PDHonline Course E352 (4 PDH)

Hydroelectric Power Plants

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2020

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Hydro-Electric Power Generation

Lee Layton, P.E

Table of Contents

Introduction

Hydropower 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.

Hydropower offers advantages over other energy sources but faces unique environmental challenges too. Hydropower is a fueled by water, so it's a clean fuel source. Hydropower doesn't pollute the air like power plants that burn fossil fuels, such as coal or natural gas. Hydropower is a domestic source of energy, produced in the United States. Hydropower relies on the water cycle, which is driven by the sun, thus it's a renewable power source. Hydropower is generally available as needed; the flow of water through the turbines can be controlled to produce electricity on demand.

Hydroelectric power plants provide benefits in addition to clean electricity. Conventional hydroelectric impoundment power plants create reservoirs that offer a variety of recreational opportunities, notably fishing, swimming, and boating. Most hydropower installations provide some public access to the reservoir to allow the public to take advantage of these opportunities. Other benefits may include water supply and flood control.

Hydroelectric power can be categorized into two broad categories: Conventional Hydroelectric power plants and marine energy-derived power plants. Conventional hydroelectric power plants include,

- Impounded water hydroelectric power plants,
- Run-of-the-river hydroelectricity, and
- Pumped-storage hydroelectricity.

Marine energy-derived power plants include,

- Tidal power,
- Wave power, and
- Ocean thermal energy.

Hydroelectricity is the most widely used form of renewable energy. Once a hydroelectric power plant 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 1,200,000 MW supplied 4,700,000 MWh of hydroelectricity in 2016. This was approximately 16% of the world's electricity, and accounted for about 70% of electricity from renewable sources.

Humans have been harnessing water to perform work for thousands of years. The Greeks used water wheels for grinding wheat into flour more than 2,000 years ago. Besides grinding flour, the power of the water was used to saw wood and power textile mills and manufacturing plants. For more than a century, the technology for using falling water to create hydroelectricity has existed. The evolution of the modern hydropower turbine began in the mid-1700's

In 1880, a brush-arc light dynamo driven by a water turbine was used to provide theatre and storefront lighting in Grand Rapids, Michigan; and in 1881, a brush dynamo connected to a turbine in a flour mill provided street lighting at Niagara Falls, New York. These two projects used direct-current technology. Of course, alternating current is used today. That breakthrough came when the electric generator was coupled to the turbine, which resulted in the first hydroelectric plant located in Appleton, Wisconsin, in 1882.

The following are a few of the major milestones in the evolution of hydroelectric power generation.

1880	Michigan's Grand Rapids Electric Light and Power Company, generating electricity by dynamo belted to a water turbine at the Wolverine Chair Factory, lit up 16 brush-arc lamps.
1881	Niagara Falls city street lamps powered by hydropower.
1882	World's first hydroelectric power plant began operation on the Fox River in Appleton, Wisconsin.
1886	About 45 water-powered electric plants in the U.S. and Canada.
1889	Two hundred electric plants in the U.S. use waterpower for some or all generation.
1907	Hydropower provided 15% of U.S. electrical generation.
1920	Hydropower provided 25% of U.S. electrical generation.
1933	Tennessee Valley Authority established.
1936	Hoover Dam built with 1,345 MW of capacity; the largest of the time.
1937	Bonneville Power Administration established.
1940	Hydropower provided 40% of electrical generation.
1942	Grand Coulee Dam built with 6,809 MW of capacity.
1980	Conventional capacity nearly tripled in United States since 1940.
1984	Brazil/Paraguay's Itaipu Dam built, with 14,000 MW of capacity.

2008 China builds the Three Gorges Dam with 22,500 MW of capacity.

The largest hydroelectric power plant in operation today is the Three Gorges Dam in China and is shown in the photograph on the right.

As Hydroelectricity has continued to develop it eventually has supplied 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 about 7% of its national energy consumption.

The United States faces many challenges as it prepares to meet its energy needs in the twenty-first century. Electricity supply crises, fluctuating natural gas and gasoline prices, heightened concerns about the security of the domestic energy infrastructure and of foreign sources of supply, and uncertainties about the benefits of utility restructuring are all elements of the energy policy challenge. Hydropower is an important part of the diverse energy portfolio that is needed for a stable, reliable energy sector in the United States.

Responding to these national energy issues, the Department of Energy (DOE) is investigating the potential for new hydroelectric power generation in the United States and is focused on:

- Assessing new potential hydroelectric generation sites of which 5,677 sites have been identified in the United States with undeveloped capacity of about 30,000 MW,
- Developing new, cost-effective, advanced technologies that will have enhanced environmental performance and greater energy efficiencies, and
- Providing supporting research in power systems integration, resource assessment, innovative technology characterization, valuation and performance metrics, industry support, and technology acceptance.

While we probably will not see many new large scale hydroelectric power plants built in the United States, there is potential to increase the efficiency of the current plants and to develop new small hydroelectric plants.

In this course we will look at the basics of hydroelectric power generation, including the types of hydroelectric power plants and the types of turbines used in these plants. Conventional hydroelectric power generation will be reviewed in detail as well as the potential for marine power generation. Finally, the environmental benefits and concerns with hydro-electric power will be discussed.

Chapter 1

Overview of Hydroelectric Power Generation

Hydropower is the renewable energy source that produces the most electricity in the United States. It accounted for 7% of total U.S. electricity generation and 46% U.S. of generation from renewables in 2016. The process of hydroelectric power generation begins with the hydrologic cycle.

Hydropower is using water to make electricity. Water constantly moves through a vast global cycle, evaporating from lakes and oceans, forming clouds, precipitating as rain or snow, then flowing back down to the ocean. The energy of this water cycle, which is driven by the sun, is tapped to produce electricity. Hydropower uses a fuel – *water* - that is not reduced or used up in the process. Because the water cycle is an endless, constantly recharging system, hydropower is considered a renewable energy source.

Water is present in the atmosphere in solid, liquid, and vapor states. It also exists as groundwater in aquifers. Water appears in nature in all three common states of matter and may take many different forms on Earth: water vapor and clouds in the sky; seawater and icebergs in the polar oceans; glaciers and rivers in the mountains; and the liquid in aquifers in the ground.

Water covers 71% of the Earth's surface; the oceans contain 97.2% of the Earth's water. The majority of water on Earth is sea water. The collective mass of water found on, under, and over the surface of a planet is called the hydrosphere. Earth's approximate water volume is estimated to be 326,000,000 cubic miles. Figure 1 shows a graphical distribution of the locations of water on Earth.

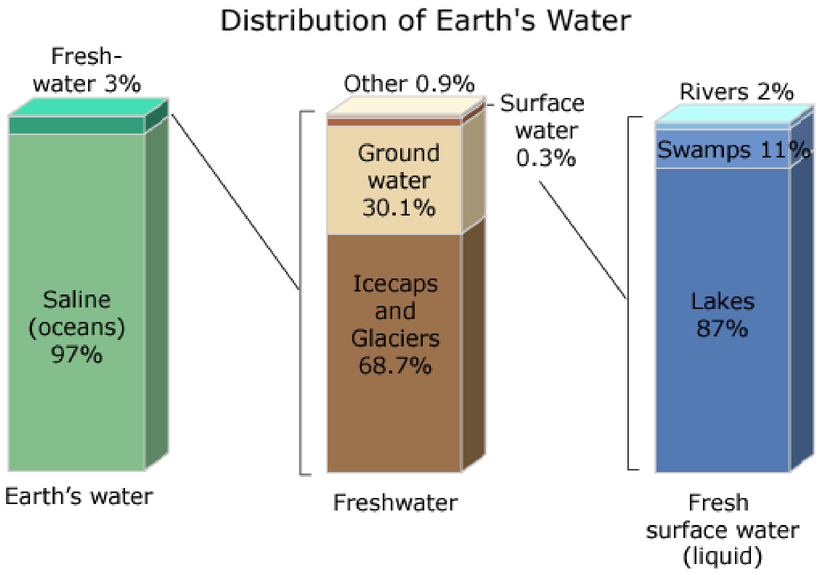

Figure 1

The water cycle, or *hydrologic cycle*, refers to the continuous exchange of water within the hydrosphere, between the atmosphere, soil water, surface water, groundwater, and plants. Water moves perpetually through each of these regions in the water cycle. Let's use Figure 2 to review the hydrologic cycle.

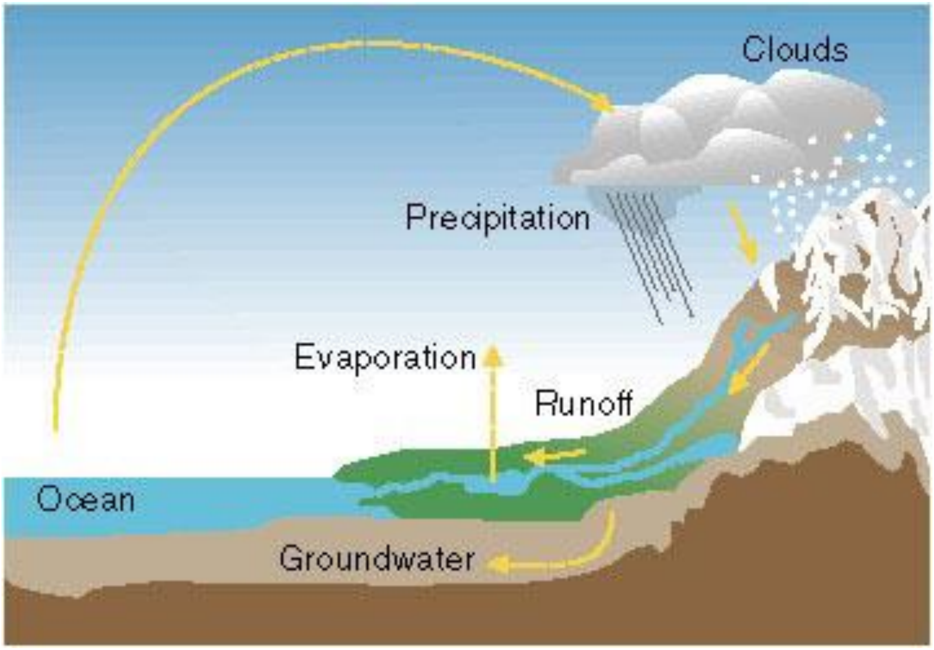

Figure 2

Understanding this cycle is important to understanding hydroelectric power. In the water cycle:

1. Solar energy heats water on the surface, causing it to evaporate,
2. This water vapor condenses into clouds and falls back onto the surface as precipitation (rain, snow, etc.), and
3. The water flows through rivers back into the oceans, where it can evaporate and begin the cycle over again.

Most water vapor over the oceans returns to the oceans, but winds carry water vapor over land at the same rate as runoff into the sea. About 34% of the annual precipitation over land is from evaporation over the ocean. Over land, evaporation and transpiration contribute the remaining 66% of annual landfall precipitation. This precipitation has several forms: most commonly rain, snow, and hail, with some contribution from fog and dew.

Water runoff often collects over watersheds flowing into rivers. This runoff water can be trapped in lakes, either created naturally or by manmade dams. At high altitude, during winter, and in the far north and south, snow collects in ice caps, snow pack and glaciers. Water also infiltrates the ground and goes into aquifers. This groundwater later flows back to the surface via springs.

Tides are the cyclic rising and falling of local sea levels caused by the tidal forces of the Moon and the Sun acting on the oceans. Tides cause changes in the depth of the marine and estuarine water bodies and produce oscillating currents known as tidal streams. The changing tide produced at a given location is the result of the changing positions of the Moon and Sun relative to the Earth coupled with the effects of Earth rotation. The strip of seashore that is submerged at high tide and exposed at low tide, the *intertidal zone*, is an important ecological product of ocean tides.

When flowing water is captured and turned into electricity, it is called hydroelectric power or hydropower. There are several types of hydroelectric facilities; they are all powered by the kinetic energy of flowing water as it moves downstream. Turbines and generators convert the energy into electricity, which is then fed into the electrical grid.

The amount of available energy in moving water is determined by its flow or fall. Swiftly flowing water in a big river, like the Columbia River that forms the border between Oregon and Washington, carries a great deal of energy in its flow. Water descending rapidly from a very high point, like Niagara Falls in New York, also has lots of energy in its flow.

In either instance, the water flows through a pipe, or penstock, then pushes against and turns blades in a turbine to spin a generator to produce electricity. In a run-of-the-river system, the force of the current applies the needed pressure, while in a storage system, water is accumulated in reservoirs created by dams, then released as needed to generate electricity.

Most hydropower is produced at large facilities built by the Federal Government, such as the Grand Coulee Dam. The West has most of the largest dams, but there are numerous smaller facilities operating around the country.

The map on the following page, which was developed by the DOE, shows areas of the country that have the potential for new hydroelectric power generation. The map also shows the location of major hydroelectric power plants in operation today. See Figure 3.

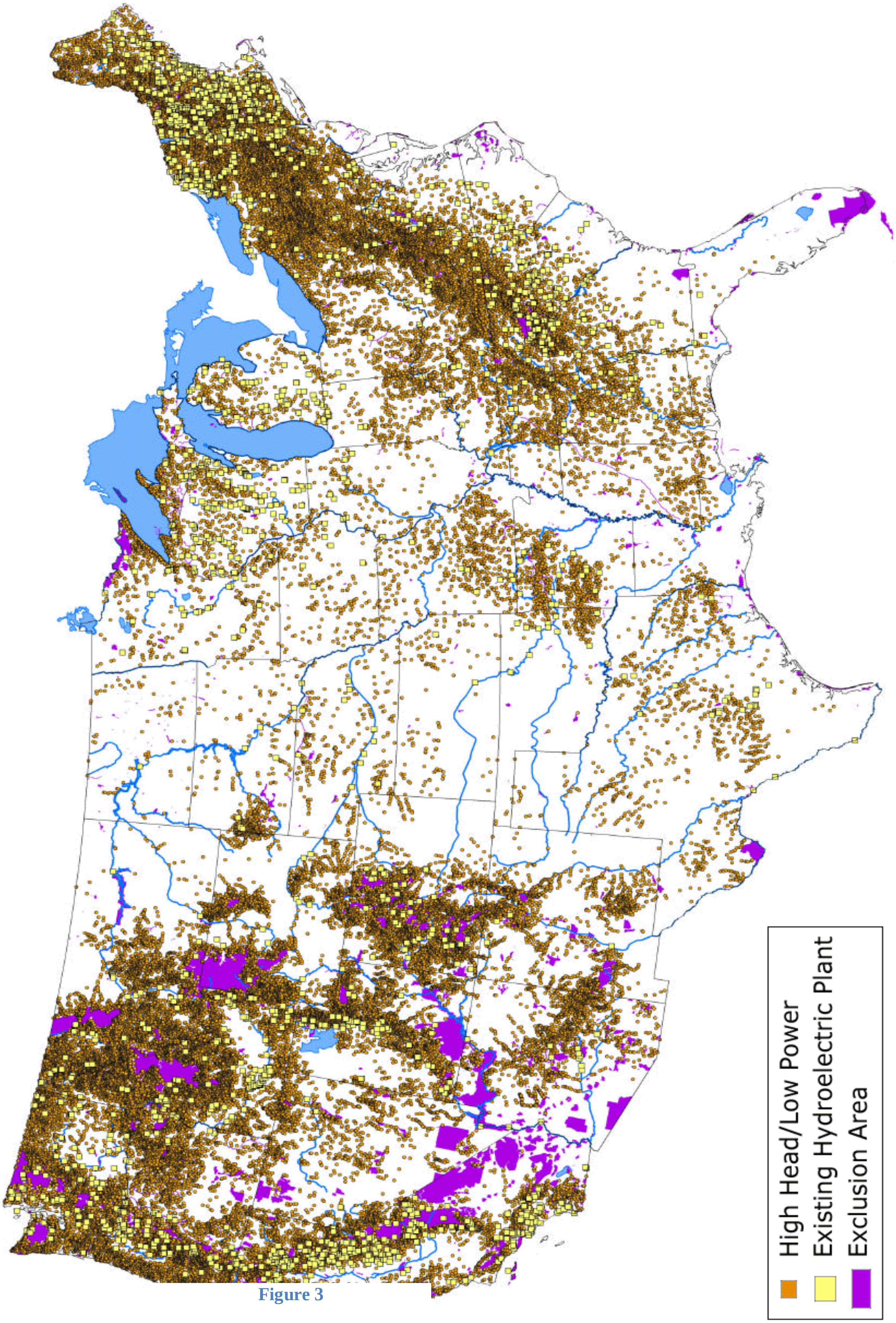
■ High Head/Low Power
■ Existing Hydroelectric Plant
■ Exclusion Area

Figure 3

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. The pie chart shown in Figure 4 has the installed capacity of hydroelectric power in the United States. This accounts for approximately 8% of the U.S. generating capacity.

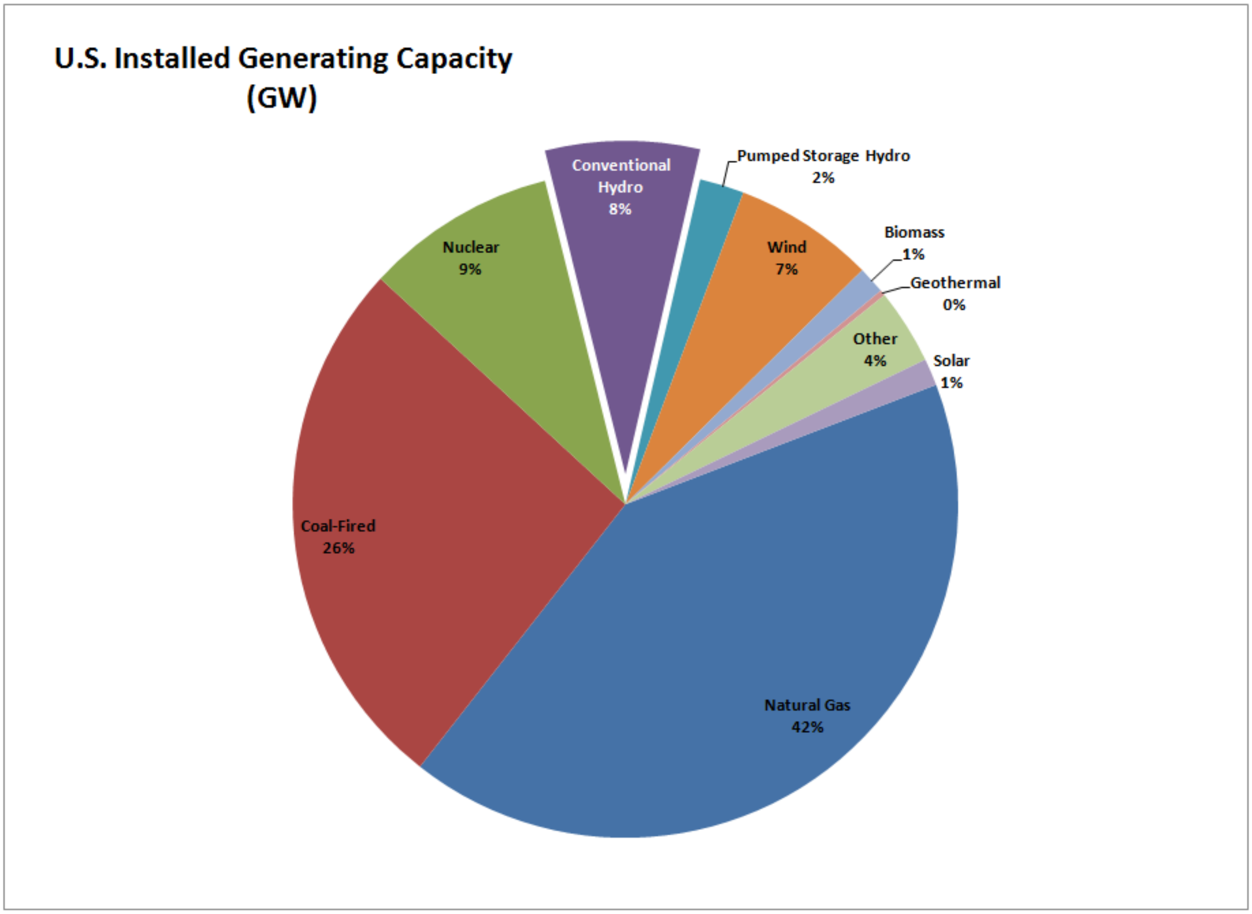

Figure 4

Figure 5, shown below, has the electric energy production shown by source. Using this measure, hydroelectric power accounts for approximately 6% of the production of energy in the United States. As you can see, coal, nuclear, and natural gas are the primary sources of energy in this country.

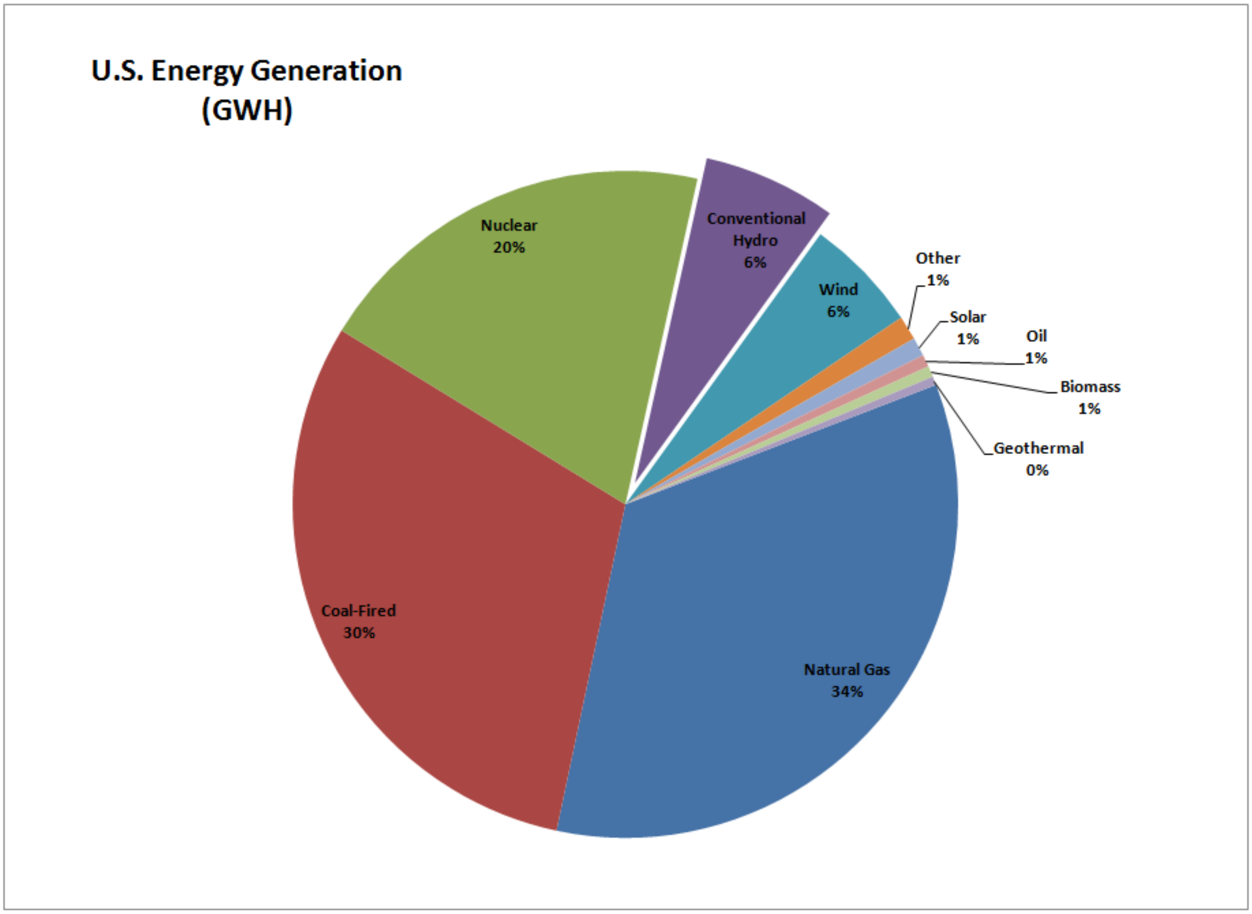

Figure 5

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% of its electricity from hydroelectric sources.

Figure 6 shows the top ten countries for hydroelectric power generation. From this chart, we see that the United States ranks fourth with a total installed capacity of approximately 102,000 MW. China is the largest with 319,000 MW of installed hydroelectric power generation.

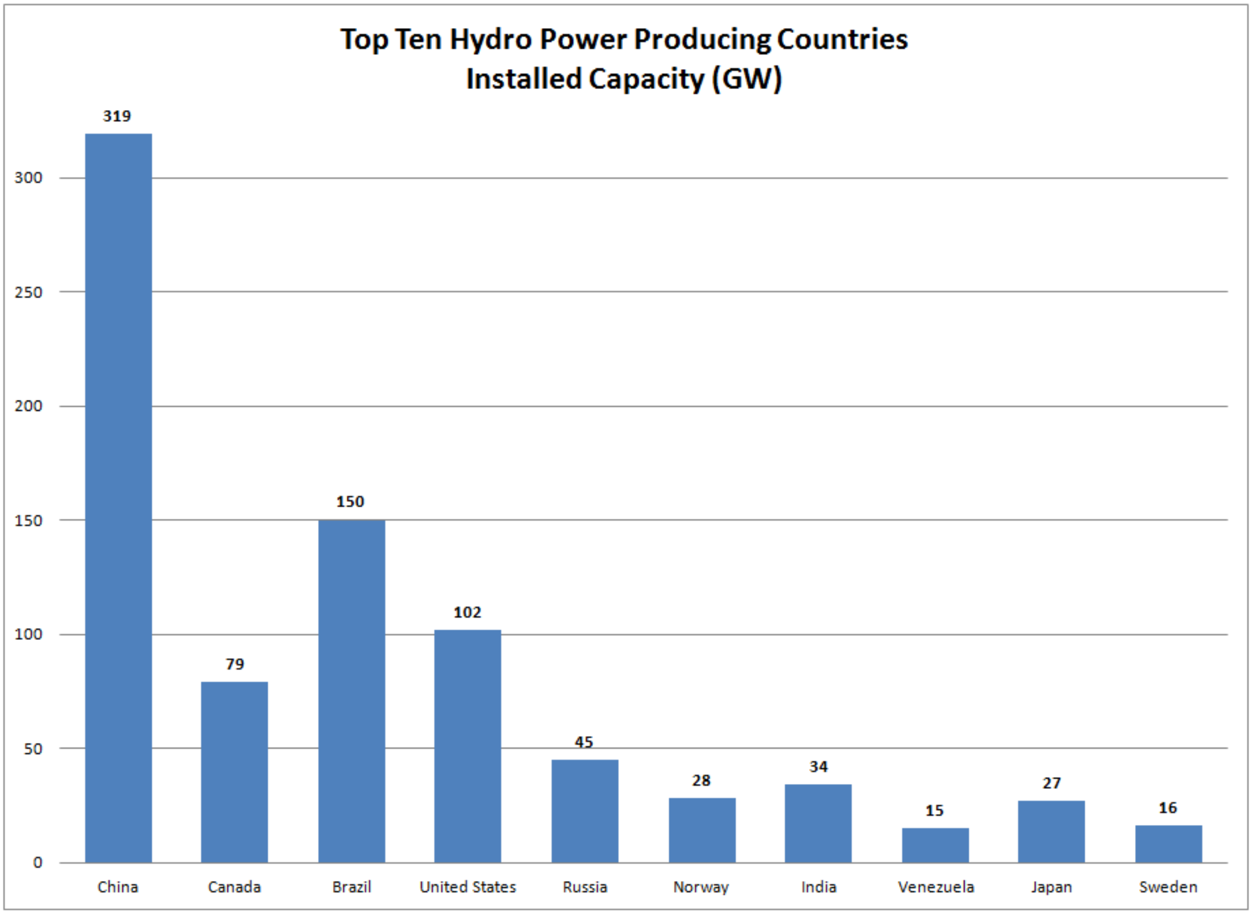

Figure 6

Sizes of Hydroelectric Power Plants

Facilities range in size from large power plants that supply many consumers with electricity to small and micro plants that individuals operate for their own energy needs or to re-sell in the energy markets.

Large Hydro Facilities

Although no official definition exist for the capacity range of large hydroelectric power stations, facilities from over 25 MW to more than 10,000 MW are generally considered large hydroelectric facilities. Presently only three facilities over 10,000 MW are in operation worldwide; Three Gorges Dam at 22,500 MW, Itaipu Dam at 14,000 MW, and Guri Dam at 10,200 MW.

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 aluminum electrolytic plants, for example.

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 25 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. Small-scale hydroelectricity production is around 85,000 MW worldwide. Over 70% of this is in China (65,000 MW), followed by Japan (3,500 MW), the United States (3,000 MW), and India (2,000 MW).

Small hydro plants may be connected to 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 an electric distribution 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.

Micro

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.

Pico

Pico hydro is a term used for hydroelectric power generation of under 5 KW. These plants are useful in small, remote communities that require only a small amount of electricity - typically one or two homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 3 feet. 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.

Types of Hydropower Turbines

There are two main types of hydro turbines: impulse and reaction. The type of hydropower turbine selected for a project is based on the height of standing water—referred to as "head"—and the flow, or volume of water, at the site.

The water pressure can apply a force on the face of the runner blades, which decreases as it proceeds through the turbine. These turbines are called *reaction turbines*. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure.

In the second case, the water pressure is converted into kinetic energy before entering the runner. The kinetic energy is in the form of a high-speed jet that strikes buckets, mounted on the periphery of the runner. Turbines that operate in this way are called *impulse turbines*. As the water, after striking the buckets, falls into the tail water with little remaining energy, the casing can be light and serves the purpose of preventing splashing.

Impulse Turbines

The impulse turbine generally uses the velocity of the water to move the runner – or turbine blades - and discharges to atmospheric pressure. The water stream hits each bucket on the runner. There is no suction on the down side of the turbine, and the water flows out the bottom of the turbine housing after hitting the runner. An impulse turbine is generally suitable for high head, low flow applications. Examples of impulse turbines include Pelton turbines, Turgo Turbines, and Cross-Flow Turbines.

1. Pelton Turbine

   A *Pelton wheel* has one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Draft tubes are not required for impulse turbine since the runner must be located above the maximum tailwater to permit operation at atmospheric pressure.

   

   With a Pelton turbine one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues through a nozzle with a needle valve to control the flow. They are only used for relatively high heads. The axes of the nozzles are in the plane of the runner. To stop the turbine - e.g. when the turbine approaches the runaway speed due to load rejection- the jet may be deflected by a plate so that it does not impinge on the buckets. In this way the needle valve can be closed very slowly, so that overpressure surge in the pipeline is kept to an acceptable minimum. Any kinetic energy leaving the runner is lost and so the buckets are designed to keep exit velocities to a minimum. The turbine casing only needs to protect the surroundings against water splashing and therefore can be very light.

2. Turgo Turbine

A *Turgo Wheel* is a variation on the Pelton. The Turgo runner is a cast wheel whose shape generally resembles a fan blade that is closed on the outer edges. The water stream is applied on one side, goes across the blades and exits on the other side.

The Turgo turbine can operate under a head in the range of 50-750 feet. Like the Pelton it is an impulse turbine, but its buckets are shaped differently and the jet of water strikes the plane of its runner at an angle. Water enters the runner through one side of the runner disk and emerges from the other. Whereas the volume of water a Pelton turbine can admit is limited because the water leaving each bucket interferes with the adjacent ones, the Turgo runner does not present this problem. The resulting higher runner speed of the Turgo makes direct coupling of turbine and generator more likely, improving its overall efficiency and decreasing maintenance cost.

3. Cross-Flow

A *cross-flow turbine* is drum-shaped and uses an elongated, rectangular-section nozzle directed against curved vanes on a cylindrically shaped runner. It resembles a "squirrel cage" blower. The cross-flow turbine allows the water to flow through the blades twice. The first pass is when the water flows from the outside of the blades to the inside; the second pass is from the inside back out. A guide vane at the entrance to the turbine directs the flow to a limited portion of the runner.

This impulse turbine, also known as *Banki-Michell* in remembrance of its inventors and *Ossberger* after a company which has been making it for more than 50 years is used for a wide range of heads overlapping those of Kaplan, Francis and Pelton. It can operate with discharges between of up to 350 Ft^3/sec and heads up to 200 feet. Water enters the turbine, directed by one or more guide-vanes located in a transition piece upstream of the runner, and through the first stage of the runner. Flow leaving the first stage attempts to cross the open center of the turbine. As the flow enters the second stage, a compromise direction is achieved which causes significant shock losses. The runner is built from two or more parallel disks connected near their rims by a series of curved blades. Their efficiency is lower than conventional turbines, but remains the same level for a wide range of flows and heads.

Reaction Turbines

A reaction turbine develops power from the combined action of pressure and moving water. The runner is placed directly in the water stream flowing over the blades rather than striking each individually. Reaction turbines are generally used for sites with lower head and higher flows than compared with the impulse turbines. The three main types of reaction turbines are: propellers, Francis, and Kinetic turbines.

1. <u>Propeller</u>
   A propeller turbine generally has a runner with three to six blades in which the water contacts all of the blades constantly. Picture a boat propeller running in a pipe. Through the pipe, the pressure is constant; if it isn't, the runner would be out of balance. The pitch of the blades may be fixed or adjustable. The major components besides the runner are a scroll case, wicket gates, and a draft tube. There are several different types of propeller turbines:

   - <u>Bulb turbine.</u> The turbine and generator are a sealed unit placed directly in the water stream.

   - <u>Straflo.</u> The generator is attached directly to the perimeter of the turbine.
   - <u>Tube turbine.</u> The penstock bends just before or after the runner, allowing a straight line connection to the generator.
   - <u>Kaplan.</u> Kaplan turbines are axial-flow reaction turbines, generally used for low heads. Large Kaplan turbines have adjustable runner blades and may or may not have adjustable guide-vanes. If both blades and guide-vanes are adjustable it is described as "double-regulated". If the guide-vanes are fixed it is "single-regulated".

     Unregulated propeller turbines are used when both flow and head remain practically constant, and are most common in micro-hydro applications.

2. Francis

   A Francis turbine has a runner with fixed buckets or vanes. Water is introduced just above the runner and all around it and then falls through, causing it to spin.

   Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In the high speed Francis the admission is always radial but the outlet is axial.

   

   Francis turbines can be set in an open flume or attached to a penstock. For small heads and power open flumes are commonly employed. Steel spiral casings are used for higher heads, designing the casing so that the tangential velocity of the water is constant along the consecutive sections around the circumference. Small runners are usually made in aluminum bronze castings. Large runners are fabricated from curved stainless steel plates, welded to a cast steel hub.

   Besides the runner, the other major components are the scroll case, wicket gates, and draft tube.

3. Kinetic

   Kinetic energy turbines, also called free-flow turbines, generate electricity from the kinetic energy present in flowing water rather than the potential energy from the head. The systems may operate in rivers, man-made channels, tidal waters, or ocean currents. Kinetic systems utilize the water stream's natural pathway. They do not require the diversion of water through manmade channels, riverbeds, or pipes, although they might have applications in such conduits. Kinetic systems do not require large civil works; however, they can use existing structures such as bridges, tailraces and channels.

Turbine Selection

The choice of which type turbine to use is based on the efficiency of the unit for a given application. Each type operates most effectively in a certain pressure and flow range. Many times the turbine types are characterized by their effective "head range". Table 1 below shows generally accepted values by turbine type.

Table 1
Turbine Selection

Turbine Style	Type	Head Range (Feet)
Reaction	Kaplan	6 – 125
Reaction	Francis	30 – 375
Impulse	Pelton	150 – 5,000
Impulse	Cross-Flow	9 – 750
Impulse	Turgo	50 – 750

Another useful tool is the graph in Figure 7 below. The graph also includes flow information, so the turbine selection is more refined. The vertical axis units are for head in meters, and the horizontal axis for flow in cubic meters per second.

Note the yellow diagonal lines in Figure 7 show the approximate generation output of various head and flow combinations. As you can see from the graph, there is quite a bit of overlap in available turbine choices in the 10-100 meter head range with flow rates of 1-10 m^3/sec.

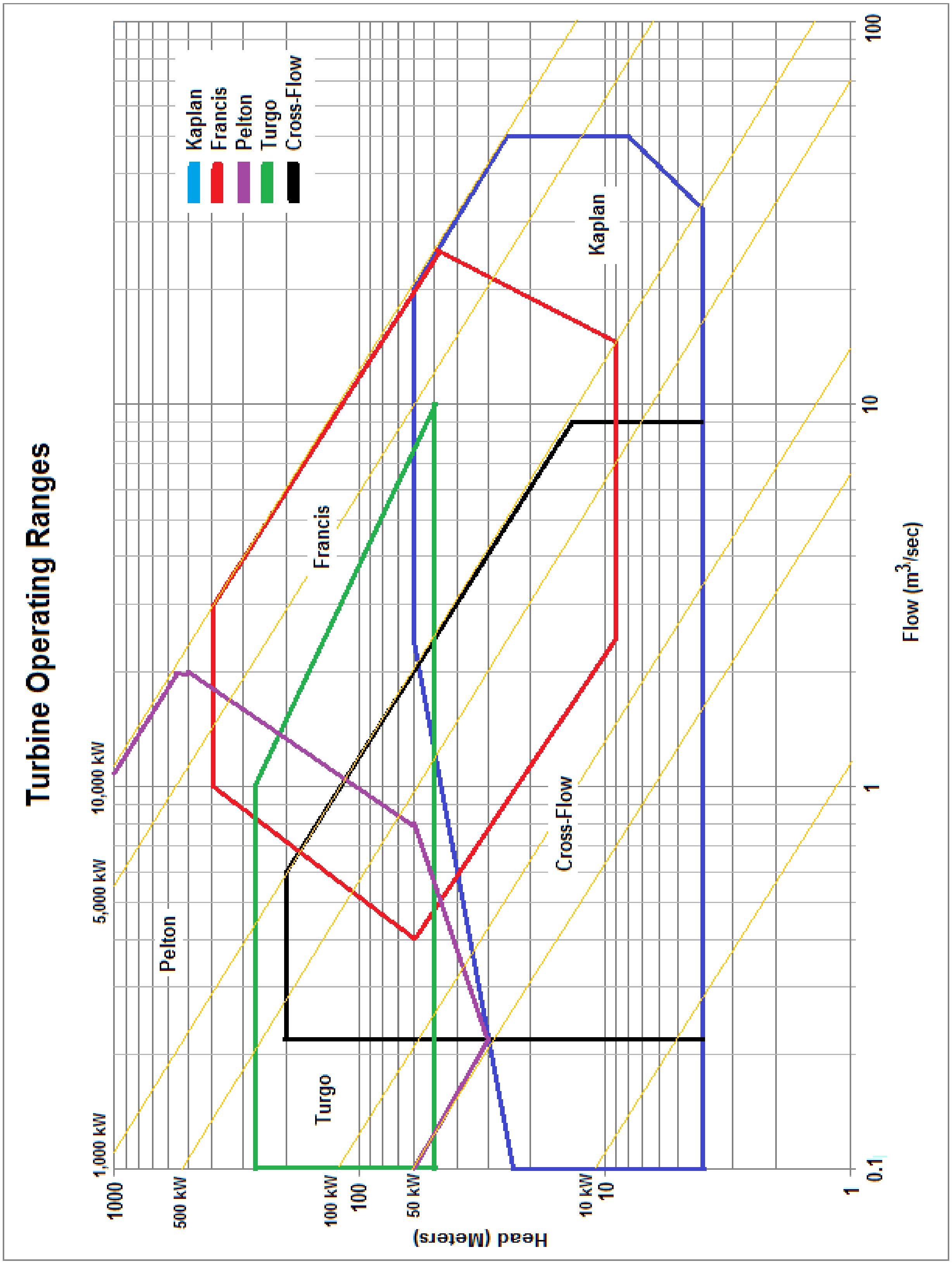
Turbine Operating Ranges
Kaplan
Francis
Pelton
Turgo
Cross-Flow
Pelton
Turgo
Francis
Cross-Flow
Kaplan
1,000 kW
5,000 kW
10,000 kW
500 kW
100 kW
50 kW
10 kW
1000
100
10
1
0.1
1
10
100
Head (Meters)
Flow (m³/sec)

Figure 7

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 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. Figure 8 shows the energy conversions necessary to convert impounded water into electricity.

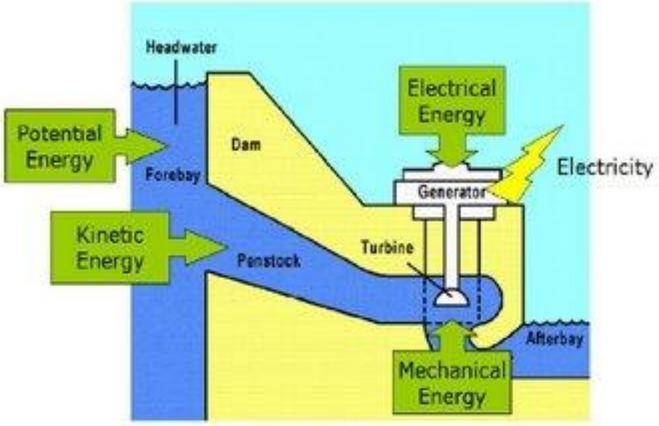

Figure 8

Hydroelectric power is defined by the fundamental physics of *Potential Energy* which states that a mass may contain energy by virtue of its velocity and or by its relative height. The Potential Energy is when the water travels from a hillside or off a waterfall. The mass of water is multiplied by the acceleration due to earth's gravity and by the height from which the water falls or is displaced. It is also defined by *Kinetic Energy* when the water is traveling down a stream, river or through a dam or when the water travel down a penstock the energy is said to be "Kinetic". Kinetic Energy states that half of a mass may contain energy by virtue of its traveling velocity squared. The Potential Energy plus the Kinetic Energy equal Mechanical Energy. Mechanical Energy is obtained by channeling the moving water to the turbine, which turns the generator, thereby converting the mechanical energy into electrical energy.

To calculate the available power from an impoundment dam we need to know the head, amount of water available, and the efficiency of both the turbine and the generator. The formula is,

$$\textbf{Power} = \frac{(\mathbf{0.746} * \boldsymbol{r} * \boldsymbol{Q} * \boldsymbol{H} * \boldsymbol{n_t} * \boldsymbol{n_g})}{\mathbf{550}}$$

Where,
Power = Electrical power, kW.
r = Density of the water, 62.4 lbs/ft^3.
Q = Quantity of the water, ft^3/sec.

H = Head of the dam, feet.
η_t = Efficiency of the turbine, decimal.
η_g = Efficiency of the electrical generator, decimal.

For example, assume we have a impoundment with a head of 200 feet and a water flow of up to 4,000 Ft^3/sec. If both the generator and the turbine have an efficiency of 85%, what is the expected power output of the dam?

$$\text{Power} = \frac{(0.746 * 62.4 * 4{,}000 * 200 * 0.85 * 0.85)}{550}$$

Power = 48,920 kW or almost 49 MW.

Of course a flow rate of 4,000 cubic feet second is almost 1.8 million gallons of water per minute, which is a lot of water.

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

Chapter 2
Conventional Hydroelectric Generation

There are three types of conventional hydroelectric power facilities: impoundment, diversion, and pumped storage. The most common type of hydroelectric power plant is an impoundment facility. Pumped storage hydroelectric plants are receiving renewed interest as a potential “energy storage medium” for other renewable resources such as solar and wind.

Impoundment

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.

Many dams were built for other purposes and hydropower was added later. In the United States, there are about 80,000 dams of which only 2,400 produce power. The other dams are for recreation, stock/farm ponds, flood control, water supply, and irrigation.

An impoundment facility, typically a large hydropower system, uses a dam to store river water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which in turn activates a generator to produce electricity. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

Figure 9 shows a typical layout for an impoundment hydropower plant.

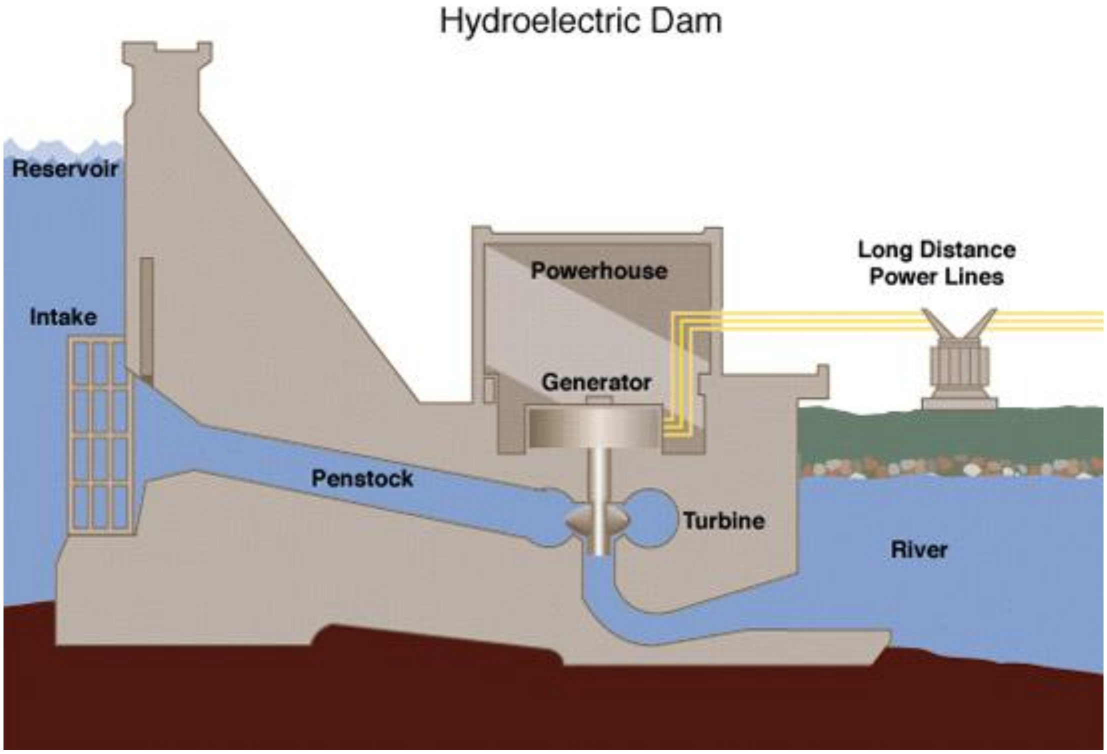

Figure 9

Using Figure 9, let's look at the operation of a conventional impoundment hydroelectric power plant.

An impoundment hydro-electric power plant begins with a *reservoir*. The reservoir is usually a large man-made lake that is the result of a dam structure constructed across a river. The size of the reservoir can vary immensely, but for a large scale power plant, the reservoir may have 50,000 – 200,000 acres of surface area. Lake Mead, for example, has a surface area of approximately 150,000 acres.

The *dam* for a hydro-electric power plants can also vary greatly in size. For large plants, the height of the dam may exceed 700 feet. As previously mentioned, two important variables in the design of a hydro-electric power plant are the head and the flow rate. The *head* is the vertical change in elevation, expressed in either feet or meters, between the head water level and the tailwater level. The *flow* is the volume of water, expressed as cubic feet or cubic meters per second, passing a point in a given amount of time.

The *intake* is a grilled opening in the dam to allow water into the penstock. The intake is designed to filter out as much debris as possible without adversely impacting the flow of water to the turbine. The *penstock* is a closed conduit or pipe for conducting water to the turbine. Look now at Figure 10 as we briefly discuss the turbine and generator unit in the dam.

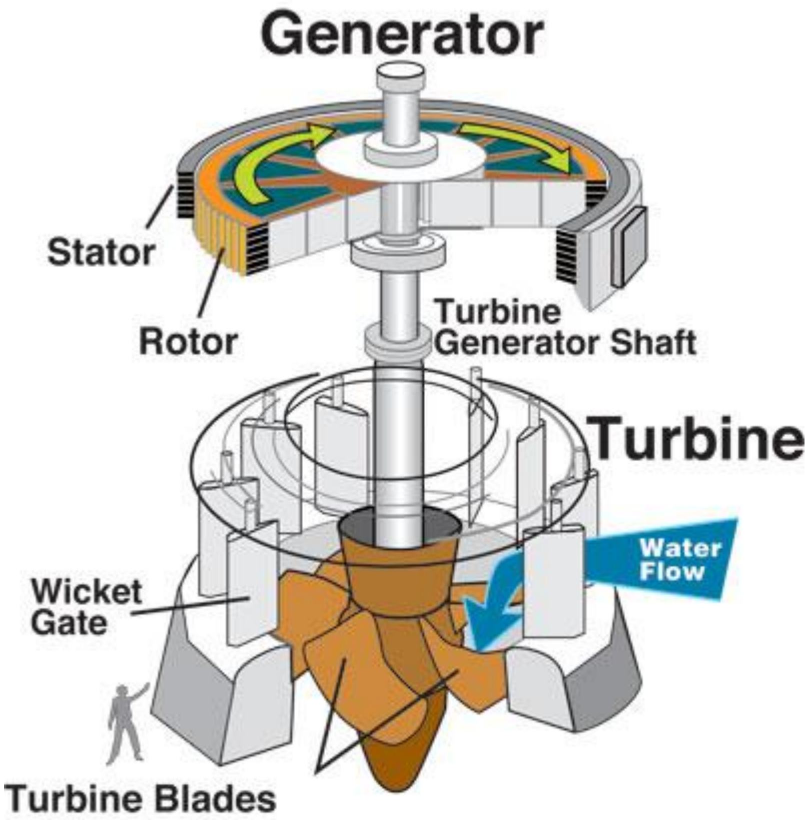

Figure 10

The water flowing through the penstock enters the wicket gates of the turbine. The *wicket gates* are adjustable elements that control the flow of water to the turbine passage. In some units there is a *scroll case*, which is a spiral-shaped steel intake guiding the flow into the wicket gates located just prior to the turbine.

The water now enters the *runner*, which in this example is a propeller type of turbine. This is the rotating part of the turbine that converts the energy of falling water into mechanical energy. A major issue with the design of a turbine structure is the prevention of cavitation. *Cavitation* is a vibration that can damage the turbine blades as a result of bubbles that form in the water as it goes through the turbine which causes a loss in capacity, head loss, efficiency loss, and the cavity or bubble collapses when they pass into higher regions of pressure.

Connected to the turbine via a shaft is an *electrical generator*. As the turbine turns, the *exciter* sends an electrical current to the rotor. The *rotor* is a series of large electromagnets that spins inside a tightly-wound coil of copper wire, called the *stator*. The magnetic field between the coil and the magnets creates an electric current.

In reaction turbines, to reduce the kinetic energy still remaining in the water leaving the runner a *draft tube* or *diffuser* stands between the turbine and the tail race. A well-designed draft tube allows, within certain limits, the turbine to be installed above the tailwater elevation without losing any head. As the kinetic energy is proportional to the square of the velocity one of the draft tube objectives is to reduce the outlet velocity. Draft tubes are particularly important in high-speed turbines, where water leaves the runner at very high speeds. In horizontal axis machines the spiral casing must be well anchored in the foundation to prevent vibration that would reduce the range of discharges accepted by the turbine.

Water leaves the turbine or draft tube in a tailrace. The *tailrace* is a channel that carries water away from a dam where it becomes the tailwater. The *tailwater* is the water downstream of the powerhouse.

Diversion Hydroelectric plants

Another form of conventional hydroelectric power plant is called a *diversion hydroelectric plant.* These facilities have smaller reservoir capacities than impoundment facilities, thus making it impossible to store water. Diversion plants are also called *run-of-the-river*, or ROR plants.

The photograph on the right is of the Tazimina Hydroelectric power plant in Alaska, which is a diversion plant. If you look closely, you can see the intake and outlets for the diversion.

The Tazimina Hydropower Plant (DOE Photo)

These units channel a portion of a river through a canal or penstock. It may not require the use of a dam. The Run-of-the-river (ROR) has either a considerably smaller water storage area or no storage is used to supply a hydro-electric generating plant. Run-of-the-river power plants are classified as with or without *pondage*. A plant without pondage has no storage and is therefore subjected to seasonal river flows and serves as a peaking power plant while a plant with pondage can regulate water flow and serve either as a peaking or base load power plant.

Run-of-the-river hydroelectricity is ideal for streams or rivers with a minimum dry weather flow or those regulated by a much larger dam and reservoir upstream. 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. Projects with pondage can store water for peak load demand or continuously for base load, especially during wet seasons. In general, 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.

ROR 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.

ROR plants do not suffer from the substantial flooding of the upper part of the river as is required for impoundment projects. 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.

A disadvantage of Run-of-River project is considered an *un-firm* source of power becuase 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, and much less during drier summer months.

Pumped-Storage Hydroelectric Power Plants

Pumped Storage Hydroelectric Power Plants (PSH) produce 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.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% 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.

Pumped storage systems require either a very large body of water or a large variation in height. 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. Projects in which both reservoirs are artificial and in which no natural waterways are involved are commonly referred to as *closed loop PSH plant*.

This system is economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and that provide base-load electricity to continue operating at peak efficiency, while reducing the need for "peaking" power plants. Capital costs for purpose-built hydro-storage are relatively 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.

A new use for pumped storage is to level the fluctuating output of intermittent power sources such as wind and solar systems. The pumped storage provides a load at times of high electricity output and low electricity demand, enabling additional system peak capacity. A new concept is to use wind turbines 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.

Look at Figure 11 for an overview of how a Pumped Storage Hydro-electric power plant works.

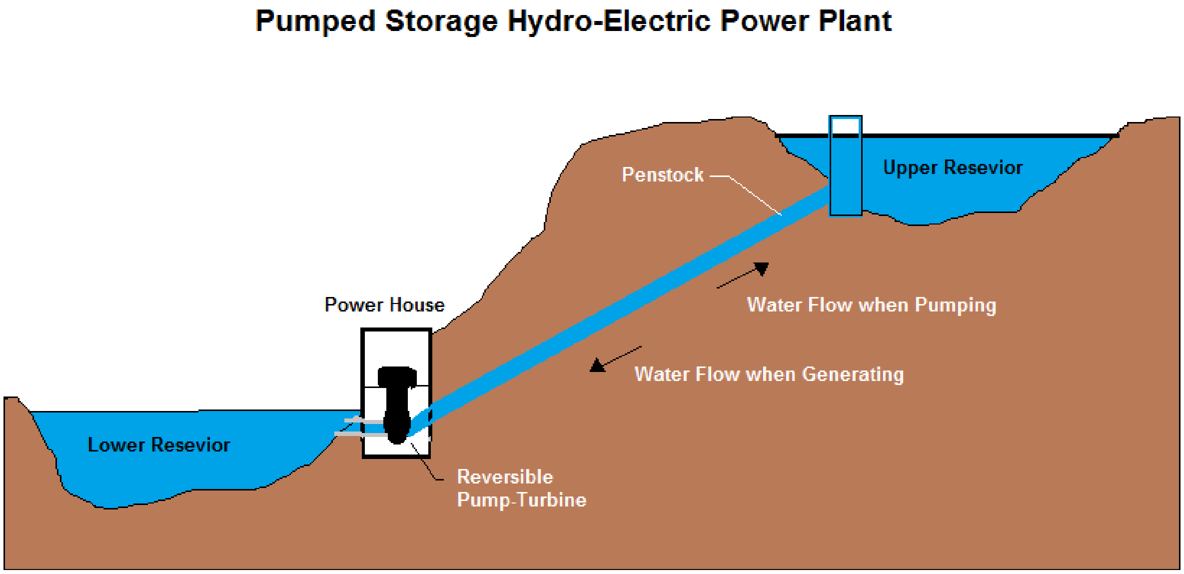

Figure 11

When power from the plant is needed, water stored in an *upper reservoir* is released into an underground tunnel. Like a conventional hydropower plant, a dam creates a reservoir. The water in this reservoir flows through the hydropower plant to create electricity. The water rushes down the *intake tunnel*. The force of the water drives huge turbines, which are underground at the base of a dam. The spinning turbines are connected to large generators, which produce the electricity. A Francis type turbine is most often used for PSH plants. The water then flows through a *discharge tunnel* and exits into a lower reservoir rather than re-entering the river and flowing downstream. When demand for electricity is low, the turbines spin backward and pump the water back up into the upper reservoir to make it available to generate electricity when it's needed. Using a reversible turbine, the plant can pump water back to the upper reservoir. This is done in off-peak hours. Essentially, the second reservoir refills the upper reservoir. By pumping water back to the upper reservoir, the plant has more water to generate electricity during periods of peak consumption.

Many PSH plants have a third reservoir that is used for ‘make-up’ water for the inevitable evaporation losses that occur in the upper and lower reservoirs.

Chapter 3
Marine Energy Electric Power Generation

In addition to the conventional hydroelectric energy sources, there is a growing interest in harvesting the energy of the oceans to create electricity. In this chapter we will look at how marine energy may be tapped to generate electricity.

Marine energy includes all forms of tidal, wave, and ocean thermal energy sources. There are only a few marine energy plants in operation today, but research is on-going in all three types of marine energy hydroelectric power plants. We will describe each of these concepts briefly.

Tidal Power

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.

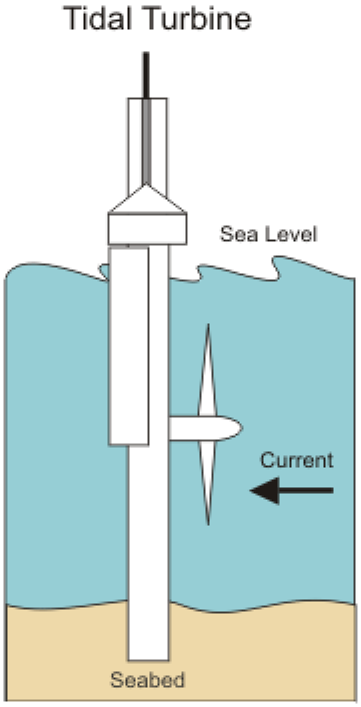

Figure 12

Tides are caused by the gravitational pull of the moon and sun, and the rotation of the Earth. Near shore, water levels can vary up to 40 feet due to tides. Tidal power is more predictable than wind energy and solar power. A large enough tidal range — 10 feet — is needed to produce tidal energy economically.

Tidal energy is captured by using tidal turbines, tidal barrages, and tidal fences.

Tidal Turbines

Tidal turbines are basically wind turbines in the water that can be located anywhere there is strong tidal flow. Because water is about 800 times denser than air, tidal turbines have to be much sturdier than wind turbines. Tidal turbines are heavier and more expensive to build but capture more energy. Figure 12 is a drawing of a tidal turbine.

Tidal Barrages

A **sluice** is a water channel that is controlled at its head by a gate.

A simple generation system for tidal energy involves a dam, known as a *tidal barrage*, across an inlet. *Sluice gates* on the barrage allow the tidal basin to fill on the incoming high tides and to empty through the turbine system on the outgoing tide, also known as the ebb tide. There are two-way systems that generate electricity on both the incoming and outgoing tides. There are three types of barrage systems. They include: Ebb generation, Flood generation, and two-basin schemes.

With an *Ebb generation* system the basin is filled through the *sluices* until high tide. Then the sluice gates are closed. The turbine gates are kept closed until the sea level falls to create sufficient head across the barrage, and then are opened so that the turbines generate until the head is again low. Then the sluices are opened, turbines disconnected and the basin is filled again. The cycle repeats itself. Ebb generation (also known as outflow generation) takes its name because generation occurs as the tide changes tidal direction.

With a *Flood generation* system the basin is filled through the turbines, which generate at tide flood. This is generally much less efficient than ebb generation, because the volume contained in the upper half of the basin (which is where ebb generation operates) is greater than the volume of the lower half (filled first during flood generation). Therefore the available level difference between the basin side and the sea side of the barrage, reduces more quickly than it would in ebb generation. Rivers flowing into the basin may further reduce the energy potential, instead of enhancing it as in ebb generation.

The final method is a *Two-basin scheme* where one basin is filled at high tide and the other basin is emptied at low tide. Turbines are placed between the basins. Two-basin schemes offer advantages over normal schemes in that generation time can be adjusted with high flexibility and it is also possible to generate almost continuously. In normal estuarine situations, however, two-basin schemes are very expensive to construct due to the cost of the extra length of barrage.

A potential disadvantage of tidal power is the effect a tidal station can have on plants and animals in the estuaries. Tidal barrages can change the tidal level in the basin and increase turbidity (the amount of matter in suspension in the water). They can also affect navigation and recreation.

There are only two commercial-sized barrages operating in the world. One is located in La Rance, France and is shown in the photograph on the right. The United States has no tidal plants and only a few sites where tidal energy could be produced economically.

Tidal Fences

Tidal fences can also harness the energy of tides. A tidal fence has vertical axis turbines mounted in a fence. All the water that passes is forced through the turbines. Tidal fences can be used in areas such as channels between two landmasses. Tidal fences are cheaper to install than tidal barrages and have less impact on the environment than tidal barrages, although they can disrupt the movement of large marine animals.

Wave Power

Ocean waves contain significant energy. Waves are caused by the wind blowing over the surface of the ocean. There is tremendous energy in the ocean waves. It's estimated that the total potential off the coast of the United States is 252 billion kilowatthours a year, about 7% of the United States' electricity consumption.

One way to harness wave energy is to bend or focus the waves into a narrow channel, increasing their power and size. The waves can then be channeled into a catch basin or used directly to spin turbines.

Many more ways to capture wave energy are currently under development. Some of these devices being developed are placed underwater, anchored to the ocean floor, while others ride on top of the waves. The world's first commercial wave farm using one such technology opened in 2008 at the Aguçadora Wave Park in Portugal.

Ocean Thermal

The energy from the sun heats the surface water of the ocean. In tropical regions, the surface water can be much warmer than the deep water. This temperature difference can be used to produce electricity. The *Ocean Thermal Energy Conversion* (OTEC) system must have a large temperature difference of at least 77°F to operate, limiting its use to tropical regions.

Hawaii has experimented with OTEC since the 1970s. There is no large-scale operation of OTEC today, mainly because there are many challenges. The OTEC systems are not very energy efficient.

Electricity generated by the system must be transported to land. It will probably be 10 to 20 years before the technology is available to produce and transmit electricity economically from OTEC systems.

Figure 13 is a diagram of a potential OTEC system.

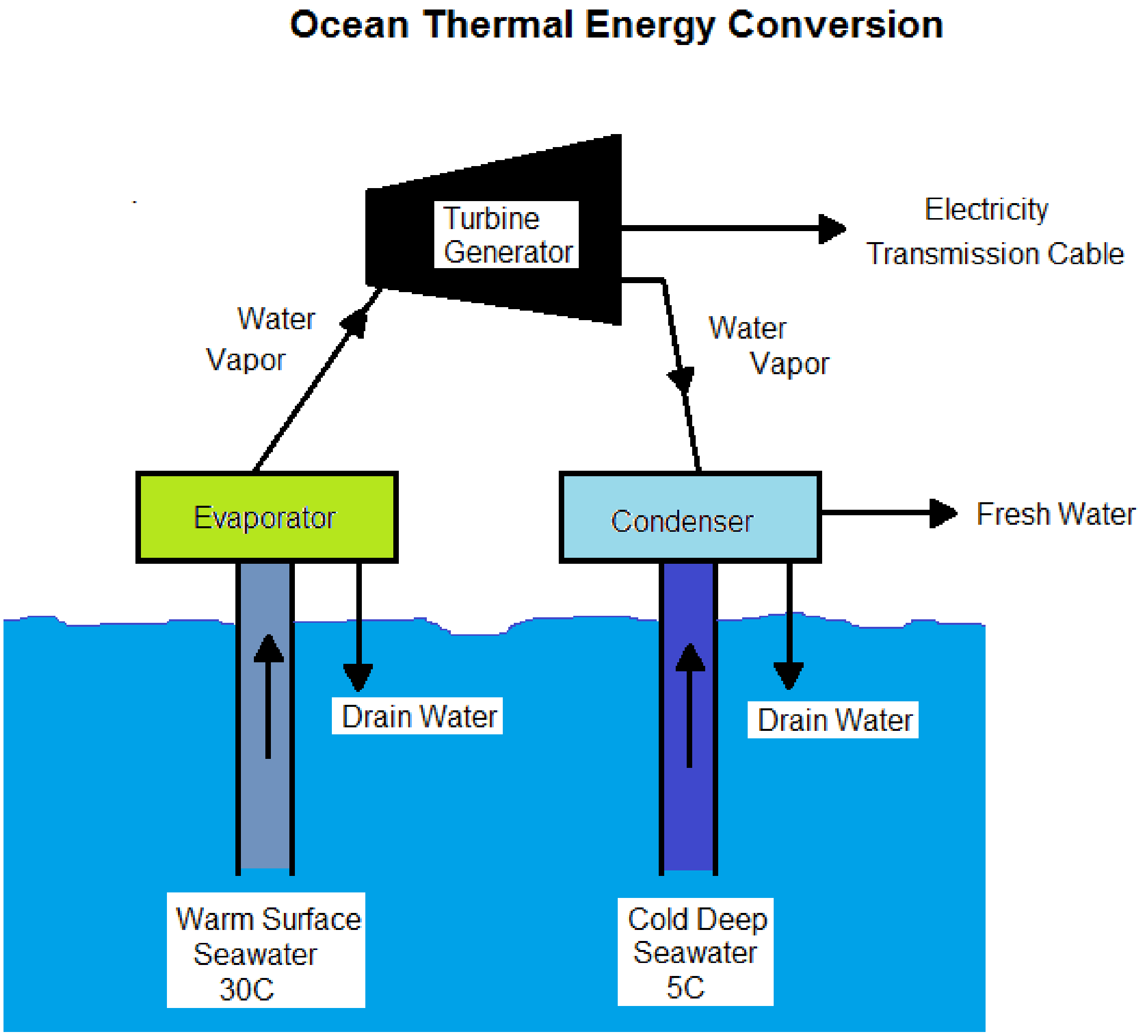

Figure 13

Chapter 4

Advantages and Disadvantages of Hydroelectric Power

The most vital asset hydropower offers is clean and renewable energy. Hydropower is renewable energy but that does not mean it is 100% good for the environment. Hydroelectric power from dams can pose serious threats to the surrounding environment. These can be reduced transport of sediment, the loss of sandbars, altered water flow regimes, decreased populations of native fish and increased populations of exotic fish. Along with land development due to plant building the natural hydrology flow is altered. This is because the hydroelectric power plant releases more water when power is needed and less water when the demand is low.

Most of the adverse impacts of dams are caused by habitat alterations. Reservoirs associated with large dams can cover land and river habitat with water and displace human populations. Diverting water out of the stream channel (or storing water for future electrical generation) can dry out streamside vegetation. Insufficient stream flow degrades habitat for fish and other aquatic organisms in the affected river reach below the dam. Water in the reservoir is stagnant compared to a free-flowing river, so water-borne sediments and nutrients can be trapped, resulting in the undesirable growth and spread of algae and aquatic weeds. In some cases, water spilled from high dams may become supersaturated with nitrogen gas and cause gas-bubble disease in aquatic organisms inhabiting the tailwaters below the hydropower plant.

If a body of water such as a river is altered to adjust for a hydro facility it may cause increased sediment build up in other areas of the river. Fish, plants, mammals and natural ecology can all be disrupted in the building a hydro plant, small or large. Large hydroelectric dams can be a high risks if not structurally safe and pose seismic risks.

So, like every other source of energy production, hydro-electric power production as advantages and disadvantages which must be considered when making a decision to develop a plant.

Advantages and disadvantages of hydroelectricity

Table 2 lists some of the advantages and disadvantages of hydro-electric power plants.

Table 2
Advantages and Disadvantages

Advantages	Disadvantages
Emissions-free	Frequently requires impoundment of large water areas
Renewable	Output dependent on rainfall
High efficiency	Impacts river flows
Dispatchable	Impoundment area uses valuable land areas
Scalable	High Capital Costs
Low Operating Costs	Long construction time
Long Service Life	Competing for other uses of the water (drinking, recreation)

Let's explore the advantages and disadvantages in a little more detail.

Advantages

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 many plants now in service which were built 50 or more 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. 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.

CO_2 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 typically a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation. Hydroelectricity produces the least amount of greenhouse gases and externality of any energy source. The extremely positive greenhouse gas impact of hydroelectricity is especially beneficial in temperate climates.

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

Hydroelectric power stations that uses dams 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. Mitigation measures such as fish ladders may be required at new projects or as a condition of re-licensing of existing projects.

For instance, in the Columbia River, along the border of Oregon and Washington, salmon must swim upstream to their spawning grounds to reproduce, but the series of dams along the river gets in their way. Different approaches to fixing this problem have been used, including the construction of *fish ladders* that help the salmon "step up" and around the dam to the spawning grounds upstream. The photograph on the right is an example of a fish ladder.

Hydro turbines kill and injure some of the fish that pass through the turbine. The U.S. Department of Energy has sponsored research and development of turbines that could reduce fish deaths to less than 2%, in comparison to fish kills of 5 to 10% for the best existing turbines.

R&D is currently underway that will help fishery biologists and turbine designers better understand what is happening in the turbine passage. Biological tests are being conducted that will quantify the physical stresses that cause injury or death to fish.

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.

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.

CO_2 Emissions

Ironically CO_2 emissions must also be listed as a disadvantage of hydroelectric power plants because the hydroelectric reservoir dams produce significant amounts of carbon dioxide and methane, and in some extreme cases may produce more greenhouse gases than power plants running on fossil fuels.

In one study it was estimated that the greenhouse effect of emissions from the Curuá-Una dam in Pará, Brazil, was more than three-and-a-half times what would have been produced by generating the same amount of electricity from oil. This is because large amounts of carbon tied up in trees and other plants are released when the reservoir is initially flooded and the plants rot. Then after this first pulse of decay, plant matter settling on the reservoir's bottom decomposes without oxygen, resulting in a build-up of dissolved methane. This is released into the atmosphere when water passes through the dam's turbines.

Seasonal changes in water depth (called “drawdown”) mean there is a continuous supply of decaying material. In the dry season plants colonise the banks of the reservoir only to be engulfed when the water level rises. For shallow-shelving reservoirs these "drawdown" regions can account for several thousand square miles.

In effect man-made reservoirs convert carbon dioxide in the atmosphere into methane. This is significant because methane's effect on global warming is much stronger than carbon dioxide's.

Methane emissions

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. Studies have shown that where the reservoir is large compared to the generating capacity 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.

Relocation

Another disadvantage of hydroelectric dams is the need to relocate the people living where the reservoirs are planned. Historically, it is estimated that 40-80 million people worldwide had been physically displaced as a direct result of dam construction. Historically and culturally important sites can be flooded and lost.

Failure hazard

Because large conventional dammed-hydro facilities hold back large volumes of water, a dam 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. Good design and construction are not an adequate guarantee of safety as dams are tempting industrial targets for wartime attack, sabotage and terrorism.

Smaller dams and micro hydro facilities create less risk, but can form continuing hazards even after they have been decommissioned. For instance, in 1967 a Georgia dam failed causing several deaths as the result of the ensuing flood and this event occurred ten years after the power plant was decommissioned.

Summary

By using the energy of water, hydropower offers advantages over other energy sources we have available today. Hydropower doesn't pollute the air like power plants that burn fossil fuels, such as coal or natural gas. Hydropower is a domestic source of energy, produced in the United States. It is a renewable power source and accounts for over one-third of all renewable energy generation in the United States.

Unlike most renewable resources, most hydroelectric power plants can be dispatched to generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand.

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.

The traditional impoundment hydroelectric power plants do create significant problems by consuming vast areas for the reservoir, and like any energy source, there are environmental issues to consider.

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