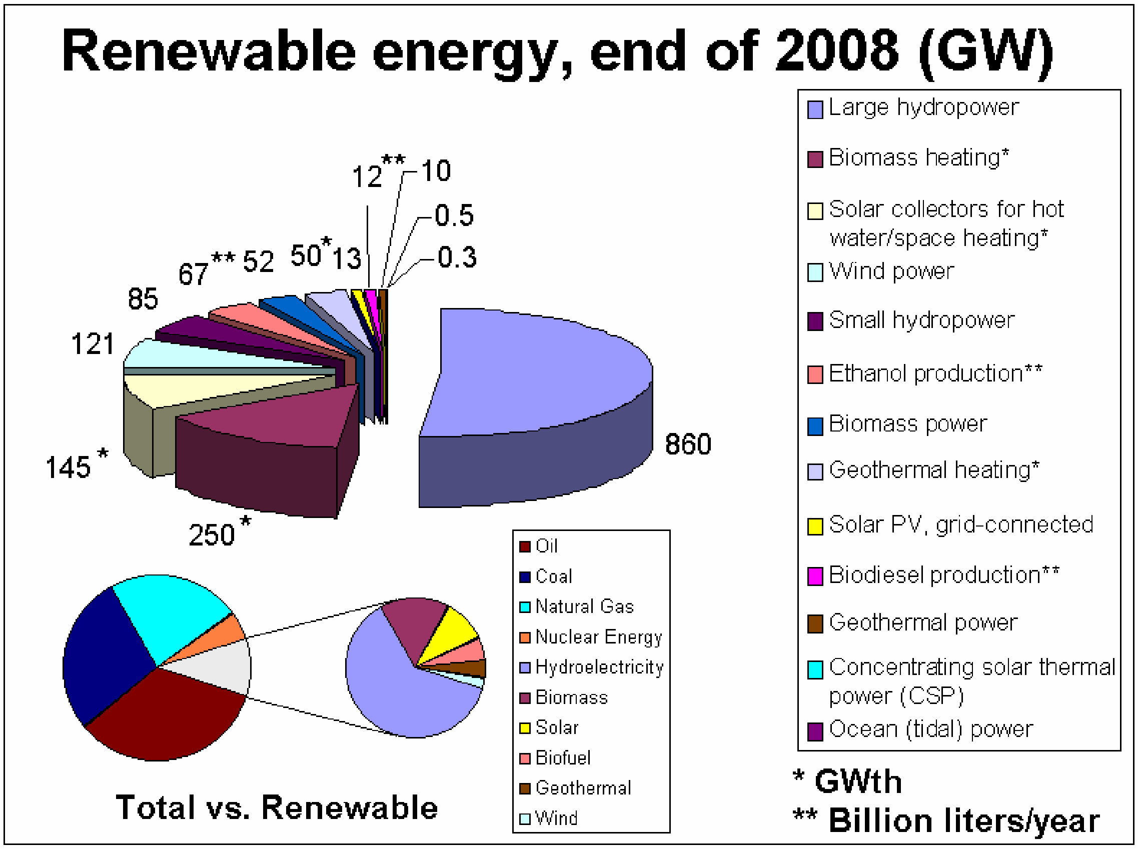
Comparison with other methods of power generation

Hydroelectricity eliminates the flue gas emissions from fossil fuel combustion, including pollutants such as sulfur dioxide, nitric oxide, carbon monoxide, dust, and mercury in the coal. Hydroelectricity also avoids the hazards of coal mining and the indirect health effects of coal emissions. Compared to nuclear power, hydroelectricity generates no nuclear waste, has none of the dangers associated with uranium mining, nor nuclear leaks. Unlike uranium, hydroelectricity is also a renewable energy source.

Compared to wind farms, hydroelectricity power plants have a more predictable load factor. If the project has a storage reservoir, it can be dispatched to generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand.

Unlike fossil-fuelled combustion turbines, construction of a hydroelectric plant requires a long lead-time for site studies, hydrological studies, and environmental impact assessment. Hydrological data up to 50 years or more is usually required to determine the best sites and operating regimes for a large hydroelectric plant. Unlike plants operated by fuel, such as fossil or nuclear energy, the number of sites that can be economically developed for hydroelectric production is limited; in many areas the most cost effective sites have already been exploited. New hydro sites tend to be far from population centers and require extensive transmission lines. Hydroelectric generation depends on rainfall in the watershed, and may be significantly reduced in years of low rainfall or snowmelt. Long-term energy yield may be affected by climate change. Utilities that primarily use hydroelectric power may spend additional capital to build extra capacity to ensure sufficient power is available in low water years.

World hydroelectric capacity



World renewable energy share as at 2008, with hydroelectricity more than 50% of all renewable energy sources.

The ranking of hydro-electric capacity is either by actual annual energy production or by installed capacity power rating. A hydro-electric plant rarely operates at its full power rating over a full year; the ratio between annual average power and installed capacity rating is the capacity factor. The installed capacity is the sum of all generator nameplate power ratings. Sources came from *BP Statistical Review - Full Report 2009*

Brazil, Canada, Norway, Paraguay, Switzerland, and Venezuela are the only countries in the world where the majority of the internal electric energy production is from hydroelectric power. Paraguay produces 100% of its electricity from hydroelectric dams, and exports 90% of its production to Brazil and to Argentina. Norway produces 98–99% of its electricity from hydroelectric sources.

Ten of the largest hydroelectric producers as at 2009.

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of total capacity
China	652.05	196.79	0.37	22.25
Canada	369.5	88.974	0.59	61.12
Brazil	363.8	69.080	0.56	85.56

United States	250.6	79.511	0.42	5.74
Russia	167.0	45.000	0.42	17.64
Norway	140.5	27.528	0.49	98.25
India	115.6	33.600	0.43	15.80
Venezuela	85.96	14.622	0.67	69.20
Japan	69.2	27.229	0.37	7.21
Sweden	65.5	16.209	0.46	44.34

Major projects under construction

Name	Maximum Capacity	Country	Construction started	Scheduled completion	Comments
Xiluodu Dam	12,600 MW	China	December 26, 2005	2015	Construction once stopped due to lack of environmental impact study.
Siang Upper HE Project	11,000 MW	India	April, 2009	2024	Multi-phase construction over a period of 15 years. Construction was delayed due to dispute with China.
TaSang Dam	7,110 MW	Burma	March, 2007	2022	Controversial 228 meter tall dam with capacity to produce 35,446 Ghw annually.
Xiangjiaba Dam	6,400 MW	China	November 26, 2006	2015	
Nuozhadu Dam	5,850 MW	China	2006	2017	
Jinping 2 Hydropower Station	4,800 MW	China	January 30, 2007	2014	To build this dam, 23 families and 129 local residents need to be moved. It works with Jinping 1

					Hydropower Station as a group.
Jinping 1 Hydropower Station	3,600 MW	China	November 11, 2005	2014	
Pubugou Dam	3,300 MW	China	March 30, 2004	2010	
Goupitan Dam	3,000 MW	China	November 8, 2003	2011	
Guanyinyan Dam	3,000 MW	China	2008	2015	Construction of the roads and spillway started.
Lianghekou Dam	3,000 MW	China	2009	2015	
Boguchan Dam	3,000 MW	Russia	1980	2010	
Chapetón	3,000 MW	Argentina			
Dagangshan	2,600 MW	China	August 15, 2008	2014	
Jinanqiao Dam	2,400 MW	China	December 2006	2010	
Guandi Dam	2,400 MW	China	November 11, 2007	2012	
Liyuan Dam	2,400 MW	China	2008		
Tocoma Dam Bolívar State	2,160 MW	Venezuela	2004	2014	This new power plant would be the last development in the Low Caroni Basin, bringing the total to six power plants on the same river, including the 10,000MW Guri Dam.
Ludila Dam	2,100 MW	China	2007	2015	Construction halt due to lack of the

					evnironmental assessment.
Shuangjiangkou Dam	2,000 MW	China	December, 2007		The dam will be 314 m high.
Ahai Dam	2,000 MW	China	July 27, 2006		
Subansiri Lower Dam	2,000 MW	India	2005	2012	

Chapter- 4

Run of the River Hydroelectricity

Chief Joseph Dam near Bridgeport, Washington, USA, is a major run-of-river station without a sizeable reservoir.

Run-of-the-river hydroelectricity is a type of hydroelectric generation whereby the natural flow and elevation drop of a river are used to generate electricity. Power stations of this type are built on rivers with a consistent and steady flow, either natural or through the use of a large reservoir at the head of the river which then can provide a regulated steady flow for stations down-river (such as the Gouin Reservoir for the Saint-Maurice River in Quebec, Canada).

Concept

Run-of-river hydroelectricity is a type of hydroelectric generation whereby the natural flow and elevation drop of a river are used to generate electricity. Such projects divert some or most of a river's flow (up to 95% of mean annual discharge) through a pipe and/or tunnel leading to electricity-generating turbines, then return the water back to the river downstream. A dam – smaller than used for traditional hydro – is required to ensure there is enough water to enter the "penstock" pipes that lead to the lower-elevation turbines.

Run-of-river projects are dramatically different in design and appearance from conventional hydroelectric projects. Traditional hydro dams store enormous quantities of water in reservoirs, necessitating the flooding of large tracts of land. In contrast, most run-of-river projects do not require a large impoundment of water, which is a key reason why such projects are often referred to as environmentally-friendly, or "green power."

In recent years, many of the larger run-of-river projects have been designed to a scale and generating capacity rivalling some traditional hydro dams. For example, one run-of-river project currently proposed in British Columbia (BC) Canada – one of the world's new epicentres of run-of-river development – has been designed to generate 1027 megawatts capacity.

Advantages

When developed with care to footprint size and location, run-of-river hydro projects can create sustainable green energy that minimizes impacts to the surrounding environment and nearby communities. Advantages include:

Cleaner Power, Less Greenhouse Gases

Like all hydro-electric power, run-of-river hydro harnesses the natural energy of water and gravity – eliminating the need to burn coal or natural gas to generate the electricity needed by consumers and industry.

Less Flooding/Reservoirs

Substantial flooding of the upper part of the river is not required for smaller-scale run-of-river projects as a large reservoir is not required. As a result, people living at or near the river don't need to be relocated and natural habitats and productive farmlands are not wiped out.

Disadvantages

"Unfirm" Power

Run-of-River power is considered an "unfirm" source of power: a run-of-the-river project has little or no capacity for energy storage and hence can't co-ordinate the output of electricity generation to match consumer demand. It thus generates much more power during times when seasonal river flows are high (i.e, spring freshet), and much less during drier summer months.

Environmental Impacts

While small, well-sited run-of-river projects can be developed with minimal environmental impacts, many modern run-of-river projects are larger, with much more significant environmental concerns. For example, Plutonic Power Corp.'s Bute Inlet Hydroelectric Project in BC will see three clusters of run-of-river projects with 17 river diversions; as proposed, this run-of-river project will divert over 90 kilometres of streams and rivers into tunnels and pipelines, requiring 443 km of new transmission line, 267 km of permanent roads, and 142 bridges, to be built in wilderness areas.

British Columbia's mountainous terrain and wealth of big rivers have made it a global testing ground for run-of-river technology. As of March 2010, there were 628 applications pending for new water licences solely for the purposes of power generation – representing more than 750 potential points of river diversion.

Many of the impacts of this technology are still not understood or well-considered, including the following:

- Diverting large amounts of river water reduce river flows affecting water velocity and depth, minimizing habitat quality for fish and aquatic organisms; reduced flows can lead to excessively warm water for salmon and other fish in summer. As planned, the Bute Inlet project in BC could divert 95 percent of the mean annual flow in at least three of the rivers).

- New access roads and transmission lines can cause extensive habitat fragmentation for many species, making inevitable the introduction of invasive species and increases in undesirable human activities, like illegal hunting.

- Cumulative impacts – the sum of impacts caused not only by the project, but by roads, transmission lines and all other nearby developments – are difficult to measure. Cumulative impacts are an especially important consideration in areas where projects are clustered in high densities close to sources of electricity demand: for example, of the 628 pending water license applications for hydropower development in British Columbia, roughly one third are located in the south-western quarter of the province, where human population density and associated environmental impacts are highest.

- Water licenses – which are issued by the BC Ministry of Environment enabling developers to legally divert rivers – have not included clauses that specify changing water entitlements in response to altered conditions; this means that conflicts will arise over the water needed to both sustain aquatic life and generate power when river flow becomes more variable or decreases in the future.

Major examples

- Beauharnois, Quebec, Canada, 1,673 MW
- Bute Inlet Hydroelectric Project, British Columbia, Canada, 1,026 MW
- Chief Joseph Dam, 2,620 MW
- East Toba/Montrose Hydro Project, British Columbia, Canada, 196 MW
- Forrest Kerr Hydro Project, British Columbia, Canada, 195 MW
- Ghazi Barotha Dam, 1,450 MW
- La Grande-1 generating station, 1,436 MW
- Satluj Jal Vldyut Nigam Ltd, Satluj River, Shimla, India, 1,500 MW
- Upper Toba Valley, British Columbia, Canada, 123 MW

List of run-of-the-river hydroelectric power stations

Bonneville Dam

Bonneville Dam

Spillway structure

Locale	Columbia River Gorge National Scenic Area, Multnomah County, Oregon / Skamania County, Washington, USA
Coordinates	45°38′39″N 121°56′26″W / 45.64417°N 121.94056°W
Construction began	1934 (First Powerhouse)

	1974 (Second Powerhouse)
Opening date	1937 (First Powerhouse) 1981 (Second Powerhouse)
Dam and spillways	
Type of dam	Concrete gravity, run-of-the-river
Impounds	Columbia River
Type of spillway	Service, gate-controlled
Reservoir	
Creates	Lake Bonneville
Power station	
Type	Yes
Turbines	20
Installed capacity	1092.9 MW

Bonneville Dam Historic District

U.S. National Register of Historic Places

U.S. National Historic Landmark District

Location:	Bonneville, Oregon
Coordinates:	45°38′39″N 121°56′26″W / 45.64417°N 121.94056°WCoordinates: 45°38′39″N 121°56′26″W / 45.64417°N 121.94056°W
Built/Founded:	1909, 1934

Architect:	Claussen & Claussen, U.S. Army Corps of Engineers
Architectural style(s):	Colonial Revival, Other
Governing body:	United States Army Corps of Engineers
Added to NRHP:	April 9, 1986 (original) March 26, 1987 (increase)
Designated NHLD:	June 30, 1987
NRHP Reference#:	86000727 (original) 86003598 (increase)

Bonneville Lock and Dam consists of several run-of-the-river dam structures that together complete a span of the Columbia River between the U.S. states of Oregon and Washington at River Mile 146.1. The dam is located 40 miles (64 km) east of Portland, Oregon, in the Columbia River Gorge. The primary functions of Bonneville Lock and Dam are electrical power generation and river navigation. The dam was built and is managed by the United States Army Corps of Engineers. Electrical power generated at Bonneville is distributed by the Bonneville Power Administration. Bonneville Lock and Dam is named for Army Capt. Benjamin Bonneville, an early explorer credited with charting much of the Oregon Trail. The **Bonneville Dam Historic District** was designated a National Historic Landmark District in 1987.

History

In 1896, prior to this damming of the river, the Cascade Locks and Canal were constructed, allowing ships to pass the Cascades Rapids, located several miles upstream of Bonneville.

Prior to the New Deal, development of the Columbia River with flood control, hydroelectricity, navigation and irrigation was deemed as important. In 1929, the US Army Corps of Engineers published the 308 Report that recommended 10 dams on the river but no action was taken until the Franklin D. Roosevelt administration and the New Deal. Now at this time, America was in the Great Depression, and the dam's construction provided jobs and other economic benefits to the Pacific Northwest. Inexpensive hydroelectricity gave rise, in particular, to a strong aluminum industry. During the New Deal and funded from the Public Works Administration, in 1934, two of the larger projects were started, the Grand Coulee Dam and the Bonneville Dam. 3,000 workers in non-stop eight-hour shifts, from the relief or welfare rolls were paid 50-cents an hour for the work on the dam as well as raising local roads for the reservoir.

To create the Bonneville Dam and Lock, The Army Corps of Engineers constructed a new lock and a powerhouse which were on the south (Oregon) side of Bradford Island, and a spillway on the north (Washington) side. Coffer dams had to be built in order to block half of the river and clear a construction site where the foundation could be reached. These projects, part of the Bonneville Dam were completed in 1937.

Both the cascades and the old lock structure were submerged by the **Bonneville Reservoir**, also known as **Lake Bonneville**, the reservoir that formed behind the dam. The original navigation lock at Bonneville was opened in 1938 and was, at that time, the largest single-lift lock in the world. Although the dam began to produce hydroelectricity in 1937, Commercial electricity began its transfer from the dam in 1938.

A second powerhouse (and dam structure) was started in 1974 and completed in 1981. The second powerhouse was built by widening the river channel on the Washington side, creating Cascades Island between the new powerhouse and the original spillway. The combined electrical output of the two power houses at Bonneville is now over 1 million kilowatts.

Despite its world record size in 1938, **Bonneville Lock** became the smallest of seven locks built subsequently at different locations upstream on the Columbia and Snake Rivers; eventually a new lock was needed at Bonneville. This new structure was built on the Oregon shore, opening to ship and barge traffic in 1993. The old lock is still present, but is no longer used.

Dimensions and statistics

- **First Powerhouse** – Constructed in 1933-37; 313 m (1,027 ft) long; 10 generators with an output capacity of 526,700 kW.
- **Spillway** – Constructed 1933-37; 18 gates over a length of 442 m (1,450 ft); maintains the reservoir (upriver) usually 18 m (59 ft) above the river on the downstream side;
- **Second Powerhouse** – Constructed 1974-82; 300.5 m (986 ft) long; 8 generators (plus two at fish ladders) with a total generating capacity of 558,200 kW.
- **Bonneville Lock** – Constructed in 1987 to 1993 at a cost of $341 million; 26 m (85 ft) wide, 206 m (676 ft) long; transit time is approx. 30 minutes.
- **Lake Bonneville** – 77 km (48 mi) long reservoir on the Columbia River created by Bonneville Dam; part of the Columbia-Snake Inland Waterway.

It was declared a National Historic Landmark in 1987.

Environmental and social implications

The Bonneville Dam blocked the migration of white sturgeon to their upstream spawning areas. Sturgeon still spawn in the area below the dam and the lower Columbia River supports a healthy sturgeon population. Small very depressed populations of white sturgeon persist in the various reservoirs upstream.

To cope with fish migration problems, the dam features fish ladders to help native salmon and steelhead get past the dam on their journey upstream to spawn. The large concentrations of fish swimming upstream serves as a tourist attraction during the spawning season. California Sea Lions are also attracted to the large number of fish, and are often seen around the base of the dam during the spawning season. By 2006, the growing number of crafty sea lions and their impact on the salmon population have become worrisome to the Army Corps of Engineers and environmentalists. Historically, pinnipeds such as sea lions and seals hunted salmon in the Columbia River as far as The Dalles and Celilo Falls, 200 miles (320 km) from the sea, as remarked upon by people such as George Simpson in 1841.

Electricity controversy

Creating electricity was sensitive at the time of the Bonneville Dam's construction. Constructed with federal dollars, the Franklin D. Roosevelt administration wanted the electricity to be a public source of power and prevent energy monopolies. Advocates for private sale of the electricity were of course opposed to this as they did not want the government to interfere. In 1937, the Bonneville Project Act was signed by Roosevelt, giving the dam's power over to the public and creating the Bonneville Power Administration (BPA). A rate of $17.50 per kilowatt/year was maintained for the next 28 years by the BPA.

In popular culture

In his song *Roll on, Columbia*, the folk singer, Woody Guthrie, spoke of Bonneville as follows:

> “ At Bonneville now there are ships in the locks
> The waters have risen and cleared all the rocks,
> Shiploads of plenty will steam past the docks,
> So roll on, Columbia, roll on. ”

Taking the tour

The fish hatchery and dam are open year-round from 9:00 am to 5:00 pm. It is best to visit the dam in the months of April through September when the salmon are more abundant.

There are fish viewing windows and visitors' centers on both the Oregon and Washington sides of the dam. Because of security concerns, visitors may be required to show ID, and it is not possible to cross the entire dam. During most of the year, more fish use the Washington shore fish ladders, so fish viewing may be better on the Washington side of the dam.

Carillon Generating Station

Carillon power station and dam

The **Carillon Generating Station** (in French: ***centrale de Carillon***) is a hydroelectric power station on the Ottawa River near Carillon, site of the Battle of Long Sault in Quebec, Canada. Built between 1959 and 1964, it is managed and operated by Hydro-Québec. It is a run-of-river generating station with an installed capacity of 752 MW, a head of 17.99 meters (59 ft), and a reservoir of 26 square kilometers (10.0 sq mi). The dam spans the river between Carillon and Pointe-Fortune, Ontario.

Upon completion, the dam raised the water level by over 62 feet (19 m) at Carillon and over 9 feet (2.7 m) at Grenville. This inundated the rapids of Long-Sault, transforming them into calm (deeper) water. The dam also includes a modern lock that facilitates traffic up the Ottawa River, superseding the Carillon Canal.

Chapter- 5

Pumped-Storage Hydroelectricity

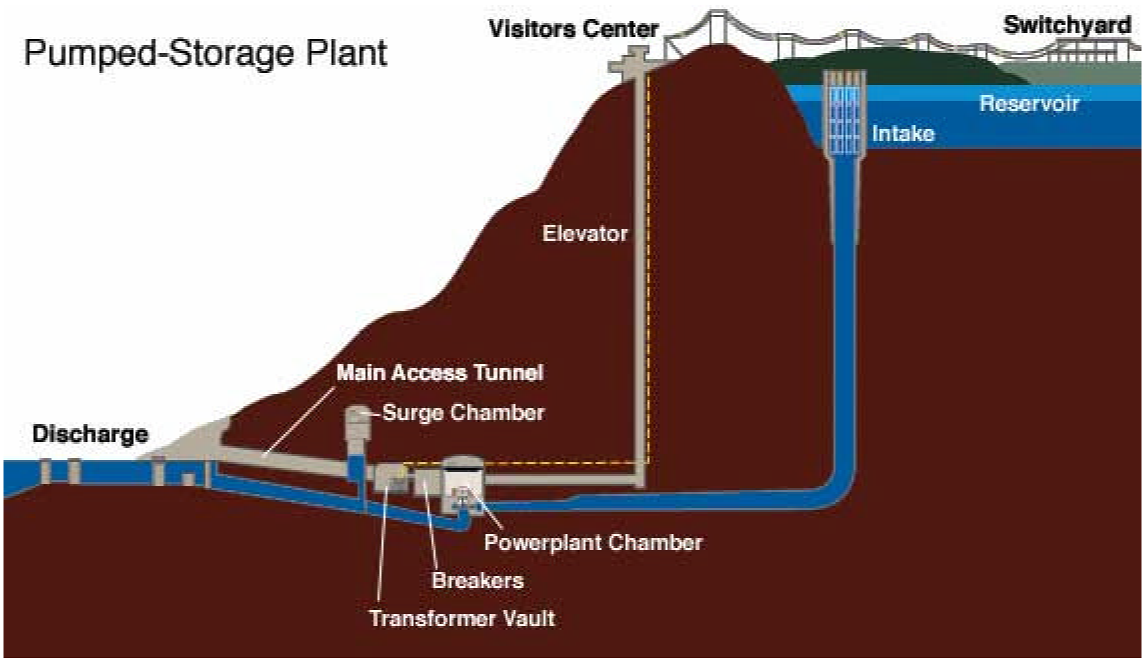
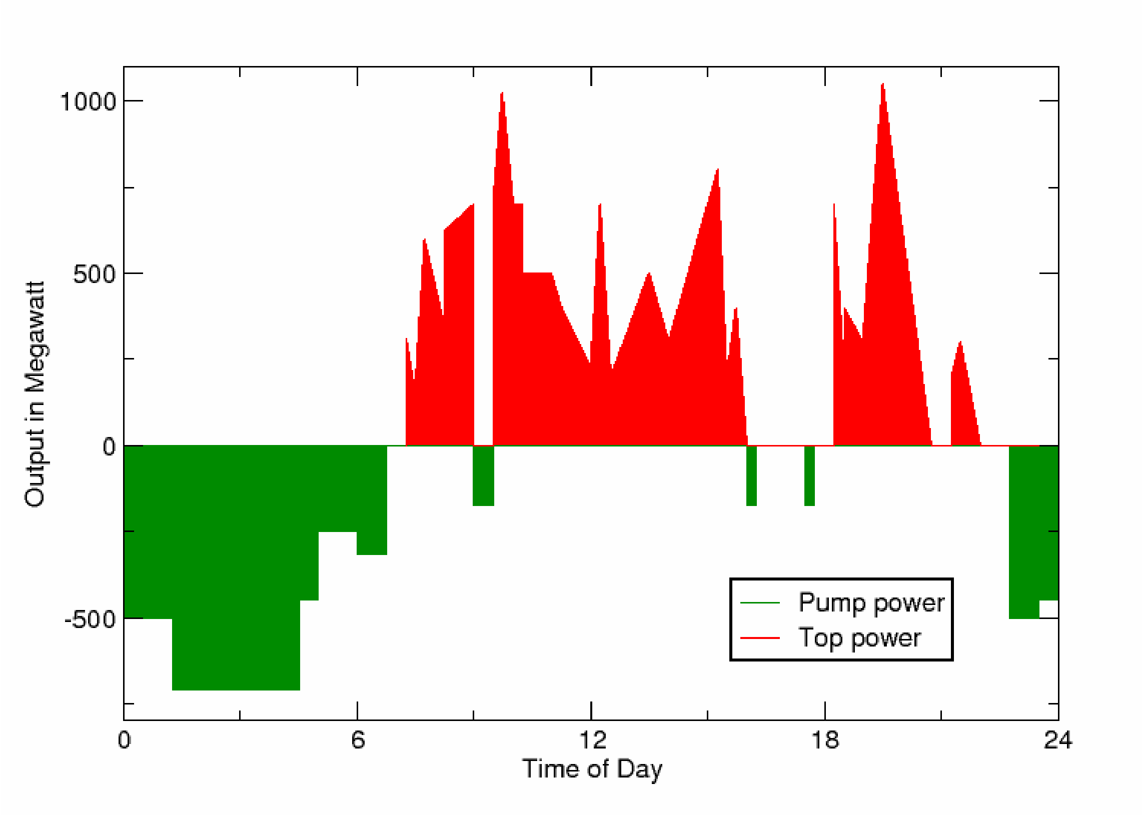


Diagram of the TVA pumped storage facility at Raccoon Mountain Pumped-Storage Plant.

Pumped-storage hydroelectricity is a type of hydroelectric power generation used by some power plants for *load balancing*. The method stores energy in the form of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines. Although the losses of the pumping process makes the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of *peak demand*, when electricity prices are highest. Pumped storage is the largest-capacity form of grid energy storage now available.

Overview



Power distribution, over a day, of a pumped-storage hydroelectricity facility. Green represents power consumed in pumping; red is power generated.

At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. Reversible turbine/generator assemblies act as pump and turbine (usually a Francis turbine design). Some facilities use abandoned mines as the lower reservoir, but many use the height difference between two natural bodies of water or artificial reservoirs. Pure pumped-storage plants just shift the water between reservoirs, but combined pump-storage plants also generate their own electricity like conventional hydroelectric plants through natural stream-flow. Plants that do not use pumped-storage are referred to as conventional hydroelectric plants; conventional hydroelectric plants that have significant storage capacity may be able to play a similar role in the electrical grid as pumped storage, by deferring output until needed.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.

The relatively low energy density of pumped storage systems requires either a very large body of water or a large variation in height. For example, 1000 kilograms of water (1 cubic meter) at the top of a 100 meter tower has a potential energy of about 0.272 kW·h (capable of raising the temperature of the same amount of water by only 0.23 Celsius = 0.42 Fahrenheit). The only way to store a significant amount of energy is by having a large body of water located on a hill relatively near, but as high as possible above, a second body of water. In some places this occurs naturally, in others one or both bodies of water have been man-made.

This system may be economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants and renewable energy power plants that provide base-load electricity to continue operating at peak efficiency (Base load power plants), while reducing the need for "peaking" power plants that use costly fuels. However, capital costs for purpose-built hydrostorage are high.

Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

The upper reservoir (Llyn Stwlan) and dam of the Ffestiniog Pumped Storage Scheme in north Wales. The lower power station has four water turbines which generate 360 MW of electricity within 60 seconds of the need arising. The size of the dam can be judged from the road below.

The first use of pumped storage was in the 1890s in Italy and Switzerland. In the 1930s reversible hydroelectric turbines became available. These turbines could operate as both turbine-generators and in reverse as electric motor driven pumps. The latest in large-scale engineering technology are variable speed machines for greater efficiency. These machines generate in synchronisation with the network frequency, but operate asynchronously (independent of the network frequency) as motor-pumps.

A new use for pumped storage is to level the fluctuating output of intermittent power sources. The pumped storage absorbs load at times of high output and low demand, while providing additional peak capacity. In certain jurisdictions, electricity prices may be close to zero or occasionally negative (Ontario in early September, 2006), indicating there is more generation than load available to absorb it; although at present this is rarely due to wind alone, increased wind generation may increase the likelihood of such occurrences. It is particularly likely that pumped storage will become especially important as a balance for very large scale photovoltaic generation.

In 2009 the United States had 21.5 GW of pumped storage generating capacity, accounting for 2.5% of baseload generating capacity. PHS generated (net) -6288 GWh of energy in 2008 because more energy is consumed in pumping than is generated; losses occur due to water evaporation, electric turbine/pump efficiency, and friction.

In 2007 the EU had 38.3 GW net capacity of pumped storage out of a total of 140 GW of hydropower and representing 5% of total net electrical capacity in the EU (Eurostat, consulted August 2009).

Potential technologies

The use of underground reservoirs as lower dams has been investigated. Salt mines could be used, although ongoing and unwanted dissolution of salt could be a problem. If they prove affordable, underground systems might greatly expand the number of pumped storage sites. Saturated brine is about 20% more dense than fresh water.

A new concept is to use wind turbines (hydroeolic) or solar power to drive water pumps directly, in effect an 'Energy Storing Wind or Solar Dam'. This could provide a more efficient process and usefully smooth out the variability of energy captured from the wind or sun.

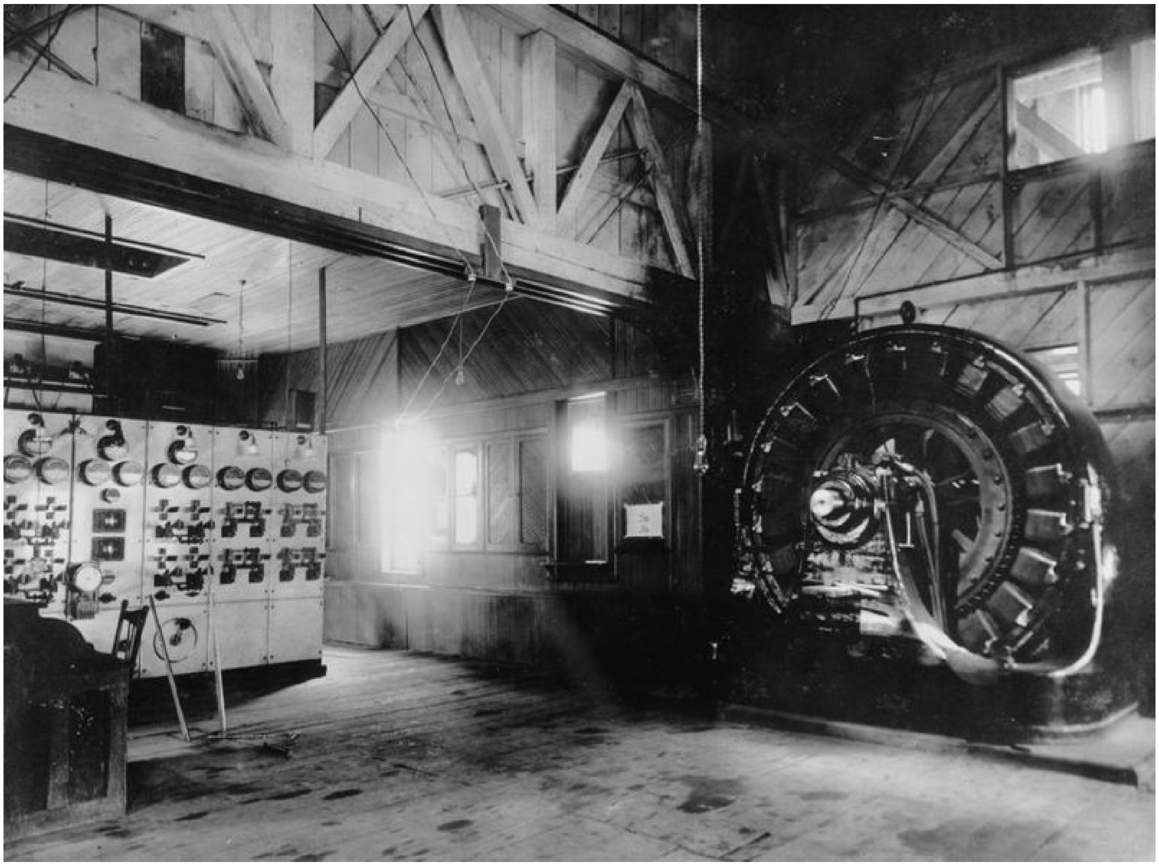
One can use pumped sea water to store the energy. A potential example of this could be used in a tidal barrage or tidal lagoon. A potential benefit of this arises if seawater is allowed to flow behind the barrage or into the lagoon at high tide when the water level is roughly equal either side of the barrier, when the potential energy difference is close to zero. Then water is released at low tide when a head of water has been built up behind the barrier, when there is a far greater potential energy difference between the two bodies of water. The result being that when the energy used to pump the water is recovered, it will have multiplied to a degree depending on the head of water built up. A further enhancement is to pump more water at high tide further increasing the head with for example intermittant renewables. Downsides: the generator must be below sea level, and marine organisms would tend to grow on the equipment and disrupt operation. This is not a major problem for the EDF La Rance Tidal power station in France.

Chapter- 6

Small, Micro and Pico Hydro

Small hydro

Micro hydro in North-West Vietnam



A 1895 hydroelectric plant near Telluride, Colorado.

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. This may be stretched up to 30 MW in the United States, and 50 MW in Canada. In contrast many hydroelectric projects are of enormous size, such as the generating plant at the Hoover Dam (2,074 megawatts) or the vast multiple projects of the Tennessee Valley Authority.

Small hydro can be further subdivided into mini hydro, usually defined as less than 1,000 kW, and micro hydro which is less than 100 kW. Micro hydro is usually the application of hydroelectric power sized for small communities, single families or small enterprise.

Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production. One tool that helps evaluate this issue is the Flow Duration Curve or FDC. The FDC is a Pareto curve of a stream's daily flow rate vs. frequency. Reductions of diversion help the river's ecosystem, but reduce the hydro system's ROI. The hydro system designer and site developer must strike a balance to maintain both the health of the stream and the economics.

Growth

During 2008 small hydro installations grew by 28% over year 2005 to raise the total world small hydro capacity to 85 gigawatts. Over 70% of this was in China (with 65 GW), followed by Japan (3.5 GW), the United States (3 GW) and India (2 GW). China plans to electrify a further 10,000 villages by 2010 under their China Village Electrification Program using renewable energy, including further investments in small hydro and photovoltaics.

Generation

Hydroelectric power is the generation of electric power from the movement of water. A hydroelectric facility requires a dependable flow of water and a reasonable height of fall of water, called the head. In a typical installation, water is fed from a reservoir through a channel or pipe into a turbine. The pressure of the flowing water on the turbine blades causes the shaft to rotate. The rotating shaft is connected to an electrical generator which converts the motion of the shaft into electrical energy.

Small hydro is often developed using existing dams or through development of new dams whose primary purpose is river and lake water-level control, or irrigation. Occasionally old, abandoned hydro sites may be purchased and re-developed, sometimes salvaging substantial parts of the installation such as penstocks and turbines, or sometimes just re-using the water rights associated with an abandoned site. Either of these cost saving advantages can make the ROI for a small hydro site well worth the use of existing site infrastructure & water rights.

Project design

Many companies offer standardized turbine generator packages in the approximate size range of 200 kW to 10 MW. These "water to wire" packages simplify the planning and development of the site since one vendor looks after most of the equipment supply. Since non-recurring engineering costs are minimized and development cost is spread over multiple units, the cost of such systems is improved. While synchronous generators capable of isolated plant operation are often used, small hydro plants connected to an electrical grid system can use economical induction generators to further reduce installation cost and simplify control and operation.

Micro-hydro plants may use purpose-designed turbines or use industrial centrifugal pumps, connected in reverse to act as turbines. While these machines rarely have optimum hydraulic characteristics when operated as turbines, their low purchase cost makes them attractive for micro-hydro class installations.

Regulation of small hydro generating units may require diversion of water around the turbine, since the project may have no reservoir to store unused water. For micro-hydro schemes feeding only a few loads, a resistor bank may be used to dissipate electrical energy as heat during periods of low demand. In a sense this energy is wasted but the incremental fuel cost is negligible so there is little economic loss.

Other small hydro schemes may use tidal energy or propeller-type turbines immersed in flowing water to extract energy. Tidal schemes may require water storage or electrical energy storage to level out the intermittent (although exactly predictable) flow of power.

Since small hydro projects usually have minimal environmental and licensing procedures, and since the equipment is usually in serial production, standardized and simplified, and since the civil works construction is also small, small hydro projects may be developed very rapidly. The physically small size of equipment makes it easier to transport to remote areas without good road or rail access.

Micro-hydro installations can also provide multiple uses. For instance, micro-hydro projects in rural Asia have incorporated agro-processing facilities such as rice mills - alongside standard electrification - into the project design .

Small scale DIY hydroplants

With a growing DIY-community and an increasing interest in environmentally friendly "green energy", some hobbyists have endeavored to build their own hydroeletric plants from old water mills, or from kits or from scratch. Usually, the DIY-community uses decayed/abandoned water mills to mount a waterwheel and other electrical components. This approach has also been popularised in TV-series as It's Not Easy Being Green. These are usually smaller turbines of ~5 kW or less. Through the internet, the community is now able to obtain plans to construct DIY-water turbines. and there is a growing trend toward building them for domestic requirements. The DIY-hydroelectric plants are now being used both in developed countries and in developing countries, to power residences and small businesses.

Micro hydro

Micro hydro in northwest Vietnam

Micro hydro is a term used for hydroelectric power installations that typically produce up to 100 kW of power. These installations can provide power to an isolated home or small community, or are sometimes connected to electric power networks. There are many of these installations around the world, particularly in developing nations as they can provide an economical source of energy without purchase of fuel.

Micro hydro systems complement photovoltaic solar energy systems because in many areas, water flow, and thus available hydro power, is highest in the winter when solar energy is at a minimum.

Micro hydro is frequently accomplished with a pelton wheel for high head, low flow water supply. The installation is often just a small dammed pool, at the top of a waterfall, with several hundred feet of pipe leading to a small generator housing.

Construction & characteristics

A penstock pipe used in an Afghanistan micro-hydro project

Construction details of a microhydro plant are site-specific, but the common elements of all hydroelectric plants are present. A supply of water is needed — this can be a mountain stream, or a river. Usually microhydro installations do not have a dam and reservoir, relying on a minimal flow of water to be available year-round. Sometimes an existing mill-pond or other artificial reservoir is available and can be adapted for power production. An intake structure is required to screen out floating debris and fish, using a screen or array of bars to keep out large objects. In temperate climates this structure must resist ice as well. The intake may have a gate to allow the system to be dewatered for inspection and maintenance.

Water withdrawn from the source must move along a power canal or a pipe (penstock) to the turbine. If the water source and turbine are far apart, the construction of the penstock may be the largest part of the costs of construction. In mountainous areas, access to the route of the penstock may provide considerable challenges.

At the turbine, a controlling valve is installed to regulate the flow and the speed of the turbine. The turbine converts the flow and pressure of the water to mechanical energy; the water emerging from the turbine returns to the natural watercourse along a tailrace channel.

The turbine turns a generator, which is then connected to electrical loads; this might be directly connected to the power system of a single building in very small installations, or may be connected to a community distribution system for several homes or buildings.

Regulation & operation

Typically, an automatic controller operates the turbine inlet valve to maintain constant speed (and frequency) when the load changes on the generator. In a system connected to a grid with multiple sources, the turbine control ensures that power always flows out from the generator to the system. The frequency of the alternating current generated needs to match the local standard utility frequency. In some systems, if the useful load on the generator is not high enough, a load bank may be automatically connected to the generator to dissipate energy not required by the load; while this wastes energy, it may be required if its not possible to stop the water flow through the turbine.

An induction generator always operates at the grid frequency irrespective of its rotation speed; all that is necessary is to ensure that it is driven by the turbine faster than the synchronous speed so that it generates power rather than consuming it. Other types of generator require a speed control systems for frequency matching.

With the availability of modern power electronics it is often easier to operate the generator at an arbitrary frequency and feed its output through an inverter which produces output at grid frequency. Power electronics now allow the use of permanent magnet alternators that produce wild AC to be stabilised. This approach allows low speed / low head water turbines to be competitive; they can run at the best speed for extraction of energy, and the power frequency is controlled by the electronics instead of the generator.

Very small installations, a few kilowatts or smaller, may generate direct current and charge batteries for peak use times.

Turbine types

Several different types of water turbines can be used in micro hydro installations, selection depending on the head of water, the volume of flow, and such factors as availability of local maintenance and transport of equipment to the site. For mountainous regions where a waterfall of 50 meters or more may be available, a Pelton wheel can be used. For low head installations, Francis or propeller-type turbines are used. Very low head installations of only a few meters may use propeller-type turbines in a pit. The very smallest micro hydro installations may successfully use industrial centrifugal pumps, run in reverse as prime movers; while the efficiency may not be as high as a purpose-built runner, the relatively low cost makes the projects economically feasible.

In low-head installations, maintenance and mechanism costs often become important. A low-head system moves larger amounts of water, and is more likely to encounter surface debris. For this reason a Banki turbine, a pressurized self-cleaning crossflow waterwheel, is often preferred for low-head microhydropower systems. Though less efficient, its simpler structure is less expensive than other low-head turbines of the same capacity. Since the water flows in, then out of it, it cleans itself and is less prone to jam with debris.

Two low-head schemes in England, Settle Hydro and Torrs Hydro use a reverse Archimedes' screw which is another debris-tolerant design. Other options include Gorlov, Francis and propeller turbines.

Another alternative is a large diameter, slow turning, permanent magnet, sloped open flow Kaplan turbine. A number of these have been installed at Trousy VLH, France.

Pico hydro

Pico hydro is a term used for hydroelectric power generation of under 5 kW. It is useful in small, remote communities that require only a small amount of electricity - for example, to power one or two fluorescent light bulbs and a TV or radio in 50 or so homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 1 meter. Pico-hydro setups typically are run-of-stream, meaning that dams are not used, but rather pipes divert some of the flow, drop this down a gradient, and through the turbine before being exhausted back to the stream.

Like other hydroelectric and renewable source power generation, pollution and consumption of fossil fuels is reduced (there is still typically an environmental cost to the manufacture of the generator and distribution methods)

Manufacturers

Two examples of pico hydro power can be found in Kenya, in the towns of Kithamba and Thimba. These produce 1.1 kW and 2.2 kW, respectively. Local residents were trained to maintain the hydro schemes. The pico hydro sites in Kenya won Ashden Awards for Sustainable Energy.

In Vietnam, several Chinese manufacturers have sold pico-powerplants at prices as low as 20-70$ for a powerplant of 300-500W. However, the devices sold are said to be low in quality and may damage connected equipment if connected improperly.

Sam Redfield of the Appropriate Infrastructure Development Group (AIDG) has developed a pico-hydro generator made from common PVC pipe and a modified Toyota alternator housed in a five gallon bucket. The generator was developed to provide power to communities without access to the electricity grid in developing countries. Envisioned as an energy source to charge cell phones, provide lighting and charge batteries, the generator is designed to be made by artisans with basic skills and can be built for less than US $150.00. The Toyota alternator used in the generator is converted to a permanent magnet alternator allowing it to generate power at low RPMs. The Five Gallon Bucket Hydroelectric Generator was the subject of a work group at the 2008 International Development Design Summit (IDDS) at the Massachusetts Institute of Technology.

Chapter- 7

Marine Energy

Marine energy or **marine power** (also sometimes referred to as **ocean energy** or **ocean power**) refers to the energy carried by ocean waves, tides, salinity, and ocean temperature differences. The movement of water in the world's oceans creates a vast store of kinetic energy, or energy in motion. This energy can be harnessed to generate electricity to power homes, transport and industries.

The term marine energy encompasses both wave power — power from surface waves, and tidal power — obtained from the kinetic energy of large bodies of moving water. Offshore wind power is generally confused as a form of marine energy, but is not as wind power is derived from the wind, even if the wind turbines are placed over water.

The oceans have a tremendous amount of energy and are close to many if not most concentrated populations. Many researches show that ocean energy has the potentiality of providing for a substantial amount of new renewable energy around the world.

Potential of ocean energy

The theoretical potential is several times greater than the actual global electricity demand, and equivalent to 4-18 million ToE.

Theoretical global ocean energy resource

Capacity (GW)	Annual gen. (TW·h)	Form
20	2,000	Osmotic power
1,000	10,000	Ocean thermal energy
90	800	Tidal power, and power from ocean currents
1,000—9,000	8,000—80,000	Wave power

Forms of ocean energy

Renewable

The oceans represent a vast and largely untapped source of energy in the form of surface waves, fluid flow, salinity gradients, and thermal.

Marine current power

Marine current power is a form of marine energy obtained from harnessing of the kinetic energy of marine currents, such as the Gulf stream. Although not widely used at present, marine current power has an important potential for future electricity generation. Marine currents are more predictable than wind and solar power.

A 2006 report from United States Department of the Interior estimates that capturing just $^{1}/_{1,000th}$ of the available energy from the Gulf Stream, which 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, would supply Florida with 35% of its electrical needs.

The energy obtained from ocean currents

Osmotic power

Osmotic power or **salinity gradient power** is the energy available from the difference in the salt concentration between seawater and river water. Two practical methods for this are reverse electrodialysis (RED) and pressure retarded osmosis. (PRO).

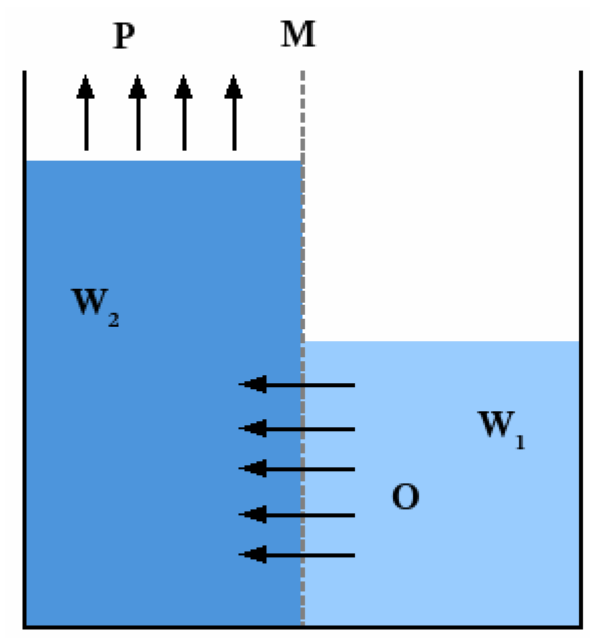
Both processes rely on osmosis with ion specific membranes. The key waste product is brackish water. This byproduct is the result of natural forces that are being harnessed: the flow of fresh water into seas that are made up of salt water.

The technologies have been confirmed in laboratory conditions. They are being developed into commercial use in the Netherlands (RED) and Norway (PRO). The cost of the membrane has been an obstacle. A new, cheap membrane, based on an electrically modified polyethylene plastic, made it fit for potential commercial use.

Other methods have been proposed and are currently under development. Among them, a method based on electric double-layer capacitor technology. and a method based on vapor pressure difference.

The world's first osmotic plant with capacity of 4 kW was opened by Statkraft on 24 November 2009 in Tofte, Norway. This plant uses polyimide as a membrane, and is able to produce $1W/m^2$ of membrane. This amount of power is obtained at 10 l of water flowing through the membrane per second, and at a pressure of 10 bar. Both the increasing of the pressure as well as the flow rate of the water would make it possible to increase the power output. Hypothetically, the output of the SGP-plant could easily be doubled.

Basics of salinity gradient power



Pressure-retarded osmosis

Salinity gradient power is a specific renewable energy alternative that creates renewable and sustainable power by using naturally occurring processes. This practice does not contaminate or release carbon dioxide (CO_2) emissions (vapor pressure methods will release dissolved air containing CO_2 at low pressures—these non-condensable gases can be re-dissolved of course, but with an energy penalty). Also as stated by Jones and Finley within their article "Recent Development in Salinity Gradient Power", there is basically no fuel cost.

Salinity gradient energy is based on using the resources of "osmotic pressure difference between fresh water and sea water." All energy that is proposed to use salinity gradient technology relies on the evaporation to separate water from salt. Osmotic pressure is the "chemical potential of concentrated and dilute solutions of salt". When looking at relations between high osmotic pressure and low, solutions with higher concentrations of salt have higher pressure.

Differing salinity gradient power generations exist but one of the most commonly discussed is Pressure Retarded Osmosis (PRO). Within PRO seawater is pumped into a pressure chamber where the pressure is lower than the difference between fresh and salt water pressure. Fresh water moves in a semipermeable membrane and increases its volume in the chamber. As the pressure in the chamber is compensated a turbine spins to generate electricity. In Braun's article he states that this process is easy to understand in a more broken down manner. Two solutions, A being salt water and B being fresh water are separated by a membrane. He states "only water molecules can pass the semipermeable membrane. As a result of the osmotic pressure difference between both solutions, the water from solution B thus will diffuse through the membrane in order to dilute the solution". The pressure drives the turbines and power the generator that produces the electrical energy.

Osmosis might be used directly to "pump" fresh water out of The Netherlands into the sea. This is currently done using electric pumps.

Methods

While the mechanics and concepts of salinity gradient power are still being studied, the power source has been implemented in several different locations. Most of these are experimental, but thus far they have been predominantly successful. The various companies that have utilized this power have also done so in many different ways as there are several concepts and processes that harness the power from salinity gradient.

At the Eddy Potash Mine in New Mexico, the technology of a salinity gradient solar pond (SGSP) is being utilized to provide the energy needed by the mine. The pond collects and stores thermal energy due to density differences between the three layers that make up the pond. The upper convection zone is the uppermost zone, followed by the stable gradient zone, then the bottom thermal zone. The stable gradient zone is the most important. Water in this layer can not rise to the higher zone because the water above has lower salinity and is therefore lighter and it can not sink to the lower level because this water is denser. This middle zone, the stable gradient zone, becomes an insulator for the bottom layer. This water from the lower layer, the storage zone, is pumped out and the heat is used to produce energy, usually by turbine.

Another method to utilize salinity gradient is called pressure-retarded osmosis. In this method, seawater is pumped into a pressure chamber that is at a pressure lower than the difference between the pressures of saline water and fresh water. Freshwater is also pumped into the pressure chamber through a membrane, which increase both the volume and pressure of the chamber. As the pressure differences are compensated, a turbine is spun creating energy. This method is being specifically studied by the Norwegian utility Statkraft, which has calculated that up to 25 TWh/yr would be available from this process in Norway. Statkraft has built the world's first prototype osmotic power plant on the Oslo fiord which was opened by Her Royal Highness Crown Princess Mette-Marit of Norway on November 24, 2009. It aims to produce enough electricity to light and heat a small town within five years by osmosis. At first it will produce a minuscule 4 kilowatts – enough to heat a large electric kettle, but by 2015 the target is 25 megawatts – the same as a small wind farm.

A third method being developed and studied is reversed electrodialysis or reverse dialysis, which is essentially the creation of a salt battery. This method was described by Weinstein and Leitz as “an array of alternating anion and cation exchange membranes can be used to generate electric power from the free energy of river and sea water.”

The technology related to this type of power is still in its infant stages, even though the principle was discovered in the 1950s. Standards and a complete understanding of all the ways salinity gradients can be utilized are important goals to strive for in order make this clean energy source more viable in the future.

A fourth method is Doriano Brogioli's watercondensor method.

Possible negative environmental impact

Marine and river environments have obvious differences in water quality, namely salinity. Each species of aquatic plant and animal is adapted to survive in either marine, brackish, or freshwater environments. There are species that can tolerate both, but these species usually thrive best in a specific water environment. The main waste product of salinity gradient technology is brackish water. The discharge of brackish water into the surrounding waters, if done in large quantities and with any regularity, will cause salinity fluctuations. While some variation in salinity is usual, particularly where fresh water (rivers) empties into an ocean or sea anyway, these variations become less important for both bodies of water with the addition of brackish waste waters. Extreme salinity changes in an aquatic environment may result in findings of low densities of both animals and plants due to intolerance of sudden severe salinity drops or spikes. According to the prevailing environmentalist opinions, the possibility of these negative effects should be considered by the operators of future large blue energy establishments.

Furthermore, impingement and entrainment at intake structures are a concern due to large volumes of both river and sea water utilized in both PRO and RED schemes. Intake construction permits must meet strict environmental regulations and desalination plants and power plants that utilize surface water are sometimes involved with various local, state and federal agencies to obtain permission that can take upwards to 18 months.

Finally, some scientists have predicted that if China does not check their irrigation withdrawals from rivers, ALL Chinese rivers will not meet the ocean at least during some part of the year by 2025. This has already happened with the mother of Chinese rivers, the Yellow river. An investment in osmotic power must consider future upstream use in the long-run.

The energy from salinity gradients.

Ocean thermal energy

The power from temperature differences at varying depths.

Tidal power

The energy from moving masses of water — a popular form of hydroelectric power generation. Tidal power generation comprises three main forms, namely: tidal stream power, tidal barrage power, and dynamic tidal power.

Wave power

The power from surface waves.

Non-renewable

Petroleum and natural gas beneath the ocean floor are also sometimes considered a form of ocean energy. An ocean engineer directs all phases of discovering, extracting, and delivering offshore petroleum (via oil tankers and pipelines), a complex and demanding task. Also centrally important is the development of new methods to protect marine wildlife and coastal regions against the undesirable side effects of offshore oil extraction.

Chapter- 8

Ocean Thermal Energy Conversion

Ocean thermal energy conversion (*OTEC* or *OTE*) uses the difference between cooler deep and warmer shallow waters to run a heat engine. As with any heat engine, greater efficiency and power comes from larger temperature differences. This temperature difference generally increases with decreasing latitude, i.e. near the equator, in the tropics. Historically, the main technical challenge of OTEC was to generate significant amounts of power efficiently from small temperature ratios. Modern designs allow performance approaching the theoretical maximum Carnot efficiency.

OTEC offers total available energy that is one or two orders of magnitude higher than other ocean energy options such as wave power; but the small temperature difference makes energy extraction comparatively difficult and expensive, due to low thermal efficiency. Earlier OTEC systems were 1 to 3% efficiency, well below the theoretical maximum of between 6 and 7%. Current designs are expected closer to the maximum. The energy carrier, seawater. Expense comes from the pumps and pump energy costs.OTEC plants can operate continuously as a base load power generation system. Accurate cost-benefit analyses include these factors to assess performance, efficiency, operational, construction costs, and returns on investment.

View of a land based OTEC facility at Keahole Point on the Kona coast of Hawaii (United States Department of Energy)

A heat engine is a thermodynamic device placed between a high temperature reservoir and a low temperature reservoir. As heat flows from one to the other, the engine converts some of the heat energy to work energy. This principle is used in steam turbines and internal combustion engines, while refrigerators reverse the direction of flow of both the heat and work energy. Rather than using heat energy from the burning of fuel, OTEC power draws on temperature differences caused by the sun's warming of the ocean surface. Much of the energy used by humans passes through a heat engine.

The only heat cycle suitable for OTEC is the Rankine cycle using a low-pressure turbine. Systems may be either closed-cycle or open-cycle. Closed-cycle engines use working fluids that are typically thought of as refrigerants such as ammonia or R-134a. Open-cycle engines use the water heat source as the working fluid.

The Earth's oceans are heated by the sun and cover over 70% of the Earth's surface.

History

Attempts to develop and refine OTEC technology started in the 1880s. In 1881, Jacques Arsene d'Arsonval, a French physicist, proposed tapping the thermal energy of the ocean. D'Arsonval's student, Georges Claude, built the first OTEC plant, in Cuba in 1930. The system generated 22 kW of electricity with a low-pressure turbine.

In 1931, Nikola Tesla released "Our Future Motive Power", which described such a system. Tesla ultimately concluded that the scale of engineering required made it impractical for large scale development.

In 1935, Claude constructed a plant aboard a 10,000-ton cargo vessel moored off the coast of Brazil. Weather and waves destroyed it before it could generate net power. (Net power is the amount of power generated after subtracting power needed to run the system.)

In 1956, French scientists designed a 3 MW plant for Abidjan, Ivory Coast. The plant was never completed, because new finds of large amounts of cheap oil made it uneconomical.

In 1962, J. Hilbert Anderson and James H. Anderson, Jr. focused on increasing component efficiency. They patented their new "closed cycle" design in 1967.

Although Japan has no potential sites, it is a major contributor to the development of the technology, primarily for export. Beginning in 1970 the Tokyo Electric Power Company successfully built and deployed a 100 kW closed-cycle OTEC plant on the island of Nauru. The plant became operational 1981-10-14, producing about 120 kW of electricity; 90 kW was used to power the plant and the remaining electricity was used to power a school and other places. This set a world record for power output from an OTEC system where the power was sent to a real power grid.

The United States became involved in 1974, establishing the Natural Energy Laboratory of Hawaii Authority at Keahole Point on the Kona coast of Hawaiʻi. Hawaii is the best U.S. OTEC location, due to its warm surface water, access to very deep, very cold water, and Hawaii's high electricity costs. The laboratory has become a leading test facility for OTEC technology.

India built a one MW floating OTEC pilot plant near Tamil Nadu, and its government continues to sponsor research.

Land, shelf and floating sites

OTEC has the potential to produce gigawatts of electrical power, and in conjunction with electrolysis, could produce enough hydrogen to completely replace all projected global fossil fuel consumption. Reducing costs remains an unsolved challenge, however. OTEC plants require a long, large diameter intake pipe, which is submerged a kilometer or more into the ocean's depths, to bring cold water to the surface.

Left: Pipes used for OTEC.
Right: Floating OTEC plant constructed in India in 2000

Land-based

Land-based and near-shore facilities offer three main advantages over those located in deep water. Plants constructed on or near land do not require sophisticated mooring, lengthy power cables, or the more extensive maintenance associated with open-ocean environments. They can be installed in sheltered areas so that they are relatively safe from storms and heavy seas. Electricity, desalinated water, and cold, nutrient-rich seawater could be transmitted from near-shore facilities via trestle bridges or causeways. In addition, land-based or near-shore sites allow plants to operate with related industries such as mariculture or those that require desalinated water.

Favored locations include those with narrow shelves (volcanic islands), steep (15-20 degrees) offshore slopes, and relatively smooth sea floors. These sites minimize the length of the intake pipe. A land-based plant could be built well inland from the shore, offering more protection from storms, or on the beach, where the pipes would be shorter. In either case, easy access for construction and operation helps lower costs.

Land-based or near-shore sites can also support mariculture. Tanks or lagoons built on shore allow workers to monitor and control miniature marine environments. Mariculture products can be delivered to market via standard transport.

One disadvantage of land-based facilities arises from the turbulent wave action in the surf zone. Unless the OTEC plant's water supply and discharge pipes are buried in protective trenches, they will be subject to extreme stress during storms and prolonged periods of heavy seas. Also, the mixed discharge of cold and warm seawater may need to be carried several hundred meters offshore to reach the proper depth before it is released. This arrangement requires additional expense in construction and maintenance.

OTEC systems can avoid some of the problems and expenses of operating in a surf zone if they are built just offshore in waters ranging from 10 to 30 meters deep (Ocean Thermal Corporation 1984). This type of plant would use shorter (and therefore less costly) intake and discharge pipes, which would avoid the dangers of turbulent surf. The plant itself, however, would require protection from the marine environment, such as breakwaters and erosion-resistant foundations, and the plant output would need to be transmitted to shore.

Shelf-based

To avoid the turbulent surf zone as well as to move closer to the cold-water resource, OTEC plants can be mounted to the continental shelf at depths up to 100 meters (328 ft). A shelf-mounted plant could be towed to the site and affixed to the sea bottom. This type of construction is already used for offshore oil rigs. The complexities of operating an OTEC plant in deeper water may make them more expensive than land-based approaches. Problems include the stress of open-ocean conditions and more difficult product delivery. Addressing strong ocean currents and large waves adds engineering and construction expense. Platforms require extensive pilings to maintain a stable base. Power delivery can require long underwater cables to reach land. For these reasons, shelf-mounted plants are less attractive.

Floating

Floating OTEC facilities operate off-shore. Although potentially optimal for large systems, floating facilities present several difficulties. The difficulty of mooring plants in very deep water complicates power delivery. Cables attached to floating platforms are more susceptible to damage, especially during storms. Cables at depths greater than 1000 meters are difficult to maintain and repair. Riser cables, which connect the sea bed and the plant, need to be constructed to resist entanglement.

As with shelf-mounted plants, floating plants need a stable base for continuous operation. Major storms and heavy seas can break the vertically suspended cold-water pipe and interrupt warm water intake as well. To help prevent these problems, pipes can be made of flexible polyethylene attached to the bottom of the platform and gimballed with joints or collars. Pipes may need to be uncoupled from the plant to prevent storm damage. As an alternative to a warm-water pipe, surface water can be drawn directly into the platform; however, it is necessary to prevent the intake flow from being damaged or interrupted during violent motions caused by heavy seas.

Connecting a floating plant to power delivery cables requires the plant to remain relatively stationary. Mooring is an acceptable method, but current mooring technology is limited to depths of about 2,000 meters (6,562 ft). Even at shallower depths, the cost of mooring may be prohibitive.

Cycle types

Cold seawater is an integral part of each of the three types of OTEC systems: closed-cycle, open-cycle, and hybrid. To operate, the cold seawater must be brought to the surface. The primary approaches are active pumping and desalination. Desalinating seawater near the sea floor lowers its density, which causes it to rise to the surface.

The alternative to costly pipes to bring condensing cold water to the surface is to pump vaporized low boiling point fluid into the depths to be condensed, thus reducing pumping volumes and reducing technical and environmental problems and lowering costs.

Closed

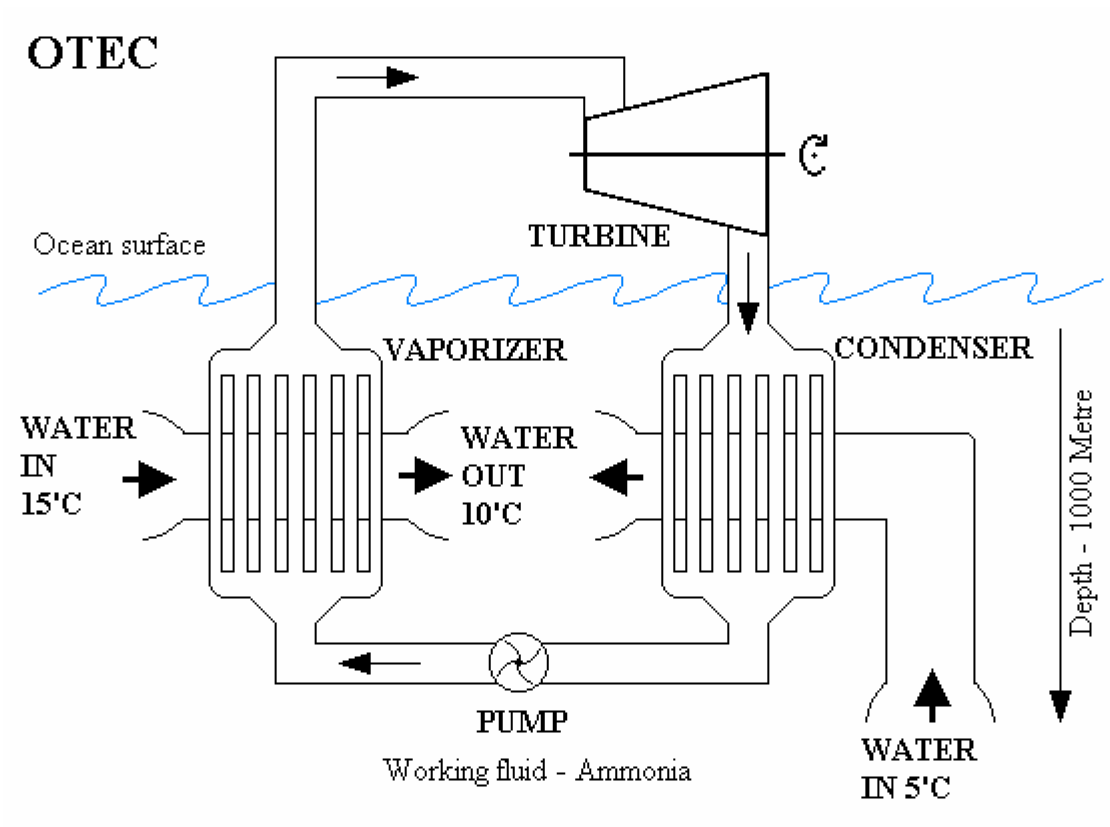


Diagram of a closed cycle OTEC plant

Closed-cycle systems use fluid with a low boiling point, such as ammonia, to power a turbine to generate electricity. Warm surface seawater is pumped through a heat exchanger to vaporize the fluid. The expanding vapor turns the turbo-generator. Cold water, pumped through a second heat exchanger, condenses the vapor into a liquid, which is then recycled through the system.

In 1979, the Natural Energy Laboratory and several private-sector partners developed the "mini OTEC" experiment, which achieved the first successful at-sea production of net electrical power from closed-cycle OTEC. The mini OTEC vessel was moored 1.5 miles (2 km) off the Hawaiian coast and produced enough net electricity to illuminate the ship's light bulbs and run its computers and televisions.

In 1999, the Natural Energy Laboratory tested a 250 kW pilot closed-cycle plant, the largest of its kind. Since that time, there have been no OTEC tests in the United States, largely because energy economics made such facilities impractical.

Open

Open-cycle OTEC uses warm surface water to make electricity. Placing warm seawater in a low-pressure container causes it to boil. The expanding steam drives a low-pressure turbine attached to an electrical generator. The steam, which left its salt and other contaminants in the low-pressure container, is pure fresh water. It is condensed into a liquid by exposure to cold temperatures from deep-ocean water. This method produces desalinized fresh water, suitable for drinking water or irrigation.

In 1984, the *Solar Energy Research Institute* (now the National Renewable Energy Laboratory) developed a vertical-spout evaporator to convert warm seawater into low-pressure steam for open-cycle plants. Conversion efficiencies were as high as 97% for seawater-to-steam conversion (overall efficiency using a vertical-spout evaporator would still only be a few per cent). In May 1993, an open-cycle OTEC plant at Keahole Point, Hawaii, produced 50,000 watts of electricity during a net power-producing experiment. This broke the record of 40 kW set by a Japanese system in 1982.

Hybrid

A hybrid cycle combines the features of the closed- and open-cycle systems. In a hybrid, warm seawater enters a vacuum chamber and is flash-evaporated, similar to the open-cycle evaporation process. The steam vaporizes the ammonia working fluid of a closed-cycle loop on the other side of an ammonia vaporizer. The vaporized fluid then drives a turbine to produce electricity. The steam condenses within the heat exchanger and provides desalinated water.

Some proposed projects

OTEC projects under consideration include a small plant for the U.S. Navy base on the British-occupied island of Diego Garcia in the Indian Ocean. OCEES International, Inc. is working with the U.S. Navy on a design for a proposed 13-MW OTEC plant, to replace the current diesel generators. The OTEC plant would also provide 1.25 million gallons per day (MGD) of potable water. A private U.S. company has proposed building a 10-MW OTEC plant on Guam.

Hawaii

Lockheed Martin's Alternative Energy Development team is currently in the final design phase of a 10-MW closed cycle OTEC pilot system which will become operational in Hawaii in the 2012-2013 time frame. This system is being designed to expand to 100-MW commercial systems in the near future. In November, 2010 the U.S. Naval Facilities

Engineering Command (NFEC) awarded the company a US$4.4 million contract modification to develop critical system components and designs for the plant, adding to the 2009 $8.1 million contract and two Department of Energy grants totaling $1 million in 2008 and March 2010.

Related activities

OTEC has uses other than power production.

Air conditioning

The 41 °F (5 °C) cold seawater made available by an OTEC system creates an opportunity to provide large amounts of cooling to operations near the plant. The water can be used in chilled-water coils to provide air-conditioning for buildings. It is estimated that a pipe 1 foot (0.30 m) in diameter can deliver 4,700 gallons per minute of water. Water at 43 °F (6 °C) could provide more than enough air-conditioning for a large building. Operating 8,000 hours per year in lieu of electrical conditioning selling for 5-10¢ per kilowatt-hour, it would save $200,000-$400,000 in energy bills annually.

The InterContinental Resort and Thalasso-Spa on the island of Bora Bora uses an OTEC system to air-condition its buildings. The system passes seawater through a heat exchanger where it cools freshwater in a closed loop system. This freshwater is then pumped to buildings and directly cools the air.

Chilled-soil agriculture

OTEC technology supports chilled-soil agriculture. When cold seawater flows through underground pipes, it chills the surrounding soil. The temperature difference between roots in the cool soil and leaves in the warm air allows plants that evolved in temperate climates to be grown in the subtropics. Dr. John P. Craven, Dr. Jack Davidson and Richard Bailey patented this process and demonstrated it at a research facility at the Natural Energy Laboratory of Hawaii Authority (NELHA). The research facility demonstrated that more than 100 different crops can be grown using this system. Many normally could not survive in Hawaii or at Keahole Point.

Aquaculture

Aquaculture is the best-known byproduct, because it reduces the financial and energy costs of pumping large volumes of water from the deep ocean. Deep ocean water contains high concentrations of essential nutrients that are depleted in surface waters due to biological consumption. This "artificial upwelling" mimics the natural upwellings that are responsible for fertilizing and supporting the world's largest marine ecosystems, and the largest densities of life on the planet.

Cold-water delicacies, such as salmon and lobster, thrive in this nutrient-rich, deep, seawater. Microalgae such as *Spirulina*, a health food supplement, also can be cultivated. Deep-ocean water can be combined with surface water to deliver water at an optimal temperature.

Non-native species such as Salmon, lobster, abalone, trout, oysters, and clams can be raised in pools supplied by OTEC-pumped water. This extends the variety of fresh seafood products available for nearby markets. Such low-cost refrigeration can be used to maintain the quality of harvested fish, which deteriorate quickly in warm tropical regions.

Desalination

Desalinated water can be produced in open- or hybrid-cycle plants using surface condensers to turn evaporated seawater into potable water. System analysis indicates that a 2-megawatt plant could produce about 4,300 cubic metres (150,000 cu ft) of desalinated water each day. Another systems patented by Richard Bailey creates condensate water by regulating deep ocean water flow through surface condensers correlating with fluctuating dew-point temperatures. This condensation system uses no incremental energy and has no moving parts.

Hydrogen production

Hydrogen can be produced via electrolysis using OTEC electricity. Generated steam with electrolyte compounds added to improve efficiency is a relatively pure medium for hydrogen production. OTEC can be scaled to generate large quantities of hydrogen. The main challenge is cost relative to other energy sources and fuels.

Mineral extraction

The ocean contains 57 trace elements in salts and other forms and dissolved in solution. In the past, most economic analyses concluded that mining the ocean for trace elements would be unprofitable, in part because of the energy required to pump the water. Mining generally targest minerals that occur in high concentrations, and can be extracted easily, such as magnesium. With OTEC plants supplying water, the only cost is for extraction. The Japanese investigated the possibility of extracting uranium and found developments in other technologies (especially materials sciences) were improving the prospects.

Political concerns

Because OTEC facilities are more-or-less stationary surface platforms, their exact location and legal status may be affected by the United Nations Convention on the Law of the Sea treaty (UNCLOS). This treaty grants coastal nations 3-, 12-, and 200-mile zones of varying legal authority from land, creating potential conflicts and regulatory barriers. OTEC plants and similar structures would be considered artificial islands under the treaty, giving them no independent legal status. OTEC plants could be perceived as either a threat or potential partner to fisheries or to seabed mining operations controlled by the International Seabed Authority.

Cost and economics

For OTEC to be viable as a power source, the technology must have tax and subsidy treatment similar to competing energy sources. Because OTEC systems have not yet been widely deployed, cost estimates are uncertain. One study estimates power generation costs as low as US $0.07 per kilowatt-hour, compared with $0.05 - $0.07 for subsidized wind systems.

Beneficial factors that should be taken into account include OTEC's lack of waste products and fuel consumption, the area in which it is available, (often within 20° of the equator) the geopolitical effects of petroleum dependence, compatibility with alternate forms of ocean power such as wave energy, tidal energy and methane hydrates, and supplemental uses for the seawater.

Variation of ocean temperature with depth

The total insolation received by the oceans (covering 70% of the earth's surface, with clearness index of 0.5 and average energy retention of 15%) is 5.457 x e^{10} Megajoules/year (MJ/yr) x .7 x .5 x .15 = 2.87 x e^{10} MJ/yr

We can use Lambert's law to quantify the solar energy absorption by water,

$$-\frac{dI(y)}{dy} = \mu I$$

where, y is the depth of water, I is intensity and μ is the absorption coefficient. Solving the above differential equation,

$$I(y) = I_0 \exp(-\mu y)$$

The absorption coefficient μ may range from 0.05 m^{-1} for very clear fresh water to 0.5 m^{-1} for very salty water.

Since the intensity falls exponentially with depth y, heat absorption is concentrated at the top layers. Typically in the tropics, surface temperature values are in excess of 25 °C (77 °F), while at 1 kilometers (1 mi), the temperature is about 5–10 °C (41–50 °F). The warmer (and hence lighter) waters at the surface means there are no thermal convection currents. Due to the small temperature gradients, heat transfer by conduction is too low to equalize the temperatures. The ocean is thus both a practically infinite heat source and a practically infinite heat sink.

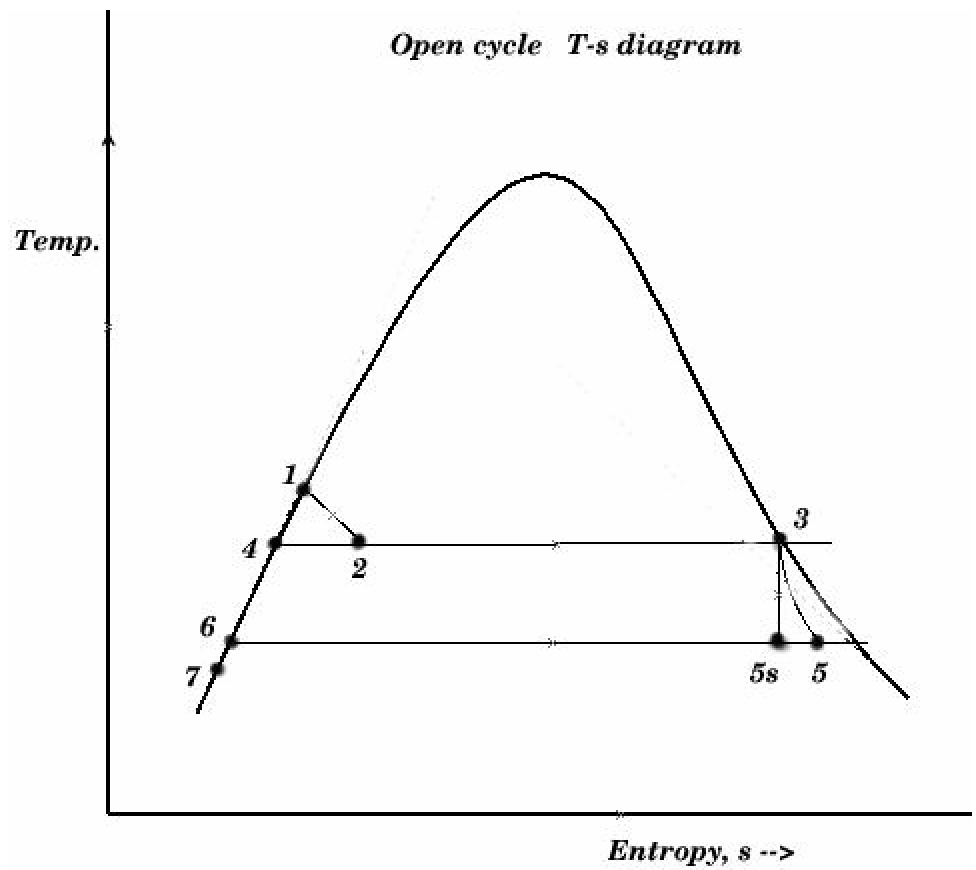
This temperature difference varies with latitude and season, with the maximum in tropical, subtropical and equatorial waters. Hence the tropics are generally the best OTEC locations.

Open/Claude cycle

In this scheme, warm surface water at around 27 °C (81 °F) enters an evaporator at pressure slightly below the saturation pressures causing it to vaporize.

$$H_1 = H_f$$

Where H_f is enthalpy of liquid water at the inlet temperature, T_1.



This temporarily superheated water undergoes volume boiling as opposed to pool boiling in conventional boilers where the heating surface is in contact. Thus the water partially flashes to steam with two-phase equilibrium prevailing. Suppose that the pressure inside the evaporator is maintained at the saturation pressure, T_2.

$$H_2 = H_1 = H_f + x_2 H_{fg}$$

Here, x_2 is the fraction of water by mass that vaporizes. The warm water mass flow rate per unit turbine mass flow rate is $1/x_2$.

The low pressure in the evaporator is maintained by a vacuum pump that also removes the dissolved non-condensable gases from the evaporator. The evaporator now contains a mixture of water and steam of very low vapor quality (steam content). The steam is separated from the water as saturated vapor. The remaining water is saturated and is discharged to the ocean in the open cycle. The steam is a low pressure/high specific volume working fluid. It expands in a special low pressure turbine.

$$H_3 = H_g$$

Here, H_g corresponds to T_2. For an ideal isentropic (reversible adiabatic) turbine,

$$s_{5,s} = s_3 = s_f + x_{5,s} s_{fg}$$

The above equation corresponds to the temperature at the exhaust of the turbine, T_5. $x_{5,s}$ is the mass fraction of vapor at state 5.

The enthalpy at T_5 is,

$$H_{5,s} = H_f + x_{5,s} H_{fg}$$

This enthalpy is lower. The adiabatic reversible turbine work = H_3-$H_{5,s}$.

Actual turbine work W_T = (H_3-$H_{5,s}$) x *polytropic efficiency*

$$H_5 = H_3 - \text{ actual work}$$

The condenser temperature and pressure are lower. Since the turbine exhaust is to be discharged back into the ocean, a direct contact condenser is used to mix the exhaust with cold water, which results in a near-saturated water. That water is now discharged back to the ocean.

H_6=H_f, at T_5. T_7 is the temperature of the exhaust mixed with cold sea water, as the vapour content now is negligible,

$$H_7 \approx H_f \ \ at\ T_7$$

The temperature differences between stages include that between warm surface water and working steam, that between exhaust steam and cooling water, and that between cooling water reaching the condenser and deep water. These represent external irreversibilities that reduce the overall temperature difference.

The cold water flow rate *per* unit turbine mass flow rate,

$$m_c = \frac{\dot{H}_5 - H_6}{H_6 - H_7}$$

Turbine mass flow rate, $\dot{M}_T = \frac{\text{turbine work required}}{W_T}$

Warm water mass flow rate, $\dot{M}_w = M_T \dot{m}_w$

Cold water mass flow rate $\dot{M}_c = \dot{M}_T \dot{m}_C$

Closed/Anderson cycle

Developed starting in the 1960s by J. Hilbert Anderson of Sea Solar Power, Inc. In this cycle, Q_H is the heat transferred in the evaporator from the warm sea water to the working fluid. The working fluid exits the evaporator as a gas near its dew point.

The high-pressure, high-temperature gas then is expanded in the turbine to yield turbine work, W_T. The working fluid is slightly superheated at the turbine exit and the turbine typically has an efficiency of 90% based on reversible, adiabatic expansion.

From the turbine exit, the working fluid enters the condenser where it rejects heat, $-Q_C$, to the cold sea water. The condensate is then compressed to the highest pressure in the cycle, requiring condensate pump work, W_C. Thus, the Anderson closed cycle is a Rankine-type cycle similar to the conventional power plant steam cycle except that in the Anderson cycle the working fluid is never superheated more than a few degrees Fahrenheit. Owing to viscous effects, working fluid pressure drops in both the evaporator and the condenser. This pressure drop, which depends on the types of heat exchangers used, must be considered in final design calculations but is ignored here to simplify the analysis. Thus, the parasitic condensate pump work, W_C, computed here will be lower than if the heat exchanger pressure drop was included. The major additional parasitic energy requirements in the OTEC plant are the cold water pump work, W_{CT}, and the warm water pump work, W_{HT}. Denoting all other parasitic energy requirements by W_A, the net work from the OTEC plant, W_{NP} is

$$W_{NP} = W_T + W_C + W_{CT} + W_{HT} + W_A$$

The thermodynamic cycle undergone by the working fluid can be analyzed without detailed consideration of the parasitic energy requirements. From the first law of thermodynamics, the energy balance for the working fluid as the system is

$$W_N = Q_H + Q_C$$

where $W_N = W_T + W_C$ is the net work for the thermodynamic cycle. For the idealized case in which there is no working fluid pressure drop in the heat exchangers,

$$Q_H = \int_H T_H ds$$

and

$$Q_C = \int_C T_C ds$$

so that the net thermodynamic cycle work becomes

$$W_N = \int_H T_H ds + \int_C T_C ds$$

Subcooled liquid enters the evaporator. Due to the heat exchange with warm sea water, evaporation takes place and usually superheated vapor leaves the evaporator. This vapor drives the turbine and the 2-phase mixture enters the condenser. Usually, the subcooled liquid leaves the condenser and finally, this liquid is pumped to the evaporator completing a cycle.

Working fluids

A popular choice of working fluid is ammonia, which has superior transport properties, easy availability, and low cost. Ammonia, however, is toxic and flammable. Fluorinated carbons such as CFCs and HCFCs are not toxic or flammable, but they contribute to ozone layer depletion. Hydrocarbons too are good candidates, but they are highly flammable; in addition, this would create competition for use of them directly as fuels. The power plant size is dependent upon the vapor pressure of the working fluid. With increasing vapor pressure, the size of the turbine and heat exchangers decreases while the wall thickness of the pipe and heat exchangers increase to endure high pressure especially on the evaporator side.

Technical difficulties

Dissolved gases

The performance of direct contact heat exchangers operating at typical OTEC boundary conditions is important to the Claude cycle. Many early Claude cycle designs used a surface condenser since their performance was well understood. However, direct contact condensers offer significant disadvantages. As cold water rises in intake pipe, the pressure decreases to the point where gas begins to evolve. If a significant amount of gas comes out of solution, placing a gas trap before the direct contact heat exchangers may be justified. Experiments simulating conditions in the warm water intake pipe indicated about 30% of the dissolved gas evolves in the top 8.5 meters (28 ft) of the tube. The trade-off between pre-dearation of the seawater and expulsion of non-condensable gases from the condenser is dependent on the gas evolution dynamics, deaerator efficiency, head loss, vent compressor efficiency and parasitic power. Experimental results indicate vertical spout condensers perform some 30% better than falling jet types.

Microbial fouling

Because raw seawater must pass through the heat exchanger, care must be taken to maintain good thermal conductivity. Biofouling layers as thin as 25 to 50 micrometres (0.00098 to 0.0020 in) can degrade heat exchanger performance by as much as 50%. A 1977 study in which mock heat exchangers were exposed to seawater for ten weeks concluded that although the level of microbial fouling was low, the thermal conductivity of the system was significantly impaired. The apparent discrepancy between the level of fouling and the heat transfer impairment is the result of a thin layer of water trapped by the microbial growth on the surface of the heat exchanger.

Another study concluded that fouling degrades performance over time, and determined that although regular brushing was able to remove most of the microbial layer, over time a tougher layer formed that could not be removed through simple brushing. The study passed sponge rubber balls through the system. It concluded that although the ball treatment decreased the fouling rate it was not enough to completely halt growth and brushing was occasionally necessary to restore capacity. The microbes regrew more quickly later in the experiment (i.e. brushing became necessary more often) replicating the results of a previous study. The increased growth rate after subsequent cleanings appears to result from selection pressure on the microbial colony.

Continuous use of 1 hour per day and intermittent periods of free fouling and then chlorination periods (again 1 hour per day) were studied. Chlorination slowed but did not stop microbial growth; however chlorination levels of .1 mg per liter for 1 hour per day may prove effective for long term operation of a plant. The study concluded that although microbial fouling was an issue for the warm surface water heat exchanger, the cold water heat exchanger suffered little or no biofouling and only minimal inorganic fouling.

Besides water temperature, microbial fouling also depends on nutrient levels, with growth occurring faster in nutrient rich water. The fouling rate also depends on the material used to construct the heat exchanger. Aluminium tubing slows the growth of microbial life, although the oxide layer which forms on the inside of the pipes complicates cleaning and leads to larger efficiency losses. In contrast, titanium tubing allows biofouling to occur faster but cleaning is more effective than with aluminium.

Sealing

The evaporator, turbine, and condenser operate in partial vacuum ranging from 3% to 1% of atmospheric pressure. The system must be carefully sealed to prevent in-leakage of atmospheric air that can degrade or shut down operation. In closed-cycle OTEC, the specific volume of low-pressure steam is very large compared to that of the pressurized working fluid. Components must have large flow areas to ensure steam velocities do not attain excessively high values.

Parasitic power consumption by exhaust compressor

An approach for reducing the exhaust compressor parasitic power loss is as follows. After most of the steam has been condensed by spout condensers, the non-condensible gas steam mixture is passed through a counter current region which increases the gas-steam reaction by a factor of five. The result is an 80% reduction in the exhaust pumping power requirements.

Cold air/warm water conversion

In winter in coastal Arctic locations, seawater can be 40 °C (104 °F) warmer than ambient air temperature. Closed-cycle systems could exploit the air-water temperature difference. Eliminating seawater extraction pipes might make a system based on this concept less expensive than OTEC.

Chapter- 9

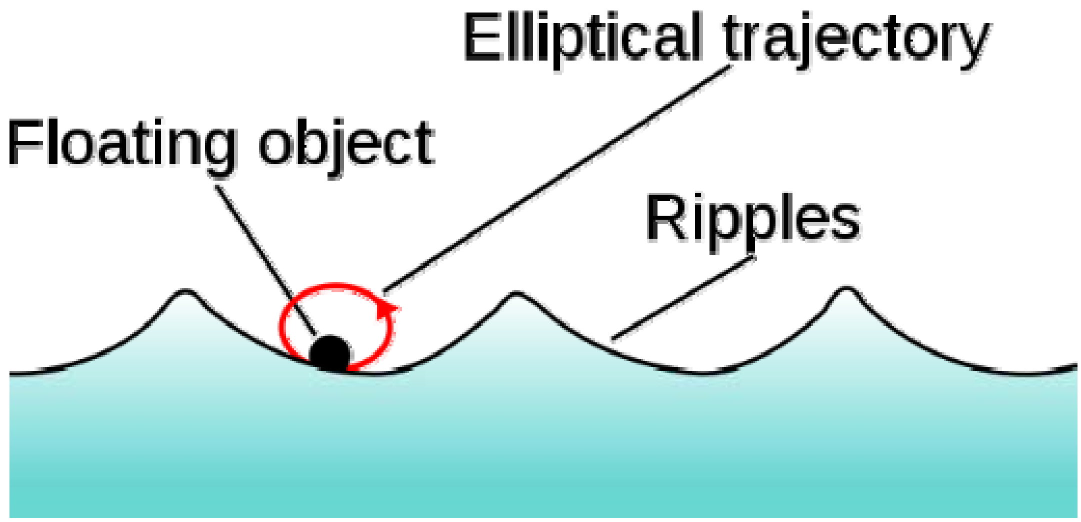
Wave Power

Large storm waves pose a challenge to wave power development

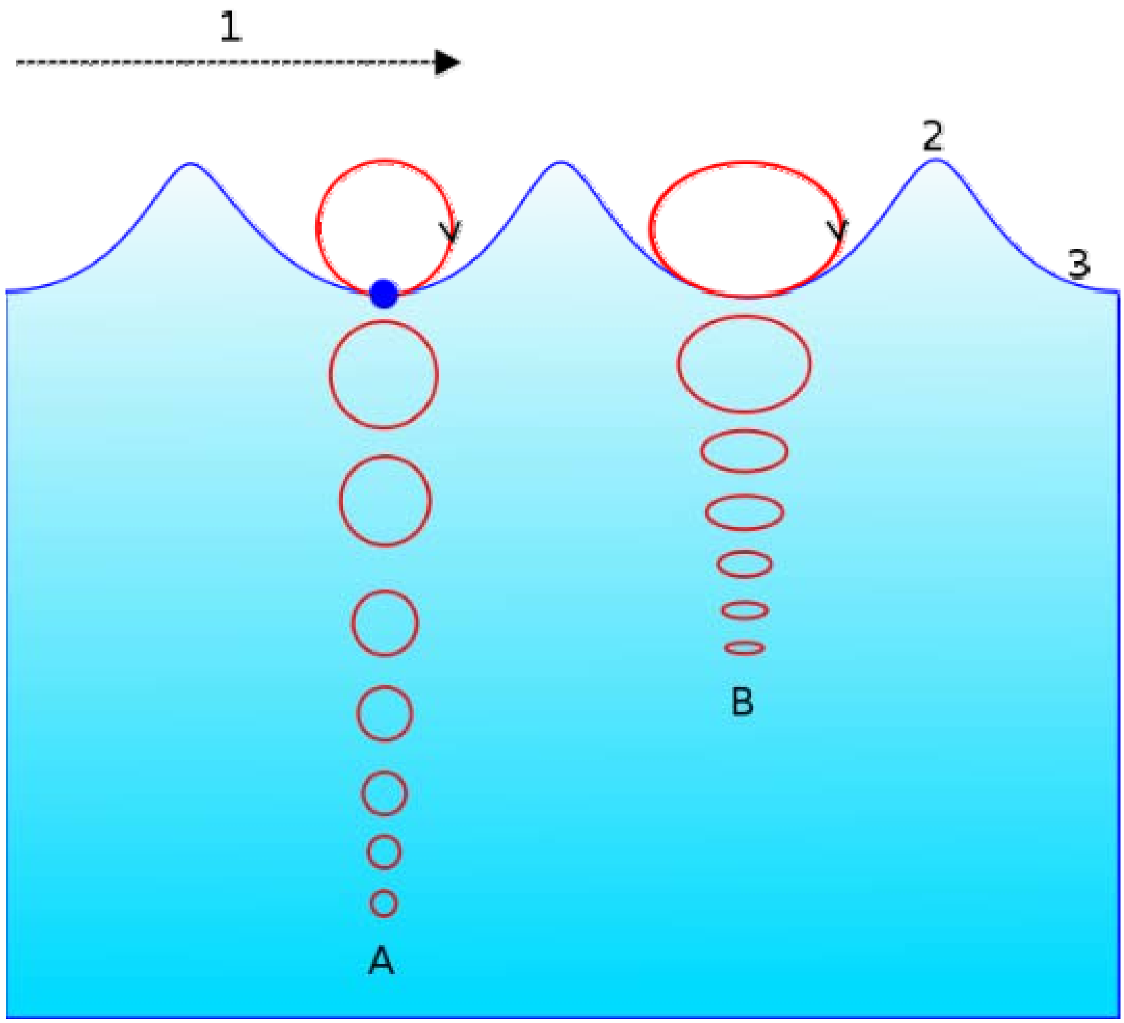
Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work — for example for electricity generation, water desalination, or the pumping of water (into reservoirs).

Wave power is distinct from the diurnal flux of tidal power and the steady gyre of ocean currents. Wave power generation is not currently a widely employed commercial technology although there have been attempts at using it since at least 1890. In 2008, the first commercial wave farm was opened in Portugal, at the Aguçadoura Wave Park.

Physical concepts



When an object bobs up and down on a ripple in a pond, it experiences an elliptical trajectory.



Motion of a particle in an ocean wave.
A = At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface.
B = At shallow water (ocean floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth.
1 = Propagation direction.
2 = Wave crest.
3 = Wave trough.

Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress causes the growth of the waves.

Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves). A given wind speed has a matching practical limit over which time or distance will not produce larger waves. When this limit has been reached the sea is said to be "fully developed".

In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density.

Oscillatory motion is highest at the surface and diminishes exponentially with depth. However, for standing waves (clapotis) near a reflecting coast, wave energy is also present as pressure oscillations at great depth, producing microseisms. These pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power.

The waves propagate on the ocean surface, and the wave energy is also transported horizontally with the group velocity. The mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, is called the wave energy flux (or wave power, which must not be confused with the actual power generated by a wave power device).

Wave power formula

In deep water where the water depth is larger than half the wavelength, the wave energy flux is

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T \approx \left(0.5 \frac{\text{kW}}{\text{m}^3 \cdot \text{s}}\right) H_{m0}^2\, T,$$

with P the wave energy flux per unit of wave-crest length, H_{m0} the significant wave height, T the wave period, ρ the water density and g the acceleration by gravity. The above formula states that wave power is proportional to the wave period and to the square of the wave height. When the significant wave height is given in meters, and the wave period in seconds, the result is the wave power in kilowatts (kW) per meter of wavefront length.

Example: Consider moderate ocean swells, in deep water, a few kilometers off a coastline, with a wave height of 3 meters and a wave period of 8 seconds. Using the formula to solve for power, we get

$$P \approx 0.5 \frac{\text{kW}}{\text{m}^3 \cdot \text{s}} (3 \cdot \text{m})^2 (8 \cdot \text{s}) \approx 36 \frac{\text{kW}}{\text{m}},$$

meaning there are 36 kilowatts of power potential per meter of coastline.

In major storms, the largest waves offshore are about 15 meters high and have a period of about 15 seconds. According to the above formula, such waves carry about 1.7 MW of power across each meter of wavefront.

An effective wave power device captures as much as possible of the wave energy flux. As a result the waves will be of lower height in the region behind the wave power device.

Wave energy and wave energy flux

In a sea state, the average energy density per unit area of gravity waves on the water surface is proportional to the wave height squared, according to linear wave theory:

$$E = \frac{1}{16}\rho g H_{m0}^2,$$

where *E* is the mean wave energy density per unit horizontal area (J/m^2), the sum of kinetic and potential energy density per unit horizontal area. The potential energy density is equal to the kinetic energy, both contributing half to the wave energy density *E*, as can be expected from the equipartition theorem. In ocean waves, surface tension effects are negligible for wavelengths above a few decimetres.

As the waves propagate, their energy is transported. The energy transport velocity is the group velocity. As a result, the wave energy flux, through a vertical plane of unit width perpendicular to the wave propagation direction, is equal to:

$$P = E\, c_g,$$

with c_g the group velocity (m/s). Due to the dispersion relation for water waves under the action of gravity, the group velocity depends on the wavelength λ, or equivalently, on the wave period *T*. Further, the dispersion relation is a function of the water depth *h*. As a result, the group velocity behaves differently in the limits of deep and shallow water, and at intermediate depths:

Deep water characteristics and opportunities

Deep water corresponds with a water depth larger than half the wavelength, which is the common situation in the sea and ocean. In deep water, longer period waves propagate faster and transport their energy faster. The deep-water group velocity is half the phase velocity. In shallow water, for wavelengths larger than twenty times the water depth, as found quite often near the coast, the group velocity is equal to the phase velocity.

The regularity of deep-water ocean swells, where "easy-to-predict long-wavelength oscillations" are typically seen, offers the opportunity for the development of energy harvesting technologies that are potentially less subject to physical damage by near-shore cresting waves.

History

The first known patent to utilize energy from ocean waves dates back to 1799 and was filed in Paris by Girard and his son. An early application of wave power was a device constructed around 1910 by Bochaux-Praceique to light and power his house at Royan, near Bordeaux in France. It appears that this was the first Oscillating Water Column type of wave energy device. From 1855 to 1973 there were already 340 patents filed in the UK alone.

Modern scientific pursuit of wave energy was however pioneered by Yoshio Masuda's experiments in the 1940s. He has tested various concepts of wave energy devices at sea, with several hundred units used to power navigation lights. Among these was the concept of extracting power from the angular motion at the joints of an articulated raft, which was proposed in the 1950s by Masuda.

A renewed interest in wave energy was motivated by the oil crisis in 1973. A number of university researchers reexamined the potential of generating energy from ocean waves, among whom notably were Stephen Salter from the University of Edinburgh, Kjell Budal and Johannes Falnes from Norwegian Institute of Technology (now merged into Norwegian University of Science and Technology), Michael E. McCormick from U. S. Naval Academy, David Evans from Bristol University, Michael French from University of Lancaster, John Newman and Chiang C. Mei from MIT.

In response to the Oil Crisis, a number of researchers reexamined the potential of generating energy from ocean waves, among whom is Professor Stephen Salter of the University of Edinburgh, Scotland. His 1974 invention became known as Salter's Duck or Nodding Duck, although it was officially referred to as the Edinburgh Duck. In small scale controlled tests, the Duck's curved cam-like body can stop 90% of wave motion and can convert 90% of that to electricity giving 81% efficiency.

In the 1980s, as the oil price went down, wave-energy funding was drastically reduced. Nevertheless, a few first-generation prototypes were tested at sea. More recently, following the issue of climate change, there is again a growing interest worldwide for renewable energy, including wave energy.

Modern technology

Wave power devices are generally categorized by the method used to capture the energy of the waves. They can also be categorized by location and power take-off system. Method types are point absorber or buoy; surfacing following or attenuator oriented parallel to the direction of wave propagation; terminator, oriented perpendicular to the direction of wave propagation; oscillating water column; and overtopping. Locations are shoreline, nearshore and offshore. Types of power take-off include: hydraulic ram, elastomeric hose pump, pump-to-shore, hydroelectric turbine, air turbine, and linear electrical generator. Some of these designs incorporate parabolic reflectors as a means of increasing the wave energy at the point of capture. These capture systems use the rise and fall motion of waves to capture energy. Once the wave energy is captured at a wave source, power must be carried to the point of use or to a connection to the electrical grid by transmission power cables.

These are descriptions of some wave power systems:

The front of the Pelamis machine bursting through a wave at the Agucadoura Wave Park

Wave Dragon seen from reflector, prototype 1:4½

- In the United States, the Pacific Northwest Generating Cooperative is funding the building of a commercial wave-power park at Reedsport, Oregon. The project will utilize the PowerBuoy technology Ocean Power Technologies which consists of modular, ocean-going buoys. The rising and falling of the waves moves hydraulic fluid with the buoy; this motion is used to spin a generator, and the electricity is transmitted to shore over a submerged transmission line. A 150 kW buoy has a diameter of 36 feet (11 m) and is 145 feet (44 m) tall, with approximately 30 feet of the unit rising above the ocean surface. Using a three-point mooring system, they are designed to be installed one to five miles (8 km) offshore in water 100 to 200 feet (60 m) deep.
- An example of a surface following device is the Pelamis Wave Energy Converter. The sections of the device articulate with the movement of the waves, each resisting motion between it and the next section, creating pressurized oil to drive a hydraulic ram which drives a hydraulic motor. The machine is long and narrow (snake-like) and points into the waves; it attenuates the waves, gathering more energy than its narrow profile suggests. Its articulating sections drive internal hydraulic generators (through the use of pumps and accumulators).
- With the Wave Dragon wave energy converter large wing reflectors focus waves up a ramp into an offshore reservoir. The water returns to the ocean by the force of gravity via hydroelectric generators.

- The Anaconda Wave Energy Converter is in the early stages of development by UK company Checkmate SeaEnergy. The concept is a 200 metre long rubber tube which is tethered underwater. Passing waves will instigate a wave inside the tube, which will then propagates down its walls, driving a turbine at the far end.
- The AquaBuOY is a technology developed by Finavera Renewables Inc. In 2009 Finavera Renewables surrendered its wave energy permits from FERC. In July 2010 Finavera announced that it has entered into a definitive agreement to sell all assets and intellectual property related to the AquaBuOY wave energy technology to an undisclosed buyer.
- The FlanSea is a so-called "point absorber" buoy, developed for use in the sourthern north sea conditions. It works by means of a cable that due to the bobbing effect of the buoy, generates electricity.
- The SeaRaser, built by Alvin Smith, uses an entirely new technique (pumping) for gathering the wave energy.
- A device called CETO, currently being tested off Fremantle, Western Australia, consists of a single piston pump attached to the sea floor, with a float tethered to the piston. Waves cause the float to rise and fall, generating pressurized water, which is piped to an onshore facility to drive hydraulic generators or run reverse osmosis water desalination.
- Another type of wave buoys, using special polymeres, is being developed by SRI
- Wavebob is an Irish Company who have conducted some ocean trials.
- The Oyster wave energy converter is a hydro-electric wave energy device currently being developed by Aquamarine Power. The wave energy device captures the energy found in nearshore waves and converts it into clean usable electricity. The systems consists of a hinged mechanical flap connected to the seabed at around 10m depth. Each passing wave moves the flap which drives hydraulic pistons to deliver high pressure water via a pipeline to an onshore turbine which generates electricity. In November 2009, the first full-scale demonstrator Oyster began producing power when it was launched at the European Marine Energy Centre (EMEC) on Orkney.
- Ocean Energy have developed the OE buoy which has completed (September 2009) a 2-year sea trial in one quarter scale form. The OE buoy has only one moving part.
- The Lysekil Project is based on a concept with a direct driven linear generator placed on the seabed. The generator is connected to a buoy at the surface via a line. The movements of the buoy will drive the translator in the generator. The advantage of this setup is a less complex mechanical system with potentially a smaller need for maintenance. One drawback is a more complicated electrical system.
- An Australian firm, Oceanlinx, is developing a deep-water technology to generate electricity from, ostensibly, easy-to-predict long-wavelength ocean swell oscillations. Oceanlinx recently began installation of a third and final demonstration-scale, grid-connected unit near Port Kembla, near Sydney, Australia, a 2.5 MW_e system that is expected to go online in early 2010, when its power will be connected to the Australian grid. The companies much smaller

first-generation prototype unit, in operation since 2006, is now being disassembled.

- An Israeli firm, SDE ENERGY LTD., has developed a breakwater-based wave energy converter. This device is close to the shore and utilizes the vertical motion of buoys for creating an hydraulic pressure, which in turn operates the system's generators. S.D.E. is currently building a new 250 kWh model in the port of Jaffa, Tel Aviv and preparing to construct it's standing orders for a 100mWh power plants in the islands of Zanzibar and Kosrae, Micronesia.
- A Finnish firm, AW-Energy Oy, is developing the WaveRoller device: that is a plate anchored on the sea bottom by its lower part. The back and forth movement of surge moves the plate. The kinetic energy transferred to this plate is collected by a piston pump.

Potential

Deep water wave power resources are truly enormous, between 1 TW and 10 TW, but it is not practical to capture all of this. The useful worldwide resource has been estimated to be greater than 2 TW. Locations with the most potential for wave power include the western seaboard of Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand. The north and south temperate zones have the best sites for capturing wave power. The prevailing westerlies in these zones blow strongest in winter. Waves are very predictable; waves that are caused by winds can be predicted five days in advance.

Challenges

- There is a potential impact on the marine environment. Noise pollution, for example, could have negative impact if not monitored, although the noise and visible impact of each design varies greatly.
- In terms of socio-economic challenges, wave farms can result in the displacement of commercial and recreational fishermen from productive fishing grounds, can change the pattern of beach sand nourishment, and may represent hazards to safe navigation.
- Waves generate about 2,700 gigawatts of power. Of those 2,700 gigawatts, only about 500 gigawatts can be captured with the current technology.

Wave farms

The Aguçadoura Wave Farm was the world's first commercial wave farm. It was located 5 km (3 mi) offshore near Póvoa de Varzim north of Oporto in Portugal. The farm was designed to use three Pelamis wave energy converters to convert the motion of the ocean surface waves into electricity, totalling to 2.25MW in total installed capacity. The farm first generated electricity in July 2008 and was officially opened on the 23rd of September 2008, by the Portuguese Minister of Economy. The wave farm was shut down two months after the official opening in November 2008 as a result of the financial collapse of Babcock & Brown due to the global economic crisis. The machines were off-site at this time due to technical problems, and although resolved have not returned to site without financial backing. A second phase of the project planned to increase the installed capacity to 21MW using a further 25 Pelamis machines is in doubt following Babcock's financial collapse.

Funding for a 3MW wave farm in Scotland was announced on 20 February 2007 by the Scottish Executive, at a cost of over 4 million pounds, as part of a £13 million funding package for marine power in Scotland. The first of 66 machines was launched in May 2010.

Funding has also been announced for the development of a Wave hub off the north coast of Cornwall, England. The Wave hub will act as giant extension cable, allowing arrays of wave energy generating devices to be connected to the electricity grid. The Wave hub will initially allow 20MW of capacity to be connected, with potential expansion to 40MW. Four device manufacturers have so far expressed interest in connecting to the Wave hub.

The scientists have calculated that wave energy gathered at Wave Hub will be enough to power up to 7,500 households. Savings that the Cornwall wave power generator will bring are significant: about 300,000 tons of carbon dioxide in the next 25 years.

A CETO wave farm off the coast of Western Australia has been operating to prove commercial viability and, after preliminary environmental approval, is poised for further development.

Patents

- U.S. Patent 3,928,967 — *Apparatus and method of extracting wave energy* - The original "Salter's Duck" patent
- U.S. Patent 4,134,023 — *Apparatus for use in the extraction of energy from waves on water* - Salter's method for improving "duck" efficiency
- U.S. Patent 6,194,815 — *Piezoelectric rotary electrical energy generator*
- US application 20,040,217,597 — *Wave energy converters utilizing pressure differences*