Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 9. Hydroenergy

Future Energy:
Opportunities and Challenges

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9
Hydroenergy

The Main Points

- **Hydroenergy is energy derived from falling or moving water.**

- **Hydroenergy sources include impounded water sources, natural river elevation changes, river flows, tides, ocean currents, and waves.**

- **Suitable U.S. sites for large dams have been used. Smaller impoundments are now under consideration.**

- **Analysts estimate that new hydroenergy in the U.S. could provide around 1.4 Quads of electricity per year (10 percent of current electricity production).**

9.1 Introduction

Hydroenergy, as defined here, is energy contained in falling or moving water.

A huge quantity of water falls on the U.S. landmass as precipitation. This water undergoes three possible fates:

- It may evaporate.

- It may enter the soil and may be absorbed by plants. It may then be released back into the air, or it may become part of underground aquifers.

- It may enter rivers by surface runoff or through springs that release underground water.

As river water flows toward eventual discharge into the sea, it may pass through regions where impoundment with dams is feasible. It is generally desirable to build dams in locations where dam height can be maximized with minimum land area flooded behind the dam. Therefore, mountainous or hilly regions are preferred over flat terrain for impounding water.

In some locations, rivers change elevation naturally over short distances. Water may be withdrawn from an upstream, elevated takeoff point and transferred through a pipe or tunnel to a turbine-generator at a lower elevation, where it is returned to the river. The Niagara Falls power plant is an example of this type of system.

Water in rivers, oceans, and estuaries experiences motion and, therefore, possesses kinetic energy that may be captured for producing electricity. River flow rates vary, but some flow typically occurs constantly. Tides cause water currents to flow into and out of estuaries and cause periodic changes in water depth. Waves cause periodic increases and decreases in water depth. Ocean currents, such as the Gulf Stream, possess energy that may someday be tapped to produce electricity to be transferred to shore.

9.2 Physics of Falling Water Energy

The potential energy in elevated water may be tapped to produce electricity. Sites where large quantities of water fall through large elevation changes provide good sites for hydropower generation.

Appendix P provides formulas for the power available from falling water. The basic formula is as follows:

$$P = gfh \tag{9-1}$$

where:

P = power
g = gravitational constant
f = mass flow rate
h = height

Appendix P gives formulas with factors expressed in various sets of units. Here, we will illustrate the calculation of power production using two different sets of units. One set uses flow expressed in cubic feet per second and height expressed in feet. The other set uses flow expressed in kilograms per second and height in meters. The formulas (see Appendix P) are as follows:

$$P(\text{watts}) = 84.6 \times \text{flow (in cubic feet per second)} \times \text{height (in feet)} \quad (9\text{-}2)$$

or

$$P(\text{watts}) = 9.81 \times \text{flow (in kilograms per second)} \times \text{height (in meters)} \quad (9\text{-}3)$$

Example 9.1
Calculate the energy in water falling 200 feet at a rate of 50,000 cubic feet per second.

$$P(\text{watts}) = 84.6 \times 50{,}000 \times 200 = 846 \text{ x } 10^6 \text{ watts or 846 megawatts}$$

Now repeat the calculation using SI units. A height of 200 feet is equal to 61 meters. The mass flow rate is given by:

Flow (kilograms per second) = 50,000 (cubic feet per second)× 62.4 (pounds per cubic foot) × 0.4545 (kilograms per pound) = 1.42 × 10^6 kilograms per second.

Equation 9.3 gives the following result:

$$P(\text{watts}) = 9.81 \times 1.42 \times 10^6 \times 61 = 846 \times 10^6 \text{ watts or 846 megawatts.}$$

This example illustrates that the formulas for SI units and for U.S. Customary units are consistent.

9.3 Turbines and Generators

The electrical power produced by a hydroelectric turbine-generator is somewhat less than the power in the falling water because of inefficiencies in the conversion to mechanical power in the turbine and the subsequent conversion from mechanical power to electrical power in the generator. Typical large turbine-generators convert the power in falling water into electrical power with an efficiency of around 90 percent or higher. Figure 9-1 shows a typical hydroelectric turbine-generator.

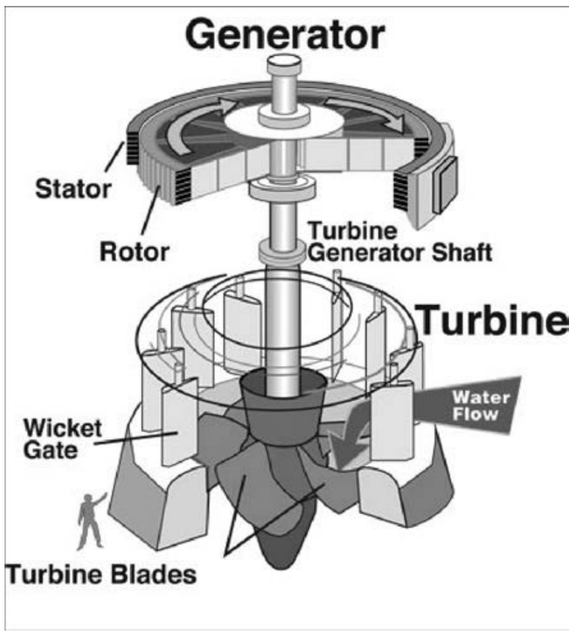

Figure 9-1. A Hydraulic Turbine-Generator
(courtesy of U.S. Army Corps of Engineers)

9.4 Falling Water Hydroelectric Systems

9.4.1 Large Commercial Systems

Large dams with electrical generating capacities of 30 to 2,000 megawatts are scattered around the U.S. Figure 9-2 shows the main components of a large electricity-producing dam. These large dams are generally found where river flows are great, where suitable topology exists for high dams, and where the terrain permits deep reservoirs without excessive surface area. There are about 2,400 such dams in the U.S., with a total generating capacity of around 35,400 megawatts. These facilities produce about 0.9 Quads of electricity per year (about 6.5 percent of total U.S. electricity production).

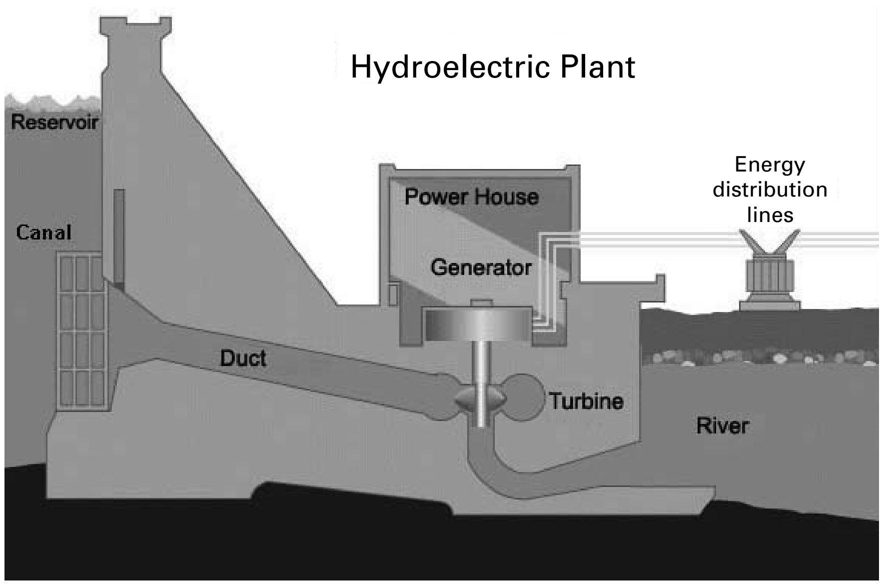

Figure 9-2. A Hydroelectric Dam (courtesy of Tennessee Valley Authority)

Since all of the best sites have been used, there is no possibility of significant new construction of large dams. However, sites still exist for smaller dams (less than 30 megawatts).

9.4.2 Small Commercial Dams

Since the sites that are suitable for large power-producing dams in the U.S. are essentially all in use, and because of a recognized need for an increase in sustainable and non-polluting energy, interest in exploiting sites with smaller generating capacity is increasing. Sites suitable for small (less than 30 megawatts) dams exist in many locations. In some cases, small dams already exist, but have no turbine-generator. Some other sites have natural elevation changes in stream flow that can be used for power generation without requiring a dam.

9.4.3 Small Private Systems

Small hydroenergy systems can provide mechanical or electrical energy for individuals who have a stream on their property. If a stream flows down a hillside or over a cliff, then the source of elevated water can feed a raceway or penstock that delivers water to the bottom of the hill. In this way, it may be possible to achieve an elevation change without building a dam. Such systems can provide nearly free energy after the construction cost has been paid.

Renewable energy advocates often state that enough off-grid power can be produced by local, renewable hydroenergy sources to satisfy the needs of a typical family. In order to avoid disappointing performance, it is essential to assess the quantitative capability of typical local energy resources. The formulas in Section 9.2 provide the capability to estimate the achievable power generation for specific stream flow rates and elevation changes.

9.5 Pumped Storage

Pumped storage systems use pumps to deliver water to elevated reservoirs (as on a mountain top). Pumping power is provided by power plants that would otherwise be idle because of low electricity demand. When electricity demand is high, the elevated water is released to turbine-generators at the lower elevation. The turbine-generator is reversed and used as a pump when pumping is required. Figure 9-3 shows a pumped storage system.

Pumped storage is especially effective in systems with power plants that have low operating costs and can operate at night, when electricity demand is typically low. Wind turbines, geothermal systems, and nuclear power plants all have low operating costs. (They typically have higher capital costs than fossil-fuel plants, but these capital costs continue whether the plant operates or not.) Since operating costs (mostly fuel costs) for fossil fuel power plants are the major part of their total power costs, they are not well-suited for providing pumping power for pumped storage. Since solar generators are idle at night when pumping power is needed, they are not suitable for providing pumping power for pumped storage.

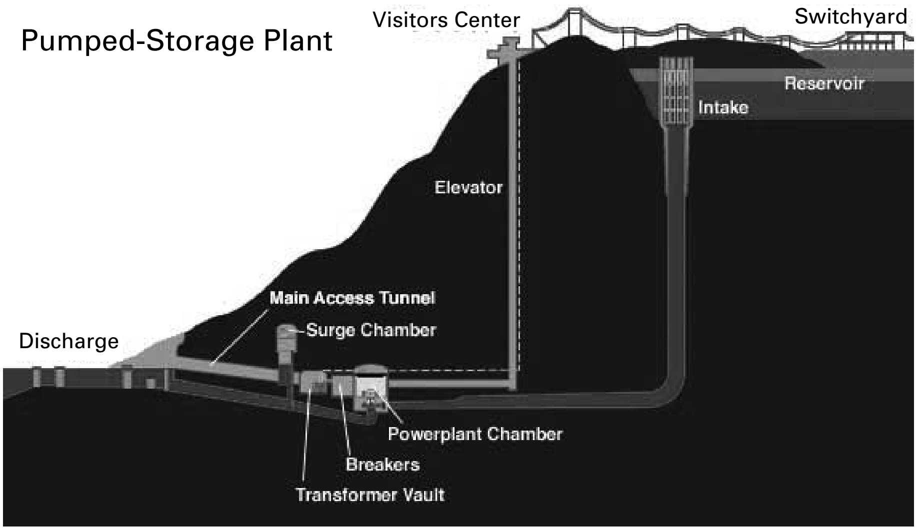

Figure 9-3. A Pumped-Storage Facility (courtesy of Tennessee Valley Authority)

The Raccoon Mountain Station is a large facility operated by the Tennessee Valley Authority near Chattanooga, Tenn[1]. TVA built a 230-foot-high dam on top of Raccoon Mountain to create a 528-acre reservoir. Water falls 990 feet when the facility is producing power. Electrical generation capacity is over 1,500 megawatts. Of course there are energy losses associated with pumping the water uphill, but the benefits outweigh this loss.

9.6 River Flow, Tidal Flow, and Ocean Current Energy Converters

Flowing water possesses kinetic energy that can be captured by a submerged turbine and transformed into electricity. These are called hydrokinetic or, for applications in rivers, run-of-river systems. The principle of operation is the same as for a wind turbine. The basic formula for the power that is possessed by flowing water is given by:

$$P = 1/2\rho A v^3 \qquad (9\text{-}4)$$

where

P = power possessed by flowing water
ρ = water mass density
A = the area swept by turbine blades, equal to πr^2
v = water velocity

Since the density of water is over 800 times the density of air, much greater power is produced for a given fluid velocity and turbine blade length. Of course, a turbine cannot capture all of the water's power. The theoretical maximum efficiency of power extraction from flowing water is 59 percent. This is the Lanchester-Betz-Joukowski limit, which also applies for wind turbines. Nevertheless, water turbines can capture a significant fraction of the stream power.

A formula for the power of a flowing water stream is obtained by substituting values for density and π into Equation 9-4 and converting units (in this case, foot pounds per second into watts). The result, as shown in Appendix P, is:

$$P(\text{watts}) = 4.13\, r^2 f^3 \qquad (9\text{-}5)$$

where

P = power in the water stream impinging on the turbine blades
r = radius of area swept by the turbine blades (feet)
f = water flow rate (feet per second)

Applying the Lanchester-Betz-Joukowski limit gives the maximum power that can be captured by the turbine:

$$P(\text{watts}) = 2.44 r^2 f^3 \qquad (9\text{-}6)$$

Example 9.2

A turbine with 10 foot blades in water flowing at 10 feet per second would have a maximum power extraction capability of:

$P_t = 2.44 \times 10^2 \times 10^3 = 244{,}000$ *watts or 244 kilowatts.*

Actual power production would be somewhat less because of losses in the turbine-generator.

Water currents that are potentially exploitable are river currents, tidal flows, and ocean currents. River current systems and tidal flow systems are similar except that tidal flow systems produce power that varies periodically with changes in flow rates and also reverses direction. Also, river systems are located in fresh water, and tidal systems are located in salty or brackish water, with an associated impact on selection of materials due to potential corrosion.

Huge ocean currents are tempting sources of useful power. To capture this power, systems must be designed that can operate far offshore, and reliable and practical transmission systems for delivering the energy to the shore must be made available.

Hydrokinetic power systems in navigable channels must be submerged deep enough to avoid interference with boats or ships that use the waterway. Consequently, submerged systems must usually use an array of small-diameter turbines rather than large units such as are used for wind energy.

As is true for any system that intrudes on an ecosystem, there is some concern about the effect of hydrokinetic systems on the aquatic habitat. Installations must result in little or no impact on fish and other aquatic creatures.

Suitable sites for hydrokinetic power systems are often very close to load centers, permitting power delivery without long transmission lines.

9.7 Wave Energy Converters

Wave energy converter devices all are installed at or near the surface of the water. Several types of converters are currently being developed:

- Terminator devices extend perpendicular to the direction of wave travel. One design is the oscillating water column device. It consists of a tethered cylinder whose bottom is open to the ocean. Air is trapped above the water column and is compressed when the water rises during wave cresting. The compressed air is released through a turbine to produce mechanical energy that drives an electrical generator.

- Point absorbers also extend perpendicular to the direction of wave travel. They consist of two concentric cylinders. The outer cylinder is moored and stationary. The inner cylinder floats and moves up and down with wave motion. If one of the cylinders houses a magnet and the other houses a conductor, then electricity is produced in the conductor as a result of the motion.

- Attenuators extend along the direction of wave travel. They are multi-segment floating structures, which bend at the interfaces between segments as waves pass. The bending can drive a pump, producing flow that can drive a turbine-generator.

- Overtopping systems consist of reservoirs that are filled by cresting waves. The wave height can be increased by using funnel-shaped channels leading to the reservoir. The water is released through an energy conversion mechanism such as a turbine-generator during wave troughing.

- Pendular devices consist of structures with hinged flaps that face incoming waves. The flaps swing back and forth with wave motion. This flap motion can drive a pump that moves fluid through an energy converter such as a turbine-generator.

- Elastic systems consist of an elastic hose that is tethered to the bottom and connected to a float. The up-and-down wave motion stretches and relaxes the hose, forcing up-and-down motion of water through the hose.

The diversity of these concepts suggests additional ingenious designs are under development or will evolve.

9.8 Tide Energy Converters

Tide energy converters are defined here as those that use the potential energy resulting from a change in water elevation caused by tides rather than the kinetic energy of tidal flows. The approach is to trap water in a reservoir at high tide, then release it through turbines at low tide. Of course, areas with large tides are preferred for tide energy converters. The ideal location is a bay having large tides and a passage to the open sea that is suitable for locating a dam (also called a *barrage*).

A tide energy system has been built on the Rance River near St. Malo, in France. It produces 240 megawatts of electricity.

Tide energy converters clearly can produce electrical energy in the few places in the world where conditions are right, but these systems inevitably affect the local aquatic ecosystem.

9.9 Hydroenergy, Environmental Effects, and Public Safety Concerns

Hydroenergy is often considered neutral with respect to environmental effects because it involves no release of pollutants or greenhouse gases. However, there are other environmental effects that warrant consideration. Some concerns are:

- Flooding large land areas when dams are built, thereby potentially eliminating farmland, relocating populations from affected areas and flooding historically significant regions.
- Changing the aquatic habitat, thereby affecting the survival of some aquatic creatures and eliminating traditional migration paths for some species.
- Reducing the natural transfer of silt to lower elevations, where it previously enhanced the fertility of the soil.

Of course, there are also effects that are considered beneficial in addition to the production of electricity. These include:

- Creating lakes with opportunities for recreation
- Controlling floods

The main safety concern related to hydropower from dams is dam failure. Dams are huge structures that appear to be permanent. However, experience shows that dams can fail, with catastrophic downstream consequences. Dam monitoring is crucial, and releasing impounded water must occur when dam integrity comes into question.

9.10 Hydroenergy and Load-Following

Electricity production must match electrical demand on the grid, and this matching must be very rapid. Hydropower systems based on falling water are well-suited for providing rapid load-following capability. Opening or closing a valve that admits water to a turbine causes an immediate change in the transfer of energy to the turbine and the generator. Thermal power plants can achieve changes in steam flow by valving, but changes in energy extraction must be matched shortly thereafter by changes in combustion rate or nuclear fission rate. Because of their superior load-following characteristics, hydropower from dams is often relied on for short-term matching of generation to demand.

9.11 Hydroenergy Contribution to Energy Needs

Electricity consumption in the U.S. is currently about 4 trillion kilowatt hours per year. Estimates of new hydroenergy potential capacity are very uncertain, but an estimate of around 400 billion kilowatt-hours per year (around 1.4 Quads of electricity per year) has been published[2]. This electrical energy includes 260 billion kilowatt-hours per year from waves, 19.6 billion kilowatt-hours per year from tidal currents and 110 billion kilowatt-hours per year from river currents. To date, little actual implementation of these newer, unconventional hydroenergy systems has occurred, but prototype systems are being tested as possible precursors to large, practical installations.

It should be noted that Canada has much greater hydroenergy potential (1,600 billion kilowatt-hours per year).

The estimates indicate new hydroenergy systems might provide around 10 percent of the 2010 electricity production level if fully developed in the U.S. This is a significant amount of energy (comparable to the energy available from forty large nuclear power plants), but hydroenergy alone cannot provide needed future increases in energy production.

References

1. Tennessee Valley Authority report, available at http://www.tva.gov/sites/raccoonmt.htm.

2. Bedard, R., et al. "North American Ocean Energy Status–March 2007" *Report to 7th European Wave and Tidal Energy Conference*, Porto, Portugal, September 2007. Available at http://oceanenergy.epri.com/attachments/ocean/reports/7th_EWTEC_Paper_FINAL_071707.pdf.

Exercises

9-1. A farmer has a creek on his property. He is considering installing a small hydroelectric system. He is considering the use of a penstock to collect water at a location 20 feet above the point of energy extraction and return of the water to the creek. The water flows in the creek at a rate of 20 cubic feet per second. How much electricity (watts) can he produce if half of the flow is diverted through the penstock and the mechanical to electrical conversion efficiency is 90 percent? How much is the electricity worth per day if the current price for electricity is 11 cents per kilowatt-hour?

9-2. Knox County, Tenn., has an area of 526 square miles and an average elevation of around 900 feet above sea level. It gets around 50 inches of rainfall per year. If half of this water flows through the rivers to the Gulf of Mexico, how much energy is released? Where does this energy come from?

9-3. The Gulf Stream is a massive stream of water flowing at around 30 million cubic feet per second in the Florida Straits. The flow rate is around 1 meter per second. How much energy (BTUs and kilowatt-hours) is contained in one cubic meter of this flowing water? How much power (megawatts and BTU per day) is contained in the whole stream? (Recall the kinetic energy is given by $KE = 1/2mv^2$. Power is the rate of energy flow or $P = 1/2(dm/dt)v^2$, where dm/dt is the mass flow rate.)

9-4. At New Orleans, the Mississippi River flows at an average rate of around 600,000 cubic feet per second. How much kinetic energy does the river possess if the speed of flow is 5 miles per hour?

9-5. Explain, in simple terms, why it is impossible to extract all the kinetic energy from flowing water.

9-6. Hoover Dam produces 2,080 electrical megawatts using water that drops 526 feet. Estimate the mass flow rate of water through the turbines. Assume a mechanical to electrical conversion efficiency of 90 percent.