ESA21
Environmental Science Activities for the 21st Century

Renewable Energy: Hydropower

Introduction

Historical

Water has always been one of mankind's most vital resources. While the human body can go weeks without food, it can only survive for a couple of days without water consumption. Crops in the field will shrivel and die without a readily available supply. We use it for cleaning; we use it for cooking. And since almost the start of recorded history, we have used it as an energy source.

Some of the first recorded mentions of hydropower go back over 2,000 years ago to ancient Greece and Egypt, where water wheels were connected to grindstones to turn wheat into flour. Harnessing water for this laborious task allowed for large quantities of food to be processed, which allowed for job specialization and civilization to grow. Later, these same water wheels were connected to rudimentary equipment such as lathes, saw blades, and looms in order to produce such goods as furniture and fabric. By the 1700's, factories were mass-producing these products, which allowed for even more specialization of jobs and the growth of large cities.

The invention of the electrical generator in the late 1800's produced a new way to exploit hydropower for the growth of civilization. By marrying water turbines to generators with belts and gears, a reliable source of electricity was created that could be used to power factories and businesses around the clock. The large supply of rivers and streams in the Eastern U.S. became a readily-available source of energy that was quickly exploited. The first hydroelectric power plant was built in Niagara Falls in 1881 to power streetlights in the city. Before the end of that decade, over 200 additional power plants were built in the U.S.[1]

The creation of the Bureau of Reclamation in 1902 further sped the development of hydroelectric power in the U.S. The Bureau was created to "reclaim" arid lands in the U.S. and make them farmable and livable. This was to be done by providing irrigation water for homesteaders in the Western U.S. who had been lobbying for more water to operate their farms and ranches. In order to meet these needs, the Bureau set out on a dam building program throughout the region. Initially, the dams were funded by selling land and mineral leases. From 1902 to 1928, this resulted in about 60 dams being built, of which 7 had hydroelectric units attached. However, in 1928, the Boulder Canyon Project Act was passed, which started U.S. Treasury funding of projects as well as allowing the selling of electricity from hydroelectric facilities. Over the following 40 years, it resulted in over 160 additional dams being built, with 49 of these having hydroelectric facilities[2]. This dam building spurt created a massive increase in the amount of hydroelectric energy produced, tripling it from 1 quadrillion BTU's of energy to over 3 quadrillion by the late 1970's. Figure 1 shows a plot of the amount of hydroelectric energy produced in the U.S. since the 1880's[3].

The year 1968, though, saw the last major dam building projects for the Bureau passed by Congress. This was done with the Colorado River Basin Projects Act. Since that time, the Bureau has built fewer than 20 dams, and hydroelectric capacity has leveled off.

Environmental Problems

What happened to this resource that once showed such great potential for growth? At one time, hydroelectric power accounted for almost 40% of America's electrical consumption. Today, it is closer to 7%. From 1980 until today, there has been no appreciable increase in hydroelectric power production,

while other forms of electricity production have been increasing. In the last decade or so, we have begun the process of tearing done dams rather than building them. The answer to this question of loss of enthusiasm for hydroelectric power is multi-faceted.

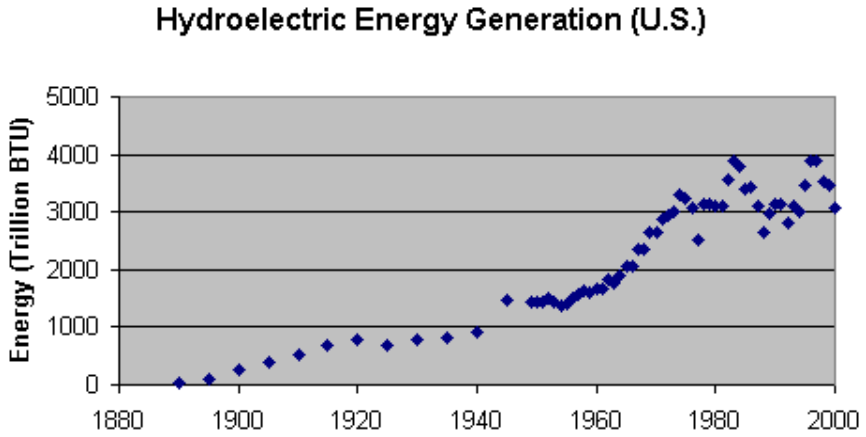


Figure 1: Historical hydroelectric energy generation in the U.S.

First of all, hydroelectric power is not as cheap as we often think. While there is no cost for fuel, as there is with coal and oil, there is a heavy cost for construction, upkeep, and land rights. The hydroelectric facilities that were built in the early part of the 1900's were usually built as part of a larger project to provide drinking and irrigation water for citizens of an area. The money made from selling electricity was used to offset the cost of building and maintaining the reservoir for these purposes. Furthermore, the dams that were built were done so in locations that the most geologically feasible. The spots that remained for dams after these were built were much less desirable, and would have required substantial amounts of engineering and construction to make them safe.

More importantly, conventional hydroelectric power is not as "clean" as we would like to believe. The dams built for these purposes have a substantial environmental impact. They convert a river ecosystem into a lake ecosystem overnight. While both of these systems have water, the type of plant and animal life in each can be radically different. Organisms that might get by fine in a river system can be completely wiped out by a lake system. A perfect example of this is the fate of the Pacific salmon, which needs to be able to navigate upstream in a river system to spawn. Even though mankind has tried many solutions to creating paths for salmon to use for migration, including building elaborate and expense "ladder" systems along the dams, population numbers have continued to increase in regions with these dams to the point were they are critical.

Building these hydroelectric dams also affects other ecosystems during this conversion process. Rivers and streams provide a natural means of transporting silt, sediment, and nutrients from steeper-sloped regions to fertile flatland and coastal regions. Many of the world's richest farmlands lie in flat regions near major river systems, where regular flooding deposits rich nutrients back to the soil. When water is stilled by entering a reservoir behind a dam, it loses its ability to keep sediments and nutrients suspended in solution, causing them to fall out of the water onto the bottom of the reservoir. When the water heads back downstream, it has lost all of the fertile material, meaning that few to no nutrients are put back into the soil. A prime example of this is what has happened along the Nile Delta region in Africa. For more than 3,000 years, farmers have been reaping tremendous yields of grains from the region without the aid of any type of natural or artificial fertilizers. However, within 30 years of the building of the Aswan Dam on the Nile River, chemical fertilizers became necessary in order to achieve profitable yields for farmers.

There are other environmental changes that are wrought by building dams. However, the one that seems to get the smallest amount of press and which might be its greatest effect is that dams are responsible for the release of greenhouse gases. At first, this seems absurd, as hydroelectric facilities do not involve any type of combustion. However, in filling up the reservoir, fast areas of land are covered in water. Before they are covered, many regions contain a fair amount of land-based plant material. After these regions

are covered with water, the plants die and begin to breakdown. If there is enough oxygen in the water, this breakdown will result in the production of carbon dioxide, which is a greenhouse gas. This is exactly the same gas into which the plants would have been broken down if the plants had died above ground. However, after awhile, the oxygen levels at the bottom of the lake will not be sufficient to support this type of breakdown of plant material. In this type of low-oxygen environment, the material is broken down into methane, which is a much more serious type of greenhouse gas. Thus, hydroelectric dams are not totally free from greenhouse gas emissions.

Physics

Two Types of Energy

How do hydroelectric dams work? What factors affect their performance? To answer these questions, let us first look at the physics behind hydroelectric power. All forms of energy can be classified into one of two categories: kinetic energy or potential energy. Kinetic energy is the energy that an object has because of its motion relative to its surroundings. It has the ability to do work on other objects by applying a force to those objects in order to change its velocity. For example, a cue ball that is rolling across the table has kinetic energy relative to the other billiard balls on the table that are static. If the cue ball hits another ball, it applies a force to the second ball over a very small distance. This force changes the cue ball's velocity while it transfers energy to the static ball, and thus, it does work.

The other category of energy is potential energy. This is the energy that is stored in a system by virtue of forces between objects that are separated by some distance. If the objects are allowed to move under the influence of the force between them, then work is done as the force displaces the objects from their initial positions, and energy is transferred. A prime example of this is gravitational potential energy. A ball that is dropped from rest at some height above the Earth's surface will begin to accelerate downward as gravity pulls it. As the ball accelerates, gravity is working on it to convert its potential energy into kinetic energy (the ball's height decreases as its velocity increases). If the ball is dropped from a higher altitude, then gravity operates over a greater distance, thereby generating more kinetic energy, i.e. the gravitational potential energy of an object depends upon the height through which an object is allowed to fall.

Gravitational Potential Energy

Newton's Universal Law of Gravity tells us that the gravitational force between two objects depends upon the inverse of the square of the distance between the objects and is, therefore, not a constant force with displacement. However, if we limit the movements of the objects to small values compared to the total distance between them, then we can consider the force of gravity to be a constant. Objects falling near the surface of the Earth fall into this category. The distance between the center of the Earth and the center of any object near the surface is over 4,000 miles. If we limit the object to fall a distance of less than a mile, then the change in the force of gravity over that distance is less than .05%. Thus, we can take it to be a constant. In this situation, Newton's Universal Law of Gravity reduces to the expression:

$$\mathbf{F_{gravity} = mass \times acceleration\ due\ to\ gravity\ near\ Earth}$$
$$\mathbf{= mass \times 9.80\ m/sec^2}$$

Since the force is a constant, the potential energy is merely this force multiplied by the distance through which the object falls. If we allow H to be the height through the object will fall, then the potential energy of the object is:

$$\mathbf{P.E. = F_{gravity} \times H = mass \times 9.80\ m/sec^2 \times H}$$

For a hydroelectric dam, the object that is "falling" is water. The mass of the water that is falling is determined by how much volume it occupies. The relationship between the two is given by the formula mass = density x volume. For fresh water, the density is 1 gm/cm^3, which is equivalent to 1000 kg/m^3. Thus, our formula for the potential energy of a volume of water V that falls through a height H is

P.E. = (9800 J/m^4) x VH

where J is the symbol for the unit of energy called the joule.

When we write about the water “falling”, we are giving a somewhat false impression of how a hydroelectric dam works. Figure 2 is a diagram of a conventional hydroelectric facility. As you can see, the water does not fall onto the turbine to turn it. Instead, the water near the bottom of the dam is forced by the pressure of the water above it past the turbines. While this is not the same as falling onto the turbines, it turns out that it is equivalent mathematically. Therefore, the formula that we derived above for potential energy is the one used for a dam, where H is the difference in heights between the surface of the water in the reservoir and the turbine.

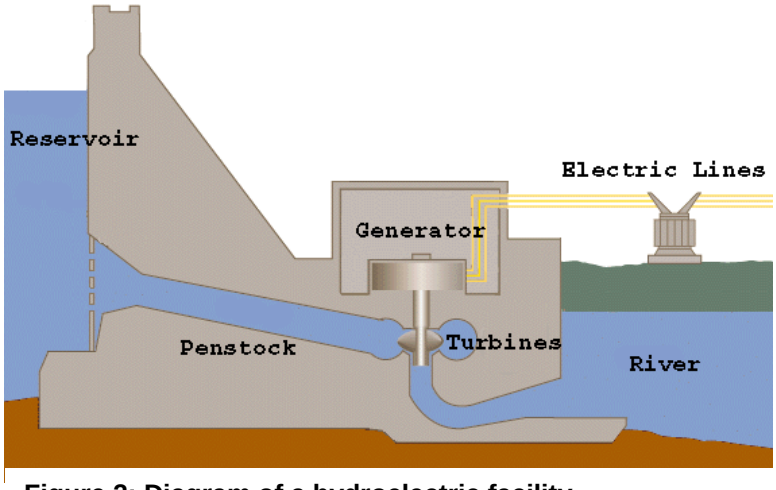


Figure 2: Diagram of a hydroelectric facility

Efficiency

This potential energy, though, will not be the actual amount of electrical energy that we can get out of the dam. This is because of the first and second laws of thermodynamics. The first law states that "Energy can neither be created nor destroyed; it can only be transferred from one form to another." While this statement of the first law is the most common expression of it, it really does not say anything about how energy can be transferred. In mathematical terms, the first law is normally stated as

$\Delta E = W + Q$

where ΔE is the change in the energy of an object, W is the work done on the object, and Q is the heat added to the object. In laymen's terms, this means that the only way to change the energy of an object is to either do work on it or add heat to it (it should be noted that having the object do work on its surroundings, or allowing the object to give off heat, are equivalent to having negative values for W or Q).

The First Law of Thermodynamics tells us that the energy involved in any transfer must be conserved. This would seem to mean that we should never run out of energy and should pay no heed to anybody talking about an energy crisis. The problem is that this is not the only law that governs energy transfers. While the total amount of energy does not change, the second law of thermodynamics puts limits on the amount of usable energy that can be transferred. One of the consequences of this law is that the total amount of usable energy that comes out of any process will be less than the total amount of energy that went into the process. The difference between the total amount of energy input and the usable energy output is expended as waste heat.

This brings us to the issue of efficiency, which is a measure of the amount of usable energy that is generated during any type of transfer. If a transfer is very efficient, then the amount of usable energy that is generated is almost equal to the total amount of energy that went into the transfer. This means that very little waste energy will be produced. An inefficient transfer, conversely, is one in which most of the energy going into the process is converted to waste heat. For example, a fluorescent light bulb converts about 20% of the electrical energy that runs through it into visible light energy. While this may not sound like a very efficient transfer, it is much better than the 5% efficiency of an incandescent light bulb, which most people use.

When discussing the efficiency of a process, we have to make sure and not forget all of the transfers that might need to take place in order to get to the one under investigation. A great example of this occurs when comparing the efficiencies of electric and internal combustion engine powered cars. The efficiency of the electric motor in a car is about 90%, while the efficiency of the internal combustion engine is only about 25%. However, these efficiencies are not the only things that need to be considered when comparing the two devices. How is the electricity that charges the car created? Where does the gasoline come from that powers the internal combustion engine? What types of transmission systems does each car have? There are many steps and energy transfers that take place in getting each type of car to move, and each one of these has its own individual efficiency. For instance, the average coal burning electric plant is only about 30-35% efficient in generating electricity (some newer natural gas plants are closer to 50-60%). This fact greatly reduces the overall efficiency of an electric car. When we consider the total efficiency, from getting the energy from its natural source to the car moving down the highway, we find that the electric car is only about 20% efficient, while the internal combustion engine automobile is about half that at 10%[4].

Turbine Generator

These same types of rules apply to a hydroelectric dam. Not all of the potential energy of the water behind the dam is realized. The water running through the pipes encounters drag forces from the pipe walls. The water hitting the turbines generates some heat, as does any type of collision. The water leaving the turbine still has some kinetic energy, which is energy not given to the turbine. Accounting for all of the energy losses in the system, the system is still about 80-90% efficient, which is one of the highest efficiencies for any type of electricity generating facility that we use in society today.

In this week's experiment, we are going to model this system in the laboratory. A picture of the type of turbine generator that will be used for this activity is shown in Figure 3. This type of generator can be purchased from scientific equipment supplies, along with probes that will measure the amount of electricity generated (the unit in Figure 3 was purchased from Pasco Scientific). This experiment transfers the potential energy of water from a plastic container that is placed a height H above the generator to the kinetic energy of the moving turbine blades on the generator. The generator then transfers this kinetic energy to electrical energy by spinning a magnetic in the wire coil on the top of the generator. This electrical energy will be sent to a computer that will monitor the output. From the energy measured by the computer, we will plot the dependence of potential energy on height, as well as calculating the efficiency of energy transfer in the turbine generator.

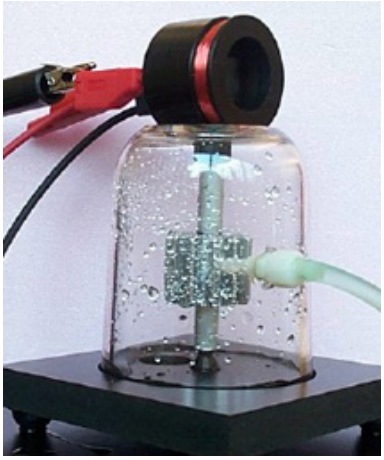


Figure 3: Turbine Generator

As stated previously, the amount of gravitational potential energy that an object has should depend upon the height through which it is allowed to fall. Theoretically, this dependence should be linear, i.e. the amount of gravitational potential energy an object is equal to some constant times the height of the object. Therefore, if everything else in the system is linear, this means that the amount of electrical energy produced should depend linearly on the height of the water.

The other issue that we are going to investigate is the efficiency of the total energy transfer from gravitational potential energy to electrical energy. By plugging in the height of each individual run, this formula gives us the total amount of energy in the system at the start. The computer will measure the amount of electrical energy that is output by the generator. Thus, we should be able to compute the efficiency of the system using the formula:

Efficiency = (electrical energy output)/(potential energy)
= (electrical energy output)/[(9800 J/m^4) x VH]

When using this formula in the lab, be sure that both the electrical energy output and the potential energy have the same units of energy. If you measure V in cubic meters and H in meters, then the units for potential energy should be in joules, which is a watt-second. Ask your instructor to make sure that you are using the proper units on your lab.

Additional Reading

The links below provide more information about hydroelectric dams and the agencies that oversee them.

Department of Energy	**Topic**: Hydropower **Summary**: Energy Efficiency and Renewable Energy division's homepage with links to various hydropower topics. **Link**: http://www.eere.energy.gov/RE/hydropower.html

Bureau of Reclamation	**Topic**: Bureau of Reclamation – Reports and Data **Summary**: Information about the generation and capacity of hydroelectric facilities under the Bureau's control. **Link**: http://www.usbr.gov/power/data/faclcap.html

Reference

1 http://www.usbr.gov/power/edu/history.htm, July 9, 2003
Updated 2006-Aug 1: New URL is http://www.usbr.gov/power/who/history.html

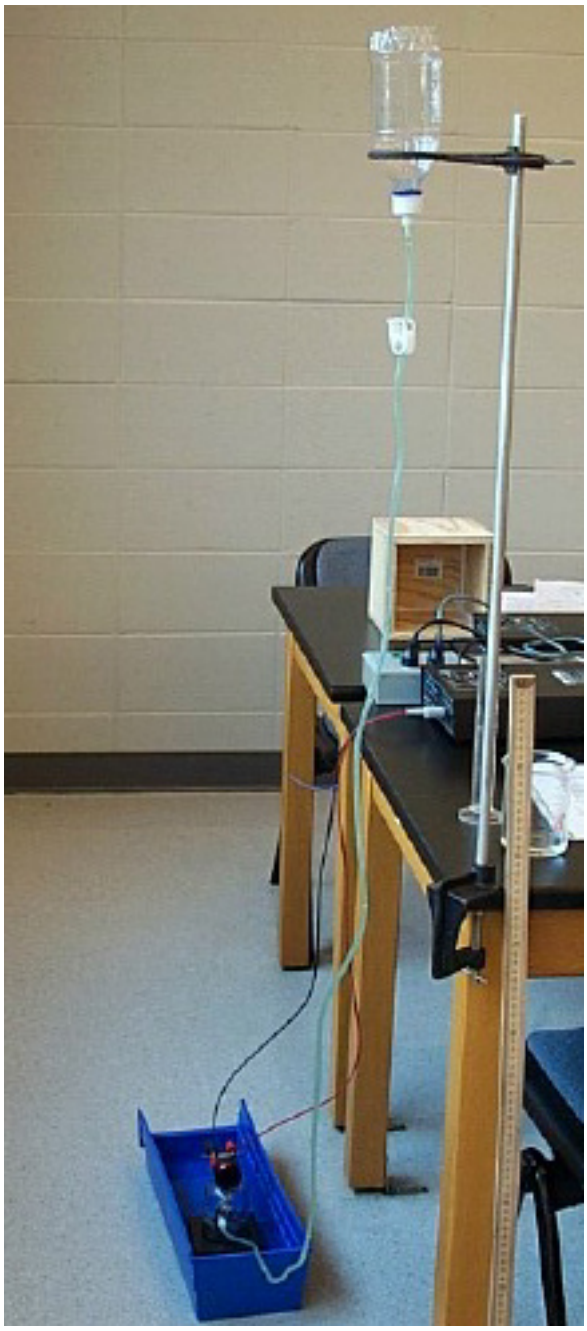
2 Personal communications with Brit Story, Senior Historian, Bureau of Reclamation.

3 http://www.eia.doe.gov/emeu/aer/txt/ptb1801a.html and
http://www.eia.doe.gov/emeu/aer/txt/ptb0103.html, July 9, 2003
Updated link: http://www.eia.doe.gov/emeu/aer/txt/ptb1701.html, August 19, 2006.

4 Energy: Its Use and the Environment, 2nd Edition by Roger A. Hinrichs, Saunders College Publishing, Orlando, 1996.

Activity

1. At your lab station, you should find an experimental set-up as shown in the diagram to the right. You should also find an 800 mL beaker and a 100 ml graduated cylinder for putting water into the upper container. If you do not find these things at your station, please see your lab instructor for help.
2. Place the turbine generator in the tray to catch the water that leaves the turbine. Note: This tray must be emptied after 2-3 runs to ensure that the hole in the bottom of the generator is not plugged by water.
3. Connect the voltage sensor to both sides of the output from the generator.
4. Make sure that the Data Studio software is running on the computer. If it is not, or if you need help running it, see your lab instructor.
5. Place the water container at a height such that the average level of the water is 1.10 meters above the generator. Make sure that the tubing is **not** sagging below the level of the generator opening. If it is, move the generator so that the water will flow constantly downward to the generator.
6. Close the water valve on the hose below the water container.
7. Pour 150 ml of water into the container.
8. Click the Start button on the Data Studio software. Open the valve on the hose to release the water after the software has started recording data.
9. After all of the water has gone through the turbine, and the generator has stopped turning, click the Stop button on the Data Studio software.
10. Record the amount of energy measured from the output, and then delete the data set from the screen.
11. Repeat 6-10 4 more times. Average the energy output for all 5 runs.
12. Increase the height of the container by .10 meters and repeat steps 2-11.
13. Repeat steps 2-12 until you have reached a height of 1.50 meters.



ESA21: Environmental Science

Activity Sheet
Turbine Generator

Name: Professor:

Energy Output From Generator

Height	Run 1	Run 2	Run 3	Run 4	Run 5	Average
1.10 meters						
1.20 meters						
1.30 meters						
1.40 meters						
1.50 meters						

Graph

Plot a graph of the energy output from the generator versus the height of the water in the area below. Be sure to label your axes appropriately.

Efficiency

Height	Avg. Elect. Energy (from above)	Potential Energy (from theory)	Efficiency
1.10 m			
1.20 m			
1.30 m			
1.40 m			
1.50 m			

Average Efficiency = _____