Voge, E. B., B. J. S. Smith, S. Enedy, J. J. Beall, et al. 1994. Initial Findings of the Geysers Unit 18 Cooperative Injection Project. *Transactions—Geothermal Resources Council* 18:353–357.

Wallace, R. H., T. F. Kraemer, R. E. Taylor, and J. B. Wesselman. 1979. Assessment of Geopressured-geothermal Resources in the Northern Gulf of Mexico Basin. In Muffler and Guffanti, 1979, 132–155.

White, D. E. 1973. Characteristics of Geothermal Resources. In *Geothermal Energy*, ed. P. Kruger and C. Otte. Stanford, CA: Stanford University Press.

White, D. E., and D. L. Williams eds. 1975. Assessment of Geothermal Resources of the United States 1975. U.S. Geological Survey Circular 726.

Wright, P. M. 1995. The Sustainability of Production from Geothermal Sources. In *Proceedings of the World Geothermal Congress* (Florence, Italy, 1995), 4:2825–2836. Florence, Italy: International Geothermal Association.

Websites of Interest

Australian Geothermal Energy Association: http://www.agea.org.au/

Australian Government, Geoscience Australia: http://www.ga.gov.au/minerals/projects.html

Energy Resources Program, US Geological Services: http://energy.usgs.gov/OtherEnergy/Geothermal.aspx European Commission Research and Innovation: http://ec.europa.eu/research/energy/eu/research/geothermal/index_en.htm

Geothermal Energy Association: http://www.geo-energy.org/

Geothermal Resources Council: http://www.geothermal.org

Geothermal Technologies Program, US DOE: http://www1.eere.energy.gov/geothermal/

A Googol of Heat beneath Our Feet (Google): http://www.google.org/egs/

International Ground Source Heat Pump Association: http://www.igshpa.okstate.edu/

New Energy and Industrial Technology Development Organization: www.nedo.go.jp/english/index.html

Samorka—Islandic Energy and Utilities: http://www.samorka.is/page/federation

Hydropower 12

The waterfall, clear and transparent, precipitates itself into this ravine, sending up a cloud of spray, and then follows its tortuous course by a channel formed for it by Nature herself.

—Juan Valera, *Pepita Jiménez*

12.1 Overview of Hydropower

Hydropower is a renewable energy resource resulting from the stored energy in water that flows from a higher to a lower elevation under the influence of the earth's gravitational field. Ultimately, hydropower is connected to solar energy and the natural hydrologic cycle of evaporating water from lakes and oceans redeposited as rain or snow. Water flowing in rivers from upstream regions above sea level toward the oceans is continuously converting part of its potential energy into kinetic energy associated with the flow velocity. Such energy exchange creates opportunities for hydropower either by converting the stored potential energy contained by a dam structure—frequently called *impoundment hydropower*—or by extracting a portion of the total energy contained in flowing water itself—called *diversion* or *run-of-river hydropower*. There is also a third type of hydropower, referred to as *pumped storage*. During periods when electricity demand is low, electricity is used to pump water from a lower reservoir up to a higher elevation, where it is stored. When electricity demand increases, the flow is reversed, and electricity is produced as water passes from the higher storage reservoir back to the lower one.

In most installations today, hydro energy is converted to electricity by flowing water through turbines to produce rotating shaft work, which turns an electric generator. Technologies for carrying out this conversion are highly developed and efficient, with hydropower installations ranging in scale from a few kW_e to over 10,000 MW_e. For several centuries, hydropower had been used to produce mechanical power to perform a range of activities, including grain milling, textile processing, and other light industrial operations. In fact, a large fraction of the Industrial Revolution in the eighteenth century in Europe and the US was "fueled" by access to hydropower. For example, many industrial plants during that period were located on rivers, which provided both power production and transportation of goods. In early times, water wheels were commonly used for mechanical power production (see Reynolds, 1983). Even today, small-scale hydropower still plays an important role in remote regions of less developed countries such as China and India.

This chapter focuses on the conventional role that hydropower plays as a major supplier of electricity around the world. Hydropower now produces 20% of the world's electricity, with about 822,000 MW_e of generating capacity in operation in more than 150 countries in 2007. According to the US National Hydropower Association (2009), 110,000 MW_e of hydroelectric capacity exists in the US, of which 96,000 MW_e is conventional impoundment (about 10% of the US total installed nameplate power-generating capacity) and about 20,000 MW_e is associated with additional pumped storage installations. Hydropower was the major contributor to renewable electricity generation in the US during the twentieth century. Those conventional facilities are still operating, but there have been no recent major new additions—probably because the best hydropower sites have already been developed. In developed countries, hydropower can still be a major player. Switzerland, Canada, and Norway, as well as regions such as the Pacific Northwest of the US, all rely heavily on hydropower. In developing countries, hydropower can be even more important, supplying on average about one-third of their electricity needs with less than 10% of the total hydropower potential exploited. However, Venezuela, which generates about 70% of its power from hydroelectric plants, has found that overdependence on hydropower can cause problems when rainfall patterns change for extended periods (e.g., as with El Niño). Several years of low rainfall depleted the Guri reservoir and resulted in rolling blackouts in early 2010. Venezuela is now looking at additional nonhydropower additions to their electric supply.

Table 12.1
Representative Mega-Scale Hydropower Projects

Name	Location	Type	Capacity (MW_e)	Reservoir Size
Grand Coulee	Columbia River, Lake Roosevelt, Washington	Impoundment dam, 550 ft (168 m) high	6,480	9.4 million acre-ft[a]
Niagara Falls	Niagara River, New York	Diversion, run of river	1,950	nil
Hoover Dam	Colorado River, Lake Mead, Nevada	Impoundment dam, 726 ft (223 m) high	1,500	28.3 million acre-ft 146,000 acres
Norris Dam TVA	Tennessee River, Norris, Tennessee	Impoundment dam, 58 ft high, aerating turbines	65	1.1 million acre-ft 33,840 acres
Glen Canyon	Colorado River, Lake Powell, Arizona	Impoundment dam, 710 ft (216 m) high	1,500	27.0 million acre-ft
La Grande complex	St James Bay, Quebec and Labrador, Canada	Impoundment, multiple dams	10,000	9,600 km^2 or about 100 Quabbins[b]
Itaipu	Paraguay/Brazil	Impoundment dam, 190 m high	12,600	23.5 million acre-ft
Three Gorges	Yangtze River, China	Impoundment dam, 185 m high	22,400	32 million acre-ft
Guri	Venezuela	Impoundment dam, 162m high	10,300	112 million acre-ft[c]
Krasnoyarsk	Russia	Impoundment dam, 124m high	6,000	59 million acre-ft

[a] 1 acre-ft = 326,000 gal.
[b] 1 Quabbin = size of the major Massachusetts reservoir system (39 square miles surface area with 12,640 acre-ft = 4.12×10^9 gal of water contained).
[c] Supplies over 70% of Venezuela's electricity. Drought and low water levels resulted in rolling blackouts during January 2010.

Hydropower installations have a reputation of being robust and durable, often operating successfully at specific sites for more than a century. Plants can be large. In fact, the 10 largest electric power stations in the world today are hydroelectric (see table 12.1 for representative examples), and substantial hydropower potential remains undeveloped worldwide. In the US, only 3% of existing dams have associated hydroelectric plants. While many of these dams are not commercially suited to electricity generation, some may merit development in the future on a regional basis, as the pairing of dispatchable hydropower (i.e., with the flexibility to modulate power generation to meet fluctuations in demand) or pumped storage with variable renewable sources, such as solar and wind, offers additional economic benefits.

Hydropower reservoirs on large rivers also can be used as part of regional flood-control plans. This is an added benefit, but requires reservoirs that are large enough for a dual purpose. For example, in 2010 unusually heavy rains upstream of the Three Gorges dam in China filled the impoundment reservoir to its maximum planned capacity. Although additional flooding was avoided, this incident shows that regional climate changes can have serious effects on hydropower installations when rainfall is excessive, as well as when it is greatly reduced, as occurred in Venezuela in the same year.

The key environmental issues involving hydropower center on impacts on fish migration, water quality, land inundation, downstream river flow patterns, and aquatic ecology. As discussed in chapters 7 and 10, land use change also may entail significant changes in GHG emissions; flooding biomass-covered land to create reservoirs usually entails increases in methane release. Although existing and new hydropower developments have come under attack in many countries during the last several decades, hydropower is important as a major, renewable, and potentially low-greenhouse-gas-emitting energy source. It can also be an economic and political force in many countries. The multiple uses of hydropower for electricity, water supply, agricultural irrigation, flood control, and recreation are important from a sustainability perspective. A recent special report on renewable energy sources and climate change mitigation devotes a detailed chapter to hydropower technologies (IPCC, 2011).

12.2 Hydropower Resource Assessment

The future growth potential of hydropower will be influenced by the environmental concerns mentioned above, the availability of suitable land areas, and other constraints on water supplies due to possible climatic changes and increased human consumption, especially for agriculture. Nonetheless, the unexploited potential for hydropower is significant. For example, in 2001 the World Energy Council estimated the gross theoretical potential to be about 40,000 TWh/year, of which 9,000 TWh/year was technically and economically feasible. This is about the 2010 world hydropower production level of 775.6 MTOE or 9,150 TWh/yr (BP, 2011). The increase in annual hydropower production from 2001 to 2010 was about 2,200 TWh. Without doubt, hydropower is strategically important worldwide. (Table 12.2 provides a regional breakdown of current capacity.)

Currently, further development of hydropower resources is limited in many countries by available capital for construction of dams and turbine-generator stations and by environmental concerns. For hydropower to grow measurably in the twenty-first century, significant national financial investments will have to be made in the face of more economically and environmentally attractive energy options. A key issue to keep in mind is that generating electricity is not the sole reason for building a dam. Broader water management concerns often dominate policy decisions. These may include flood control, water supplies to meet agricultural irrigation needs, or even recreational considerations.

Table 12.2
Global Hydropower Capacity and Investment Estimates

North America 660,761 GWh/yr	Europe 693,187 GWh/yr
South America 650,643 GWh/yr	Asia 891,024 GWh/yr
Africa 95,552 GWh/yr	Australia 41,862 GWh/yr

Sources: ICOLD (2011); World Commission on Dams (2002).
Notes: 1,560 North American plants (5,000 units); 13,000 international plants (42,000 units); world total capacity = 822,000 MW_e; world total output = 2,999,000 GWh/yr; world total investment = approx. US$2 trillion, or annualized to $50 billion/yr.

Although Canada and the US were formerly the largest producers of hydropower, China and Brazil are passing them, and other developing countries are expanding their capacity (see table 12.3). Even though hydropower installations in developed OECD countries are mature, with higher-grade resources already exploited, there still is considerable growth potential. For example, consider the expansions that occurred in the US from 1945 to 1990 under the auspices of the Bonneville Power Administration and the Tennessee Valley Authority. The gigantic Grand Coulee Dam in eastern Washington had its generating capacity increased by over 2,000 MW_e in the 1980s to its 2010 level of 6,809 MW_e.

With newer, more environmentally friendly technologies and proper policy incentives, expanding, repowering, and upgrading turbine generators at existing dams could significantly increase capacity. For example, there is the potential to install 35,000 to 70,000 MW_e of new capacity in the US alone using existing dam structures and reservoirs. Only 3% of the nation's dams presently generate electricity. The many small dams are mostly used for irrigation or the production of mechanical work (in a small mill, for example). By developing "small hydro" at presently non-powered dams, about an additional 60,000 MWe capacity might be added by 2025 (US National Hydropower Association, 2009). If run-of-river technologies become feasible, the potential for expanding US capacity is still higher (see section 12.3).

As we move from country to country and from region to region, one notes large differences in the relative importance of hydropower as a producer of primary electricity (see table 12.4). For example, in Norway, Switzerland, Austria, and Brazil, 80–100% of electricity comes from hydropower, while in the US and China, it is about 10% or less. In South America, about 75% of the continent's electric power is supplied by hydropower dams. The major national players are Brazil, Argentina, Paraguay, Colombia, Peru, and Venezuela, with Chile and others not far behind. Large increases in capacity are currently under construction or planned for the near future in South America (e.g., for Brazil [53,000–94,000 MW_e], Argentina [8,750–12,000 MW_e], and Venezuela [12,200–27,600 MW_e]).

Table 12.3
Hydropower Capacity Estimates by Continent, Based on Large-Dam Technology

Continent	Capacity in 2008		Maximum Theoretical Potential	Technically Possible	Economically Possible
	GW_e	TWh/yr	TWh/yr	TWh/yr	TWh/yr
North America	220	639	6,150	2,700	>1,500
(US)	(141)				
South America	159	660	7,400	3,000	>2,000
(Brazil)	(86)				
Africa	25	97	10,120	1,150	>200
Middle East	12				
Europe	294	628	5,000	2,500	>1,000
Asia	361	935	16,500	5,000	>2,500
(China)	(187)				
Oceania[a]	20	38	1,000	300	>100
World total	1,160	2,999	46,170	14,650	>7,300

Sources: EIA (2009); World Energy Council (2001); ICOLD (2001); World Commission on Dams (2002); Moreira and Poole (1993).
[a] Includes Australia and New Zealand.

Table 12.4
Potential for Hydropower Development in Selected Countries Based on Technical Potential and Economic Potential in Today's (2009) Energy Markets

Country	Hydro as % of Total Electricity	Ratio of Theoretical Potential to Actual	Ratio of Economic Potential to Actual
Norway	99	5.8	1.8
Brazil	83.9	5.4	3.0
Switzerland	56	—	1.1
Canada	59	3.8	1.5
India	17.5	4.2	3.0
France	8	1.1	1.0
China	15.5	10	6.6
Indonesia	7	30	3.13
United States	7	1.8	1.3
World total	15.9	18	2.78

Sources: IPCC (2011); IJHD (2010).

Capacity increases in China are not as well documented, except for large projects like the Three Gorges Dam complex that has reached a 2011 installed capacity of 22,500 MW_e. In 2003, although only 1,855 dams were officially listed for China in the *World Register of Large Dams*, other sources had estimated that an additional 22,000 nonregistered dams existed in China (Economist, 2003). By 2011, the *Register* listed 5,191 large dams in China, and other sources suggest the existence of as many as 80,000 dams of all types. China also is involved in building over 200 large dams worldwide, some of which cause local concerns about environmental impacts and political issues of water rights (Biello, 2009). In 2011, the US had the most large dams (9,265), with India (5,101) and Japan (3,076) following China, and with Korea, Canada, South Africa, and Spain each having about a thousand dams (ICOLD, 2011; World Commission on Dams, 2002). If a significant fraction of China's existing dams are equipped with turbines, then its hydropower capacity could increase markedly.

One of the strong attributes of hydropower is the dispatchability that results from the system's ability to store energy in the water contained behind a dam or by periodically pumping water into a temporary storage reservoir. Given the general increase in electrification that is occurring worldwide, the demand for using hydropower reservoirs for both baseload and peaking applications is rising. The storage capacity for pumped energy is likely to grow as well. For example, in 1950 the US had less than 5,000 MW_e of pumped storage capacity; today, there is over 20,000 MW_e. Worldwide, pumped storage capacity now exceeds 120,000 MW_e, with about 30% in Europe, 20% in Japan, and 20% in the US (extrapolated from Moreira and Poole, 1993; Ingram, 2010). In the long term, other factors may also lead to increased interest in hydropower. The variable nature of renewable energy sources, like wind and solar, make pairing with hydro energy storage an attractive option for integrated supply systems.

12.3 Basic Energy Conversion Principles

The primary energy sources for hydropower are solar and gravitational. The overall process is tied to the natural hydrologic cycle of evaporation and condensation in the earth's atmosphere, which redistributes water from lower elevations (sea level in the oceans) to higher elevations on land. This redistribution increases the potential energy of the water, which then flows in rivers back to the ocean under the influence of gravity. Given the intermittent nature of rain and snowfall, the amount of water stored or flowing at any time varies diurnally and seasonally. The change in potential energy that occurs as water makes its way back to the ocean provides an opportunity to extract a portion of that energy in the form of hydropower. In principle, hydro energy can be produced from any change in water elevation, but for practical purposes, changes due to tidal flows, ocean waves, or currents are classified differently (see chapter 14).

In today's hydropower applications, changes in both potential and kinetic energy of the flowing water are used to generate mechanical power to drive a generator to produce electric power. Before 1900, direct mechanical power applications were prevalent for a number of industries, including weaving, fiber spinning, and grain grinding. With subsequent availability of fossil fuels and the development of electricity as an energy carrier, interest in large-scale hydropower facilities and dams grew rapidly. Smaller dams and water systems remained important for irrigation and localized uses.

While all hydro resources differ in some detail, hydroelectric plants have many common components. For instance, water is brought to a hydro plant via a conduit, called a penstock, then enters an energy converter or turbine generator, and is discharged to the river in a tailrace. (Figure 12.1 schematically illustrates these components in a conventional impoundment or dam structure.) The range of power generation capacity for hydro systems is enormous, varying by over seven orders of magnitude from 1 to 100 kW$_e$ for micro hydro systems, from 0.1 to 30 MW$_e$ for small hydro systems, and up to 12,000 MW$_e$ for large or mega-sized installations.

The main device used to capture hydro energy is the hydraulic turbine, which produces rotating shaft work that powers the electric generator. Although there are

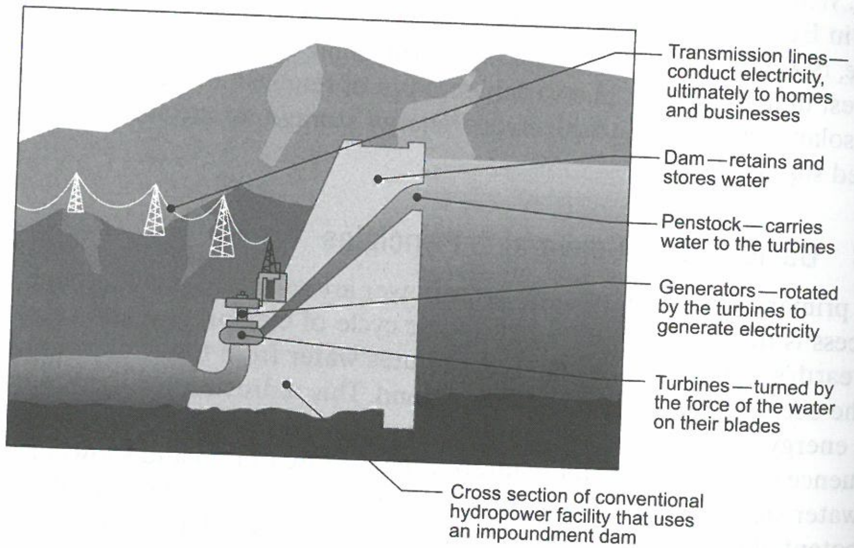

Figure 12.1
Schematic of a typical impoundment type hydropower installation. Source: INEEL (2003).

many types of hydraulic turbines, their basic approach is similar. They use a change in potential energy to increase fluid pressure and/or velocity (kinetic energy) and then deposit a portion of this hydraulic or kinetic energy on a turbine bucket to rotate a centrally located shaft. Thus, as fluid passes through the turbine, the change in its potential energy is continuously converted to mechanical power. The step to electric power is straightforward and achieved by connecting the rotating shaft from the hydraulic turbine to an electric generator. The hydro generator operates in a manner similar to those used in fossil-fired, gas turbine or steam, or even wind-power applications. Hydro machines tend to be larger and slower in rotation speed than vapor or gas turboexpanders, and may be oriented vertically or horizontally.

The overall power that can be extracted from any device will depend on the available potential and kinetic energy, as reflected by the magnitude of the total (static plus dynamic) hydraulic head and the conversion efficiency of this particular combination of hydraulic turbine/device and electric generator. Power output can be represented by a simple formula:

$$\begin{aligned} Power &= (\textit{total hydraulic head}) \times (\textit{volumetric flowrate}) \times (\textit{efficiency}) \\ Power &= [\rho g Z + \tfrac{1}{2}\,\rho \Delta(v^2)] \times Q \times \varepsilon \end{aligned} \quad . \qquad (12.1)$$

The first term in parentheses on the right-hand side contains the contributions of the static head, ρgZ, and the dynamic head, $\tfrac{1}{2}\rho\Delta(v^2)$, in units of kg/ms^2. Q is the volumetric flow rate in units of m^3/s, Z is the net height of the water head in m, ρ is density of water in kg/m^3, g is the acceleration of gravity 9.8 m/s^2, and $\Delta(v^2)$ is the difference in the square of the inlet and exiting fluid velocity across the energy converter. (Note that $v = Q/A$ where A is the cross-sectional area of the energy converter that is open to flow.) For hydro installations that are impoundment structures with the static head providing the energy, the dynamic head, given by the $\tfrac{1}{2}\rho\Delta(v^2)$ term, is effectively zero. For a low-head, run-of-river system, the dynamic head could be comparable to or greater than the static head, ρgZ.

The efficiency of the conversion process is represented by the term $\varepsilon < 1.0$, which captures the losses that occur due to friction and other dissipative effects. Using state-of-the-art technology, turbine-generator efficiencies can approach 0.9 for large-flow machines. Older, poorly serviced plants or smaller (micro) installations typically have lower efficiencies in the range of 0.6–0.8 or less.

By using a representative value of 1,000 kg/m^3 or 62.4 lb/ft^3 for the density of water in an impoundment hydropower application where there is no dynamic velocity head effect, we can simplify equation (12.1) to:

$$Power = 9.81 \times 10^{3}\, ZQ\varepsilon \text{ in watts} = 9.81 \times 10^{-3}\, ZQ\varepsilon \text{ in MWe} \qquad (12.2)$$

where metric units are used for both Z and Q. We see immediately that the power generated is directly proportional to the head and the volumetric flow rate. For example, consider a hydropower dam with a static head of 100 m and a volumetric flow rate of 1000 m^3/s through the hydraulic turbine with an efficiency of 0.8. By using equation (12.2), the power generated is 785 MW_e. If the head were increased to 1,000 m, then a flow rate of only 100 m^3/s would be required to achieve the same power output.

To understand the scale of mega-sized hydro projects, let's take a look at the Grand Coulee hydropower complex, which is the largest in the US. According to table 12.1, its output is 6,480 MW_e and the dam height is 168 m. Assuming $\varepsilon = 0.8$ and $Z = 160$ m, then the required flow rate is 5,160 m^3/s or 182,000 ft^3/s.

12.4 Conversion Equipment and Civil Engineering Operations

12.4.1 Civil engineering aspects of dam construction and waterway management

The natural conditions that exist at each site, including surface topography, river flows, water quality, and annual rainfall and snowfall cycles, determine the particular design selected for a hydropower installation. When suitable hydraulic heads are not present, dams are constructed across rivers to store water and create the hydraulic head needed to drive the turbomachinery. Dams are typically designed to last for 50 to 100 years and, as such, are constructed of durable materials, such as reinforced concrete, earth, and crushed rock. They vary substantially in terms of height and storage volume, depending on the local topography. There are several design approaches that are used for concrete dams, including solid and hollow, gravity and arch geometries. On a life-cycle basis, the CO_2 emissions associated with the production of concrete for dams should be considered (see section 19.4). Many of the largest disasters associated with energy systems and their infrastructure have been caused by dam failure. In reaction to these failures, construction methods and materials have been improved and new technology has been developed for diagnostic testing; consequently, the reliability and integrity of dam structures have improved markedly during the past century to keep pace with public concerns. Advancements have included roller-compacted concrete for improved performance, easier construction, and lower costs, and the use of polymeric materials for waterproof liners (Moreira and Poole, 1993).

In addition to the actual dam structure, there are a number of other major design considerations. For example, the turbine inlet manifold, or penstock, which usually includes screens to keep debris and fish from entering the turbine, as well as the discharge or tailrace system, must be designed to maintain the hydraulic head and minimize the effects of sedimentation and silt buildup. Figure 12.2 illustrates a common arrangement of these features.

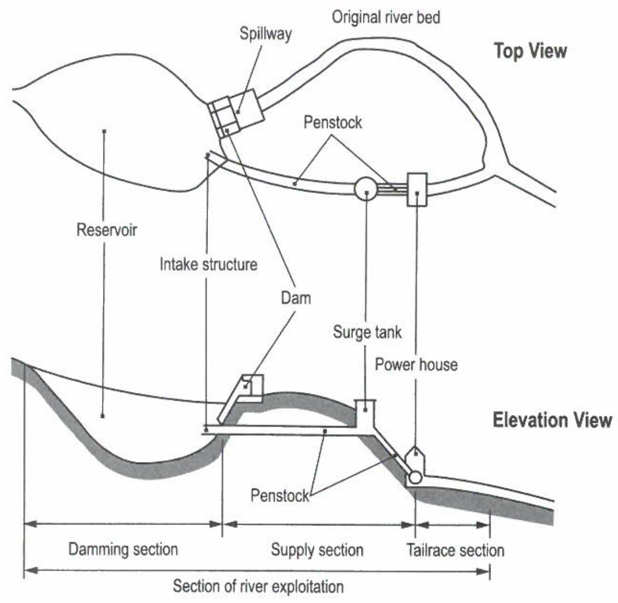

Figure 12.2
The characteristic components of a river-diversion hydroelectric plant. Adapted from Raabe (1985). From *Renewable Energy* by Laurie Burnham et al., eds. © 1993 Island Press. Reproduced by permission of Island Press, Washington, DC.

12.4.2 Turbines as energy converters

Conventional hydraulic turbines are typically categorized as either *impulse* or *reaction* machines. Impulse or Pelton-type turbines convert the fluid's potential energy change (hydraulic head) into kinetic energy (fluid velocity) by expansion in a stationary nozzle to form a jet, which is then directed toward buckets attached to a rotating turbine wheel to create extractable rotating shaft work. Francis and Kaplan turbines are reaction machines that utilize both hydraulic pressure and kinetic energy to create rotating shaft work. As we can see from figure 12.3, each turbine type has a specific operating range in terms of hydraulic head, volumetric flow, and/or power output. Given that there is some overlap among turbine types, choices are made depending on site characteristics and unit costs.

Pelton turbines may have single or multiple nozzles that accelerate flow to produce high-velocity jets that impinge on a set of rotating turbine buckets to transfer their kinetic energy. Mechanical torque from the rotation of the wheel is transmitted directly to an electric generator. In contrast to a reaction turbine, the fluid contained in the impulse machine does not completely fill all available void space, and the turbine wheel operates at ambient pressure.

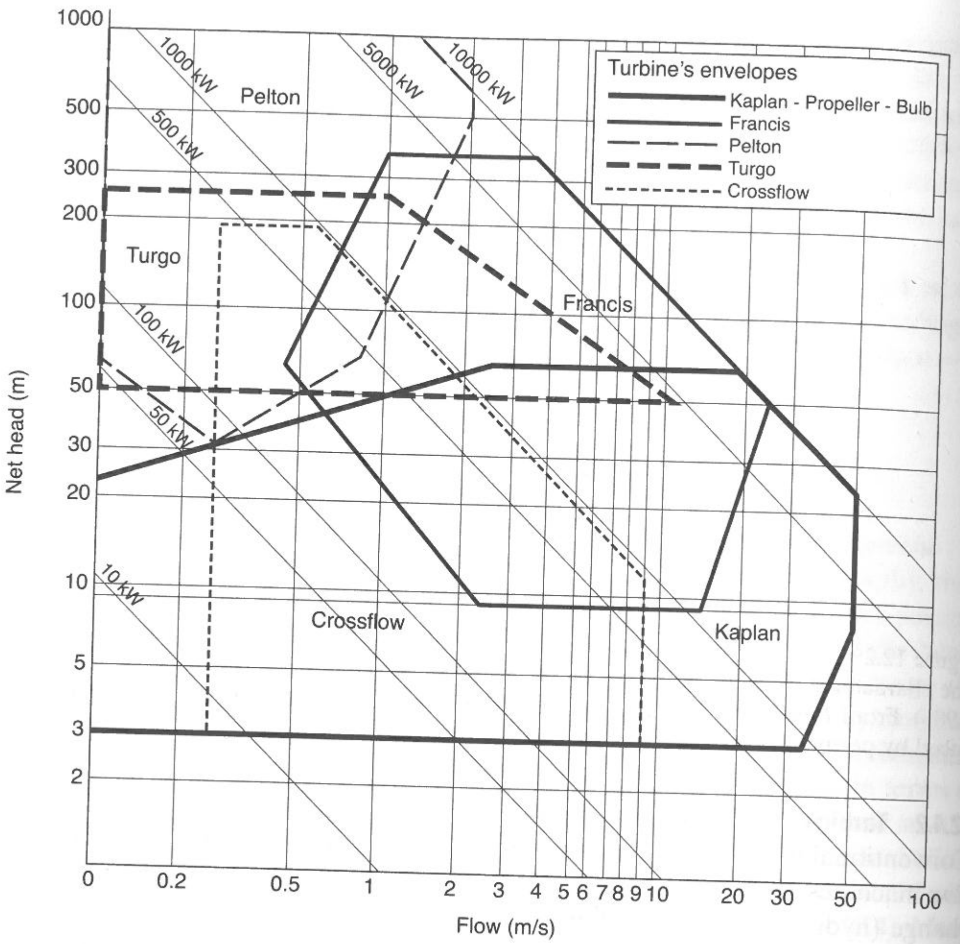

Figure 12.3
Practical operating regions for Pelton, Francis, Kaplan, and other hydro turbines. Source: Author-generated, J. W. Tester, 2010.

Although Pelton wheel devices were commonly deployed in the early days of hydropower, their lower efficiencies at low hydraulic heads in comparison to reaction machines made them less attractive. Nonetheless, Pelton turbines are ideally suited for high-head resources (200 m) and are typically used for smaller power outputs (<50 MW_e). Figure 12.3 shows that operating Pelton wheel plants can be as large as 300 MW_e.

Reaction turbines convert a portion of the hydraulic head to fluid kinetic energy by expansion through a stationary nozzle impinging on the rotating turbine buckets, while the remainder is converted to kinetic energy within the runner structure of the rotating turbine blades themselves. When fluid enters the device, it fills all void passages. Operating at pressures above atmospheric, the dynamic forces created by the processes of fluid acceleration and impingement on a set of turbine blades lead to a net torque on the turbine shaft, which translates to rotational power.

The Francis turbine utilizes a set of fixed vanes that guide the fluid to the buckets that make up the turbine runner and are mounted on a central shaft (see figure 12.4). Note that water enters the machine radially, perpendicular to the rotating shaft, and it exits the machine axially, parallel to the shaft. Francis turbines have a large optimal operating range, with heads from about 40–500 m and unit sizes approaching 1,000 MW_e.

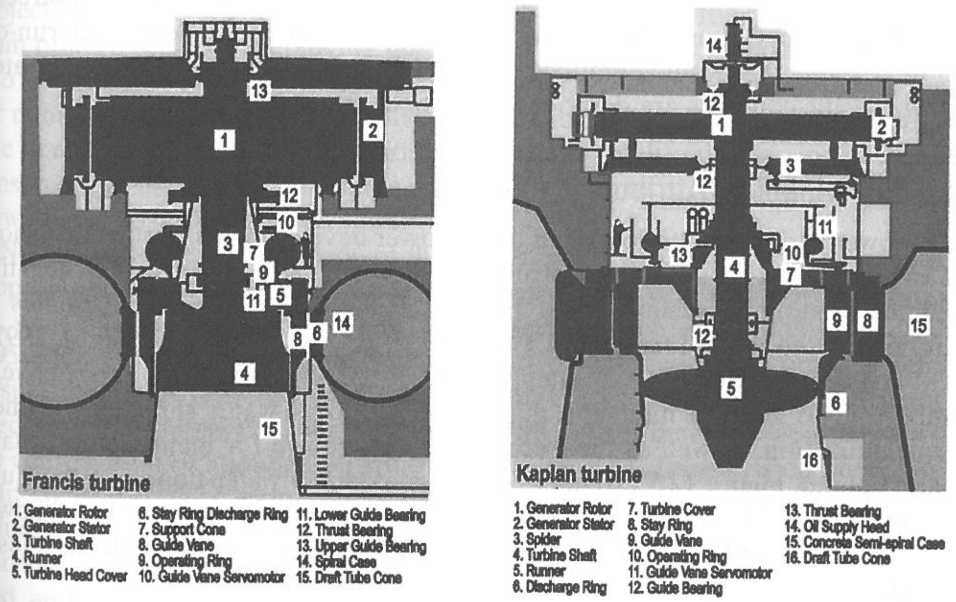

Figure 12.4
Francis and Kaplan hydroturbine schematics. Source: Franke et al. (1997).

Kaplan turbines have many features similar to those of Francis turbines, but as seen in figure 12.4, the turbine blade angle can be adjusted to improve performance under different flow conditions. Kaplan machines work well at low heads, from less than 10 m to about 100 m with power outputs up to 200 MW_e or more.

Hydroturbine development has had a long, rich history, spanning over a century. This has led to the evolution of designs that have been focused on rotary energy converter concepts that operate at high efficiency and are durable. For example, James Francis built his first water wheel turbine in 1849 with many of the basic features of today's designs, including a fully flooded chamber with adjustable blades. The Niagara Falls project, which began in the late 1880s, introduced hydropower for providing large amounts of baseload electricity using rotary turbine-generators with a high-head, diversion resource. This established a landmark precedent for future development.

As a consequence, hydroturbine technology has evolved to require hydraulic heads from 10 m to over 300 m, and has led to dam construction on rivers where nature does not provide such a resource as exists at Niagara Falls. The resulting impoundment of water, while providing useful seasonal storage, can lead to substantial inundation if the local topography is relatively flat, as well as a number of other environmental problems (see section 12.5).

Alternative approaches to conventional hydraulic turbines are being developed in which the kinetic energy of a flowing stream or river may be converted directly to mechanical shaft work. Such designs could lead to practical low-head, run-of-river technology that would eliminate the need to impound large volumes of water. (A few specific concepts are described in section 12.6.)

12.5 Sustainability Attributes

Hydropower and the multiple uses of hydropower developments, particularly those that involve mega-scale dam construction, illustrate both positive and negative attributes relating to sustainability. Table 12.5 outlines the major attributes of hydropower (see also Moreira and Poole, 1993; Brower, 1991; Economist, 1997a, 2003). The central issue is water management. From a sustainability perspective, it is important to keep in mind the magnitude of global water supplies and their current utilization, as well as their ecological importance for maintaining aquatic life and habitat. Figure 12.5 provides estimates of global water flows and their use. As a renewable resource that, in many settings, is emissions-free, hydropower should be considered for its role in displacing our dependence on depletable fossil fuels and in reducing the emission of greenhouse gases such as CO_2.

Many also argue that the construction project itself can improve the local economy of developing regions. This view appears in the political dogma of the

Table 12.5
Major Attributes of Hydropower

Positive	Negative
Emissions-free operation, with virtually no CO_2, NO_x, SO_x, hydrocarbons, or particulates	Frequently involves impoundment of large amounts of water with loss of habitat due to land inundation
Renewable resource with high conversion efficiency to electricity (>80%)	If not properly designed and constructed can lead to silt buildup with shortened lifetime and/or reduced productivity
Dispatchable with storage capability	Some GHG emissions from concrete used in dam construction and from land inundation
Usable for base load, peaking, and pumped storage applications	Variable output—dependent on annual rainfall and snowfall
Scalable from 10 kW_e to 10,000 MW_e	Impacts on river flows and aquatic ecology, including fish migration and oxygen depletion
Low operating and maintenance costs	Social impacts of displacing indigenous people
Long lifetime (50 years typical)	Health impacts in developing countries
Multiuse dams often provide flood control and stored water for agricultural irrigation and managed water supplies	High initial capital costs
	Long lead time in construction of mega-sized projects
	Impacts natural downstream water flows and availability

massive Three Gorges project in China and other mega-scale projects in India or South America. Think back to what happened in the 1930s with the Hoover Dam project in Nevada. The US was in a deep depression, and projects like the Hoover Dam offered relief by employing hundreds of construction workers. The dam was also viewed as a sustainable means of providing reliable, low-cost electric power for millions of people. Other positive elements of hydropower dams include their role in mitigating floods and in storing water for agricultural irrigation and human consumption. In addition, providing opportunities for recreational activities is often viewed as a positive factor.

Nonetheless, the negative side of the ledger is full, with public resistance to both proposed and existing hydropower installations. Issues center on the environmental, social, and health impacts (see, for example, Rosenberg, Bodaly, and Usher, 1995; Biello, 2009). In addition, because many mega-sized hydro projects need to be sited where the resource exists, long-distance electric transmission lines are often needed. For example, the James Bay–Churchill Falls project in Canada has led to the construction of about 8,000 km of high-voltage AC transmission lines.

In some instances, induced seismic risks are large and can lead to structural failure of the dam that impacts surrounding communities. Effects associated with land inundation include displacement of indigenous people, loss of agricultural land, and, in some cases, the production of greenhouse gases (both CO_2 and CH_4) from decaying organic matter submerged by the inundation (see, for example,

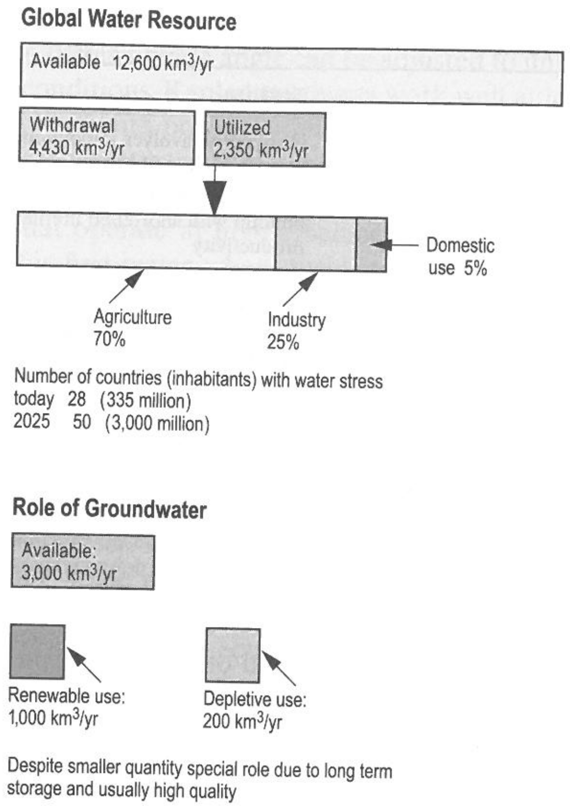

Figure 12.5
Global water supply and utilization. Adapted from AGS/ETHZ (1998). Note: This can be compared to figure 7.3, which shows total US water withdrawals of about 410 billion gallons per day. (For comparison, global withdrawals of 4,430 km^3/yr amount to about 3,200 billion gallons per day.)

Gardner and Perry, 1995; Lei, 1998; Grossman and Shulman, 1990). Dams upset the natural flow of rivers and streams and have an impact on aquatic ecology and biodiversity, including altering normal flooding cycles and impeding fish migration (a major issue in the US). The scale of land inundation can also be massive. Consider again the James Bay–Churchill Falls project, where Phase 1 of the La Grande development has flooded over 9,600 km^2 of boreal forest (Rosenberg, Bodaly, and Usher, 1995), largely a result of the minimal topological relief in that region. As a consequence, dams may reduce or remove habitats of indigenous plants and animals that depend on natural river flows, and they may compromise water quality in general. For example, mercury contamination of fish has been attributed to hydropower reservoir formation (Rosenberg, Bodaly, and Usher, 1995).

While these effects are clearly present, quantifying their impacts and environmental costs is often difficult and mired in tradeoffs that are based more on qualitative values or perceived impacts than substantive facts. To frame the debate with all of the environmental, ecological, and social elements included, we must consider the views both of those who think creating a large water body behind a dam offers highest societal value and of proponents of sustaining our wild rivers and natural habitats.

Erosion and sedimentation effects are often present at hydropower developments. If not controlled properly in river systems that contain large quantities of suspended matter, rapid silting out can occur and greatly reduce the effective head and power output of a project. In addition, water diversion in hydropower dams disrupts the flow of nutrients contained in the sediment downstream. The oxygen content of waters contained behind dam structures is often lower than normal; such oxygen depletion may have a detrimental effect on native fish and other wildlife. These large stagnant bodies of water can become breeding grounds for bacterial and viral infections, which, particularly in developing countries, can pose significant health risks. For instance, the appearance of malaria, lymphatic filariasis, and schistosomiasis are frequently associated with hydro development projects where large quantities of water are impounded in warm climatic regions (Moreira and Poole, 1993).

The problem of fish migration has been particularly polarizing in the western US, where salmon migration on major rivers, such as the Columbia, has been threatened (PCAST, 1997; Economist, 1997b; Odeh, 1999). While the migration of adult salmon upstream to spawn can be achieved using well-designed fish ladders and similar concepts, the newborn young salmon fry have a high mortality rate during their migration downstream when they pass through the hydraulic turbines. A modest amount of research is under way in the US to understand what is causing the problem and to develop more "fish-friendly" turbine technologies (see section 12.6.3 for more details). Without such technologies, the current approach has been to divert a portion of the flow around the turbine. While this diversion technique saves a few migrating salmon fry, it also de-rates the power output of the plant, thereby diminishing its value as a renewable energy resource.

Environmental concerns have led to flow de-rating and other systemic changes aimed at mitigation, as regulated by the US Federal Energy Regulatory Commission (FERC) in their relicensing of existing hydro facilities. These concerns often lead to long delays in approving new hydropower facilities. On average, the US is experiencing an 8% decline in hydropower generation for relicensed facilities, mainly as a result of regulated stream flows. To maintain existing US hydropower capacity, let alone increase it in response to national objectives for more renewable energy, a better quantitative understanding of environmental, social, and ecological effects and tradeoffs, as well as the development of new, more environmentally friendly technologies for hydropower, are essential.

12.6 Status of Hydropower Technology Today

12.6.1 Economic issues

At least US$2 trillion has been spent on hydropower developments worldwide during the last century (World Commission on Dams, 2002). This expenditure has created over 635,000 MW_e of capacity and contributed roughly 19% of the world's total generation of electricity (see figure 12.6). In many instances, hydro provides the lowest cost option for generating electric power in a given area. Furthermore, its dispatchable characteristic makes hydropower an important component for meeting peak and seasonal loads in the generation mix of a particular company or utility and for balancing increasing amounts of variable wind and solar power inputs.

Based on US DOE/EIA statistics, hydropower's annual revenues in the US are in excess of $25 billion for an estimated capital investment of $150 billion (INEL, 2007). As a renewable asset, its value in displacing carbon dioxide emissions and reducing dependence on depletable fossil resources is significant. Given the maturity of the technology, the costs for hydropower correlate with the age of the facility and the environmental concerns, which continue to grow.

Hydropower costs vary considerably, depending on the extent of civil engineering work required, which in turn depends on the natural terrain and climate of the

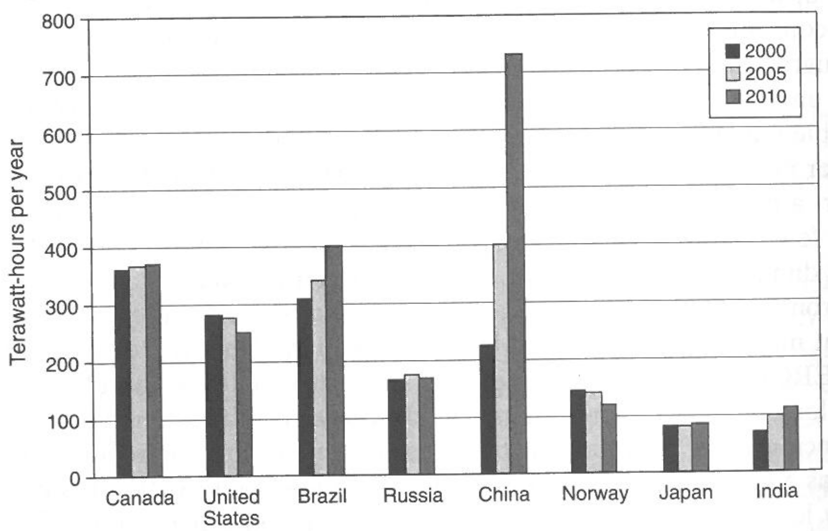

Figure 12.6
World's leading producers of hydropower. Source: BP (2011). Note: BP uses a 38% efficiency in converting MTOE to TWh.

region. Compare, for example, placing a hydro plant in the Alps of Europe with significant mountainous relief to placing one in the flatter, dryer regions of the US Midwest. As there can be large seasonal variations in available water (by factors of two to ten), the effects that needed reserve capacity has on reservoir and dam structure can be large. Furthermore, there can be significant economies of scale for the energy conversion equipment and effects of different capacity or availability factors.

Another aspect that makes hydropower different from other energy sources in economic terms is its low maintenance costs and long lifetimes—50 or more years is typical, and many systems are approaching 100 years. Most of the mega-scale hydropower projects that were developed in the US between 1930 and 1970 during a period of rapid expansion under the auspices of the TVA, BPA, BLM, the US Army Corps of Engineers, and other government agencies, still produce power today. The busbar costs for these mature installations are in the 1–2¢/kWh range, which represents mostly operating and maintenance costs since the initial capital investment was paid off during the first 20 years of operation at most. For new installations, the situation is completely reversed, as projects are capital-intensive. The larger the hydro project is, the more time it takes to plan and build, thus increasing the impact of invested capital before any revenues from power sales appear.

We estimate a range of about $1,000 to $2,500 per installed kW_e of capacity for larger new plants (>250 MW_e), while smaller-sized plants would be proportionally more costly. For plants <20 MW_e, costs might range from $4,000 to $6,500/$kW_e$, and for those between 20 and 250 MW_e, from $2,000 to $4,000/$kW_e$. With these ranges of capital investments and the other risks of hydropower projects in developing countries, agencies like the World Bank and the Inter-American Development Bank provide financial sponsorship only after careful analysis of risks and benefits. Externalities are playing a larger role in determining the feasibility of sponsoring hydro projects, as environmental and social impacts are factored into the total project cost.

In the US, the DOE/EIA estimates capital costs for an average-size hydro installation of 31MW_e as ranging from $1,700 to $2,300/$kW_e$—annualized to about 1.8¢/kWh, operating and maintenance costs of about 0.8¢/kWh, for a total levelized generating cost of about 2.6¢/kWh, assuming a plant lifetime of 50 or more years and a 40–50% capacity factor (INEL, 2007).

12.6.2 Potential for growth

Although hydropower is currently the largest and most important producer of electricity from a renewable energy source, with over 800 GW_e of capacity and 3,000 TWh produced annually, its future role is less certain for the long term. While the potential for adding additional hydropower worldwide is substantial in terms of availability and reasonable capital investment (7,300 TWh/yr or more), environmental concerns, particularly those associated with mega-scale projects that involve dams and their subsequent land inundation, pose substantial barriers to deployment and growth of hydropower as a renewable resource. In addition, changes in rainfall patterns in certain regions due to climatic changes could have large impacts on the hydropower generation for existing installations.

There are also barriers to the possibility of expanding hydropower capacity by utilization of existing dams in countries that already have developed substantial hydro assets. For example, a number of studies from credible sources such as FERC and the US DOE estimate that the US has the potential to expand its hydro capacity by 30,000 to 73,000 MW_e, using currently available technology and with reasonable financial investments on a $\$/kW_e$ basis. Yet when environmental issues such as fish migration and river ecosystem health are debated in the current licensing process, the FERC regulatory machinery usually imposes long delays or flow and power reductions, or rejects proposals outright. Decisions regarding extension or expansion of hydropower capacity often do not consider the environmental tradeoffs also involved with power generation from other sources such as coal or natural gas. The result is that many informed groups, including advocates for hydropower like the National Hydropower Association, predict that no new US hydro capacity will be added unless policies are changed.

An approach that could change these trends would be to develop improved quantitative understanding of the environmental and ecological impacts of hydro on river systems and to develop new technologies that would mitigate these effects. Although there are a number of opportunities for achieving more sustainable hydropower systems, the level of R&D support for such undertakings has been too low to achieve much for the last 20 years.

12.6.3 Advanced technology needs

Advanced technology needs can be divided into two categories: *near-term improvements* to enable existing hydro installations to address problems with fish migration and oxygen depletion, and *long-term innovations* for utilizing low-head and run-of-river resources that reduce the ecological impacts resulting from the land inundation and reduced river flows associated with dams.

Near-term improvements Many people have the perception that, because hydropower is a mature technology with substantial capital investments in place, it cannot be markedly influenced by modern technology. While it is certainly true that hydropower has been around for a while, the opportunity for retrofitting existing facilities, where impacts on fish migration and oxygen depletion are significant, has led to a number of new technological approaches for reducing these problems. Regarding fish passage, the first steps have been focused on understanding exactly what was causing such high levels of mortality in young fish, followed by turbine

redesigns to make them more "fish-friendly." The Alden Research Laboratory and Voith Hydro have been working on improved hydro technology for a number of years with private (EPRI) and public (US DOE) funding (see, for example, Odeh, 1999; Franke et al., 1997). Their work has led to better understanding of what causes fish mortality in hydro turbines and has generated a number of innovations that would reduce the problem. Advanced modeling methods employing computational fluid mechanics (CFD) have identified locations and conditions inside existing turbines that are problematic to successful fish migration. The main injury mechanisms are driven by rapid pressure changes, impingement and abrasion on turbine blades, and damage induced by cavitation. One optimistic approach that uses both CFD modeling and experimentally validated methods with electronically tagged fish has resulted in proposed designs of the internal turbine blading that could be retrofitted in Francis and Kaplan units to reduce mortality. Another important aspect of these proposed fish-friendly retrofits is that the conversion efficiency would be preserved or even increased. A team of engineers at the Alden Research Lab and the Northern Research and Engineering Corporation (ARL-NREC) has also designed a completely new turbine (as illustrated in figure 12.7) that uses a three-bladed centrifugal screw concept with rounded blade edges that would facilitate the migration of small fish and operate at efficiencies approaching 90% (Amaral et al., 2009).

Figure 12.7
ARL-NREC fish-friendly hydro turbine design. Courtesy of Voith Hydro.

Oxygen depletion in the water discharged from hydro turbines also is a problem in many installations. Aerating weirs and turbine runners are being developed by Voith Hydro and others to increase oxygen content. Voith Hydro is also looking at possible retrofits to existing low-head, smaller hydro dams that would increase power output with little environmental damage.

Long-term innovations If the so-called ultralow-head (<1 m) or run-of-river energy converter concepts could be developed economically, then a large jump in the potential for hydropower would materialize that would match most, if not all, of the desirable sustainability attributes of energy systems. These concepts would allow for fish migration, maintain the natural flow and flooding cycles of rivers by eliminating or minimizing impoundment, and keep water quality at high levels.

Matrix turbines and specially designed ultralow-head turbines are being considered by a number of groups. For example, Gorlov (1998, 1992) at Northeastern University has developed several low-cost alternatives using (1) slow rpm turbines made of composite plastics that operate efficiently with ultralow heads (<1 m) and can capture both the potential and the kinetic energy of flowing water in rivers or tidal basins, and (2) high rpm, air-driven Francis turbines that are powered by hydraulically activated chambers that compress air using river flows and low hydraulic heads (1–3 m).

Schneider and associates at the MIT Energy Laboratory (1995–2001) have taken a different approach. In order to capture a river or tidal basin's hydroenergy directly as kinetic energy ($\frac{1}{2}\rho v^2$), they have used a "hydroengine" consisting of a horizontal cascade of foils that are mechanically connected to the drive mechanism by looping around two axles resembling a Venetian blind structure. The Schneider hydroengine utilizes natural river flows enhanced by low hydraulic heads (<3 m), while keeping fluid pressure changes and velocity and acceleration levels within safe ranges for fish passage. Voith Hydro (1999) is also working on ultralow-head machines employing matrix turbines and a redesigned power wheel concept. Both of these concepts have now been demonstrated; and work to validate performance, including efficiency and durability, and to ensure reasonable costs is progressing, although more work is needed before advanced machines will be widely deployed commercially.

Problems

12.1 Estimate the required flow for a 10,000 MW_e hydro installation as a function of the effective hydraulic head from 10 to 300 m.

12.2 Describe how you estimate the amount of land that will be inundated by a large-scale hydropower project such as Three Gorges in China on the Yangtze River or the La Grande complex in St. James Bay, Canada.

12.3 Assume that the US wants to expand its hydropower capacity to its full technical potential without building any new dams as a means of offsetting carbon dioxide emissions from coal-fired plants. Estimate the impact on annual carbon dioxide emissions. What would be your estimate of capital investment needed to accomplish this?

12.4 You have been asked to finance US R&D for advanced hydropower technology for reducing the impact of current installations on fish migration and on developing economically and technically viable low-head, run-of-river technologies by allocating a portion of the current revenues generated from electricity sales from hydro resources. Estimate the revenue stream that would be produced annually as a function of the "sustainable R&D trust fund surcharge" amount in ¢/kWh. You can assume that the average generating base price for hydropower in the US is $0.03/kWh.

12.5 A megascale hydro project being considered will require approximately 1 million tons of concrete for the dam structure alone. The plant should produce about 2,000 MW_e of power for its entire lifetime of about 100 years. How large an impact might this plant have on GHG emissions?

References

AGS/ETHZ. 1998. Alliance for Global Sustainability Proceedings, Eidgenössische Technische Hochschule Zürich (ETHZ).

Amaral, S., G. Allen, G. Hecker, D. Dixon, and R. Fisher. 2009. Development and Application of an Advanced Fish-Friendly Hydro Turbine. In Proceedings of the HYDRO 2009 conference, Session 2, Lyon, France, October 26–28, 2009, 14 pp.

Biello, D. 2009. The Dam Building Boom: Right Path to Clean Energy? *Environment 360*. Report, February 23, 2009. Yale University, New Haven, CT.

BP. 2011. *Statistical Review of World Energy June 2011*. London. http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

Brower, M. 1991. Energy from Rivers and Oceans. In *Cool Energy*, 111–118. Cambridge, MA: MIT Press.

Economist. 2003. Damming Evidence: The Pros and Cons of Big Earthworks. *Economist* 368 (8333):9–11.

Economist. 1997a. Asia—Stopping Yangtze's Flow. *Economist* (August 2).

Economist. 1997b. Dam-Busting: Victory for the Fishes. *Economist* 345 (8046):28.

EIA (US Energy Information Administration). 2009. International Energy Outlook 2009. http://www.iea.org/weo/2009.asp

Franke, G. F., D. R. Webb, R. K. Fisher, D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, L. T. Iaczo, Y. Ventikos, and F. Sotiropoulis. 1997. *Development of Environmentally Advanced Hydropower Turbine System Concepts*. Voith Hydro, Inc. Report no. 2677-0141. Contract no. DE-AC07-96ID13382. Idaho Falls, ID: INEEL.