12

Run of River and Pump Storage Hydroelectric Plants

12.1. Overview

As already discussed, hydroelectric power schemes use the available water energy from a river, stream, canal system, or reservoir to produce electrical energy. Hydroelectric schemes can be further divided as; reservoir and run of river hydroelectric schemes. Reservoir hydroelectric schemes uses dam to store water, which may be released either to meet changing electricity needs or for other purposes, such as irrigation. Run of river hydroelectric power plants do not store water (except as storage of means for regulating the flow), the plant uses water as it comes and can use water as and when available. Such plants depend for their generating capacity primarily on the rate of flow of water. During rainy season high flow rate may mean some quantity of water to go as waste while during low run-off periods, due to low flow rates, the generating capacity will be low. Many creeks and rivers are permanent, that is, they never dry up, and these are the most suitable for hydropower production. Stand-alone run of river hydroelectric systems are used to provide power to homes, farms and small commercial businesses. There are also numerous commercial electricity generating plants using runoff, feeding the energy grids around the world. Before considering this type of hydro system, the site must be assessed as having sufficient volume of falling water in the stream or river. The basic difference between the two hydroelectric schemes is that in case of a hydroelectric scheme with dam, the potential energy of water is converted to electrical energy; whereas in the case of run-of-river hydroelectric schemes the kinetic energy of water is converted to electrical energy.

There are two major issues with reservoir schemes, which require serious thinking that might help to approach them independently. The first issue is the large, manmade lakes behind the dams. Thousands of acres of land lie below these lakes, once a habitat for countless plants, animals, and people. These reservoirs swarm with wildlife, both underwater and along the shoreline. The second issue is the fish migration, in part because of the recent addition of salmon to the endangered species list. The stream still flows in parallel with the hydro system, providing an unencumbered path for fish migration. Traditional hydro dams thus store enormous quantities of water in reservoirs, necessitating the flooding of large tracts of land. In contrast, most run-of-river projects do not require a large impoundment of water, which is a key reason why such projects are often referred to as environmentally friendly, or 'green power'. Run of river and pump storage hydro plants have many advantages. In contrast to reservoir hydropower, such hydroelectric projects typically cast a very small ecological footprint provided good design principles are exercised. Because most such hydro systems are smaller; typically a few hundreds megawatts, they occupy very little space and tend to blend into the environment. This makes them ideal for smaller streams and rivers where a reservoir system is not considered appropriate. A side benefit is that it can be made to serve the local population in which case the transmission lines are much shorter. This reduces transmission losses by providing locally generated power instead of requiring lines from large generating plants that may be hundreds of miles away. These are important considerations today, as potential sites for large reservoir systems are extremely limited and often give rise to political and socio-economic issues. There are thousands of smaller streams that could be used for run of river hydroelectric schemes with minimal visual and environmental impact.

12.2. Run of River Plants

Run of the river hydroelectric plant is a type of hydroelectric generation whereby the natural flow and elevation drop (hydraulic gradient) of a river are used to generate electrical energy. Hydraulic gradient of a water channel is obtained by.dividing the difference of elevation between two selected points by the horizontal distance between the selected points. Power stations of this type are built on rivers with a consistent and steady flow, either natural or through the use of a suitable size reservoir at the head of the river which then can provide a regulated steady flow for stations down-river. A reservoir, often smaller than that used for traditional hydroelectric schemes is required to ensure that there is enough water to enter the penstock or conduit leading to the lower-elevation turbines. Such projects divert some or most of a river's flow (up to 95% of mean annual discharge) through a pipe and/or tunnel leading to the turbines, then return the water back to the river downstream. Run of river projects are dramatically different in design and appearance from traditional hydroelectric schemes with dams. In recent years, many of the larger runs of river projects have been designed to a scale and generating capacity comparable to some traditional hydroelectric schemes. The classification, however, is according to the quantity of water available and whether storage is incorporated or not.

12.2.1. Run of River Plants without Storage

Run of river hydroelectric plants of this type use the natural downward flow of rivers and a turbine and generator to convert the kinetic energy carried by water into electrical energy at the generator output. The most suitable place to build run of river hydroelectric plant is in hilly areas or region of gradient where the water flows efficiently. The distance that the water drops on its way to the power plant is known as the head. Increasing the head of run of river plant will impart the water with more energy, thus allowing more electrical energy from a smaller volume of water. Figure 12.1 shows a schematic diagram of a run of river hydroelectric scheme without incorporating storage. Typically, water is taken from the river at a suitably higher point and fed down a pipe or channel by gravity to a lower point where it emerges through a turbine generator and re-enters the river downstream. A low level diversion weir raises the level of the river water just enough so that a structure for intake can be situated on, or next to the river. A stream bed intake requires no weir. The power plant is located at as low a level as possible to obtain maximum possible head for the turbine. The water leaves the power plant and is returned to the river without altering the existing flow or water levels. The run of river plant of this type, however, have a drawback of fluctuations of water flow in streams. The fluctuating water flow causes the output electrical power to fluctuate, thus posing a problem of regulation.

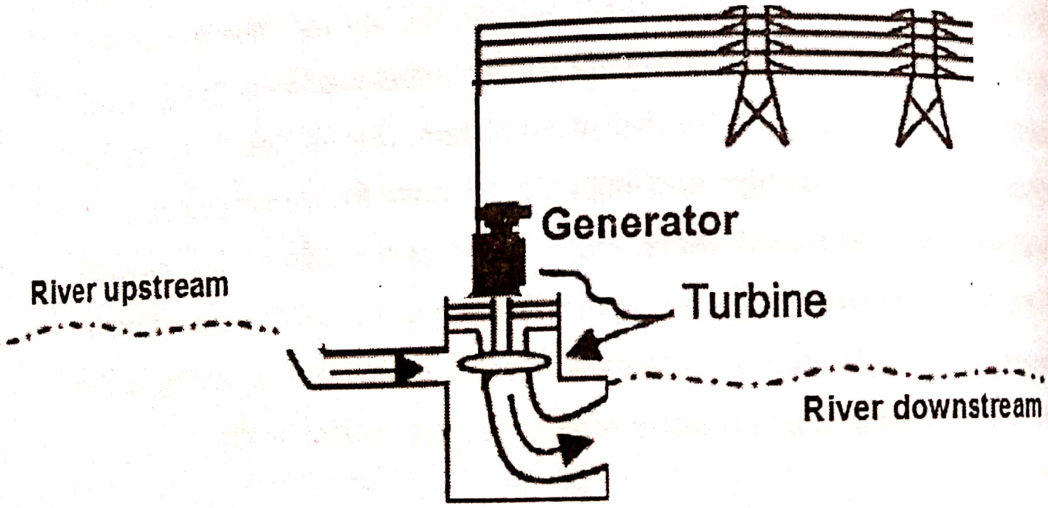

Figure 12.1: Run off River Plant without Storage

Run of river projects are much less costly than dams because of the simpler civil works requirements. They are, however, susceptible to variations in the rainfall or water flow which reduce or even cut off potential power output during periods of drought. Because of these limitations and if the construction of a dam is not possible, run of river installations may need to incorporate some form of power supply backup to the community from the grid.

12.2.2. Run of River Plants with Storage

Figure 12.2 is a diagram of run of river plant with reservoir. Installing a reservoir is a useful way to regulate the amount of flow through run of river power plant. Installing a dam will provide a reservoir of water that can also generate power during dry spells and limit excessive flow rates. During flood conditions the installation may not be able to accommodate the higher flow rates and water must be diverted around the turbine losing the potential generating capacity of the increased water flow. Water is routed to power plant from the top of the dam or weir through a pipe. Dams artificially increase the height of the stream's head, making system more efficient. Although dams can make power plant more effective, however, building a dam is an expensive process that requires extensive surveys and legal permits.

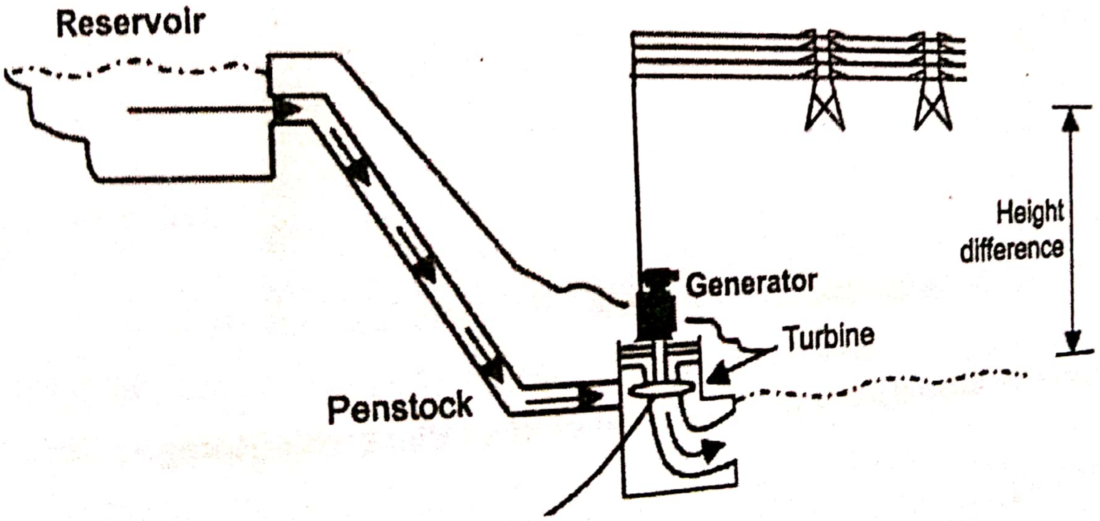

Figure 12.2: Plant with Reservoir

In conventional multipurpose reservoirs and run of river systems, hydropower production is just one of many competing purposes for which the water resources may be used. Competing water uses include irrigation, flood control, navigation, and municipal and industrial water supply. In these plants, storage permits accumulation of water during off peak periods and use of this water during peak periods. Depending on the size of storage provided it might be possible to cope with hour-to-hour fluctuations. This type of plant can be used on parts of the load curve as required, and is more useful than a plant without storage. When providing storage, tailrace conditions should be such that floods do not raise tailrace water level, which can reduce the head on 'he plant and thus impairing its effectiveness. This type of plant is comparatively more reliable and its generating capacity is less dependent on available rate of flow of water. A residual flow must be maintained in the river to support the hydrological and ecological health of the river and vicinity. Ghazi Barotha hydroelectric power plant shown in Pakistan shown in figure 12.3 is an example of this type.

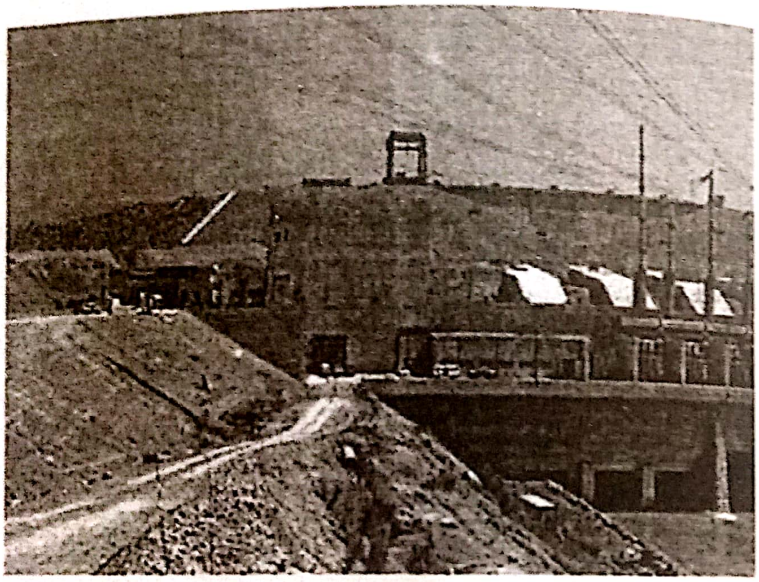

Figure 12.3: Ghazi-Barotha (Pakistan) Run of River Plant with Storage

12.3. Working

In a run of river facility, a portion of the river water is diverted to a concrete intake structure, called the forebay. The water from the forebay flows through a steel grill, called a trash-rack, which removes any additional debris as discussed in chapter 11. The purpose of the forebay is therefore to allow large debris in the water to settle so that none enter the facility. Debris can seriously damage the turbine. If a small dam or weir is used, the water from the head pond flows through a trash-rack and gate. In this arrangement, a spillway might be provided to allow excess water to flow downstream, and a fish ladder might be installed to aid fish to swim upstream past the dam or weir.

The water then flows into some combination of canal, tunnel, pipeline, and penstock (pressurized pipeline), where it is delivered to the powerhouse, which could be located as much as two miles downstream from the intake. Canals are generally excavated and follow the contours of the terrain. Drilling and blasting are used to excavate tunnels. Pipelines can follow the contours of the land or be buried. Pipelines and penstocks can be made of steel, plastic, or concrete. Water from a fast flowing river or stream is diverted through these channels to a turbine, often a Pelton wheel impulse type that drives the electrical generator. Impulse turbines which are only partially submerged are more commonly employed in fast flowing run of river installations while in deeper, slower flowing rivers, submerged Kaplan turbines may be used to extract the energy from the water flow. The head of water is essentially zero and the turbine converts the kinetic energy of the flowing water into the rotational energy of the turbine and the generator.

12.4. Available Power

The maximum power output from a turbine used in a run of river application can be obtained by realizing the kinetic energy of the water flux incident on the blades. That is:

$$KE = \frac{1}{2}mv^2 \tag{12.1}$$

Where v is the velocity of the water flow. From the definition of the density; mass is equal to ρV. Substituting in equation 12.1, we have:

$$KE = \frac{1}{2}\rho V v^2$$

Taking the efficiency η of the system and its installation into account, the maximum output energy E is given by:

$$E = \frac{1}{2}\eta\rho V v^2 \text{ Joules} \qquad 12.2$$

If both sides of equation 12.2 are divided by time t, then the left hand side will be the electrical power output P_{max} and using the definition of discharge (volume per unit time); $q = V/t$, where V is the volume, then:

$$P_{max} = \frac{1}{2}\eta\rho q v^2 \text{ Watts}$$

The available power therefore depends on the quantity of water flowing through the turbine and the square of its velocity. Since: $v = \sqrt{2gh}$, then:

$$P_{max} = \eta\rho q g h \text{ Watts} \qquad 12.3$$

Thus the power generated by one cubic meter of water flowing at one meter per second through a turbine with 100% efficiency will be 0.5 kW or slightly less when the inefficacies in the system are taken into account. Run of river power is considered an 'unfirm' source of power, since most run of river project without storage has little or no capacity for energy storage and hence sometimes cannot co-ordinate the output of electricity generation to match consumer demand. It can, however, generate much more power during times when seasonal river flows are high and much less during drier summer months and winter.

Example 12.1: The water for a small run of river plant is to be diverted from a river upstream through a conduit (penstock) with diameter of 1 meter. Calculate the maximum amount of electrical power that can be obtained if the velocity of flow of water is 3.5 m/s assuming the overall efficiency of the system to be 75%.

Given that:

$v = 3.5$ m/s

$\eta = 75\%$ or 0.75

Conduit diameter: $d = 1$ m.

Therefore the area of cross section of the conduit is:

$$A = \frac{\pi d^2}{4} = \frac{3.14 \times 1}{4} = 0.785 \text{ m}^2$$

The available discharge q is then:

$$q = Av = 0.785 \times 3.5 = 2.74 \text{ m}^3/\text{s}$$

The electrical power that can be made available is then calculated using:

$$P_{\max} = \frac{1}{2}\eta\rho q v^2$$

Or

$$P_{\max} = \frac{1}{2} \times 0.75 \times 1000 \times 2.74 \times (3.5)^2 = \mathbf{12.6\ kW}$$

Example 12.2: A hotel in a holiday resort is located near a waterfall where the effective head of 30 meters is available by diverting water through a stream. The hotel requires continuous power of 650 kW throughout the year. The hydrograph of the stream is as follows:

Number of months	Discharge (m^3/s)
5	10.5
1	6.5
6	2.2

Assuming an overall efficiency of 78%, calculate the maximum electrical power that can be made available with and without water storage.

Given that:

Head: $h = 30$ m

Efficiency: $\eta = 78\%$ or 0.78

First let us calculate the amount of power that can be made available when no water storage system is incorporated; that is straight run of river without storage. The year-round power can be calculated for each discharge given in the table. Thus for the first 5 months the electrical power will be:

$$P_{max} = \eta \rho q g h = 0.78 \times 1000 \times 10.5 \times 9.81 \times 30 = \textbf{2410.32 kW}$$

For the next one month when the discharge is 6.5 m^3/s, the electrical power that can be generated will be:

$$P_{max} = 0.78 \times 1000 \times 6.5 \times 9.81 \times 30 = \textbf{1492.1 kW}$$

For the next six months when the discharge is 2.2 m^3/s, the electrical power that can be generated will be:

$$P_{max} = 0.78 \times 1000 \times 2.2 \times 9.81 \times 30 = \textbf{505 kW}$$

It can be seen that the hotel will require a standby plant to fulfill its electricity requirements for six months of the year when the discharge is minimum. Next, let us calculate the availability of power all round the year when a water storage system is incorporated. The water storage system must have a capacity so that a uniform flow is available for the whole year. Thus in this case the average discharge q_{av} for the whole year is worked out as:

Thus: $$q_{av} = \frac{10.5 \times 5 + 6.5 \times 1 + 2.2 \times 6}{12} = 6.01 \text{ m}^3/\text{s}$$

The average power is: $P_{av} = \eta \rho q_{av} g h = 0.78 \times 1000 \times 6.01 \times 9.81 \times 30 =$ **1381.15 kW**

Thus by incorporating storage, the hotel will not only be self sufficient to fulfill its requirements but will be in a position to sell electrical energy to the national grid.

Example 12.3: The hydrograph figures of weekly discharge of a stream flowing near a housing scheme are given in the table.

Month	January	February	March	April	May	June
Discharge (m^3/s)	500	690	880	850	920	865
Month	July	August	September	October	November	December
Discharge (m^3/s)	900	875	795	650	600	550

It is desired to build a run of river hydroelectric plant incorporating storage. Calculate the maximum power that can be produced with an overall efficiency of 80% at an effective head of 18 meters. If the load factor of the housing scheme is 60%, estimate the size of the reservoir required and the rating of the generator.

Given that:

Head: $h = 18$ m

Efficiency: $\eta = 80\%$ or 0.80

The average annual discharge q_{av} is:

$$q_{av} = \frac{500+690+880+850+920+865+900+875+795+650+600+550}{12}$$

or

$$q_{av} = 756.25 \text{ m}^3/\text{s}$$

The average discharge will provide the average power. Therefore using:

$$P_{av} = \eta \rho q_{av} g h$$

Or

$$P_{av} = 0.8 \times 1000 \times 756.25 \times 9.81 \times 18 = \textbf{106.83 MW}$$

Pondage required will be in accordance with the volume of water available to give an average annual discharge of 756.25 m^3/s. Thus the volume of water required is:= 756.25 x 365 x 24 x 3600 = **2.385 x 10^{10} m^3**

The rating of the generator will be based on maximum demand, which can be calculated by knowing the average power and the load factor; that is:

$$F_{LD} = \frac{P_{av}}{P_{max}}$$

Or

$$P_{max} = \frac{P_{av}}{F_{LD}} = \frac{106.83}{0.6} = \textbf{178 MW}$$

12.5. Advantages of Run of River Plants

1. Like conventional hydroelectric power with dams, run of river hydroelectric schemes also harnesses the natural energy of water and gravity thus eliminating the need to burn coal or natural gas to generate the electricity needed by consumers and industry and is thus regarded as environmental friendly.

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

12.6. Disadvantages of Run of River plants

1. Diverting large amounts of river water reduce river flows affecting water velocity and depth, which might minimize habitat quality for fish and aquatic organisms. Reduced flows can lead to excessively warm water for salmon and other fish in summer. This means that conflicts will arise over the water needed to both sustain aquatic life and generate power when river flow becomes more variable or decreases in the future.

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

12.5. Pump Storage Plant

In a conventional hydropower plant, the water from the reservoir flows through the plant, exits and is carried down stream. In a pump storage plant, the water, once flow past the turbine system is directed to another reservoir, which can then be re-used. The first use of pumped storage plant was in Italy and Switzerland in the 1890s. In the 1930s reversible hydroelectric turbines became available, which could operate as both turbine-generators and in reverse as electric motor driven pumps. The latest in pump storage hydroelectric engineering technology; are variable speed machines to achieve greater efficiency. These machines can generate in synchronization with the network frequency, and can operate asynchronously (independent of the network frequency) as motor-pumps. Pump storage hydroelectric plants can act as peak load and emergency plants. A new use for pumped storage is to level the fluctuating output of wind powered generators.

A layout of a pump storage plant is shown in figure 12.4. Pumped storage hydroelectricity is a method of storing and producing electricity to supply high peak demands by moving water between reservoirs situated at different elevations. At times of low electrical demand, excess electrical capacity is used to pump water into the higher or upper reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating hydroelectricity. A pumped-storage plant has two reservoirs:

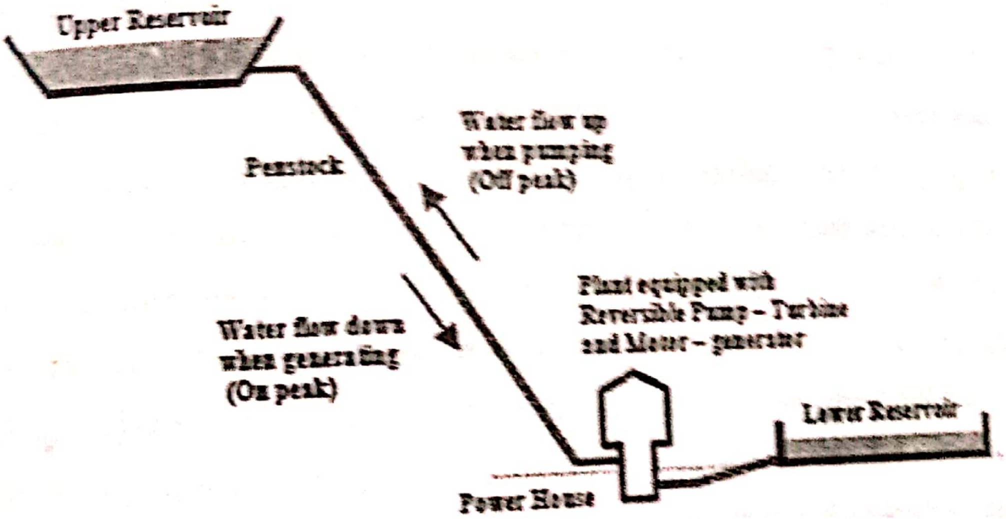

Figure 12.4: Layout of a Pump Storage Hydroelectric Plant

Upper Reservoir: The upper or intake reservoir is situated at a hieght, producing the necessary head for the generation of power, like a conventional hydropower plant in which case a dam creates a reservoir. The water in this reservoir is collceted from streams of rain water. Constant supply of water, however, depends on the precipitation in the area. This type of power station is therefore beneficial in hilly areas which receive ample amount of rainfall and where the rain water can be collected in estuaries, forming ponds and lakes. The water in this reservoir flows through the hydropower plant to create electrical energy.

Lower Reservoir: Once water is made to flow past the turbine system, water from the hydropower plant flows into a lower or tailrace reservoir rather than re-entering the river and flowing downstream. Some facilities use abandoned mines as the lower reservoir, but many use the height difference between two natural bodies of water or artificial reservoirs.

Reversible turbine/generator assemblies act as pump and turbine (usually a Francis turbine design). Using a reversible turbine, the plant can pump water back to the upper reservoir. This is usually done in the off-peak hours. Essentially, the lower 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 load. During peak hours, water is released back into the lower reservoir through a turbine, generating electricity. Pure pumped-storage plants just shift the water between reservoirs to produce electrical energy. On the other plants can be designed as combined run of river and pump-storage plants generating electricity during rainy or high flow seasons through natural stream-flow besides operating as traditional pump storage plant during dry seasons.

Pumped storage hydroelectric plants works on a remarkably simple principle. To start with, two reservoirs at different altitudes are required. As illustrated in figure 12.4, water stored at height offers valuable potential energy. During periods of high electrical demand, the water is released to the lower reservoir to generate electricity. When the water is released, kinetic energy is created by the discharge through high-pressure conduits, which direct the water through reversible turbine connected to generator / motor. The turbine drives the generator to produce electrical energy. After the generation process is complete, water is pumped back by grid supply system to the upper reservoir for storage, the generator now working as a motor. The supply can be made available from external grid during off-peak hours. The process usually takes place overnight when electricity demand is at its lowest. The plant is then ready for the next similar cycle of generating electrical energy during peak hours. While pumped storage facilities are net energy consumers, they are valued by a utility because they can be rapidly brought on-line to operate in a peak power production mode. This process benefits the utility by increasing the load factor and reducing the cycling of its base load units. In most cases, pumped storage plants run a full cycle every 24 hours.

Pumped storage projects are net consumers of energy in that for every one kWh of energy generated during peak periods, more than one kWh of off-peak energy is required for pumping. Due to evaporation losses from the exposed water surface and mechanical efficiency losses during conversion, only between 70% and 85% of the electrical energy used to pump the water into the elevated reservoir can be regained in this process. This system is still economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants that provide base-load electricity to continue operating at peak efficiency while reducing the need for 'peaking' power plants that use costly fuels (for example diesel electric and gas turbine power plants). Along with energy management, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds. The technique is currently the most cost-effective means of storing large amounts of electrical energy. The relatively low energy density of pumped storage systems requires 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 pond of water located on a hill relatively near, but as high as possible above, a second pond of water. In some places this occurs naturally, in others one or both ponds of water can be man-made.

Because of the energy losses inherent in pumped storage, the carbon dioxide emissions associated with its use will be higher than that of the original power source. When coal-fired power is the driver of the pumped storage, there is likely a net increase in system carbon dioxide emissions. However, a net reduction in greenhouse gas emissions can be realized with pumped storage when the fuel providing electricity for pumping have comparatively lower carbon content (or no carbon content as in the case of wind energy or nuclear power) than the fuel being displaced by the pumped storage generation.

Example 12.4: Calculate the maximum energy per cubic meter volume of water that can be made available at 70% plant efficiency from a pump storage plant with difference of height between reservoirs of 100 meters.

Given that:

Head: $h = 100$ m

Efficiency: $\eta = 70\%$ or 0.70

Multiplying both sides of equation 12.3 by time in seconds and incorporating $V = q \times time$, we have:

$$E_{max} = \eta \rho g h V \quad \text{(Watts-second)}$$

Therefore: $$E_{max} = \frac{0.70 \times 1000 \times 9.81 \times 100 \times 1}{1000 \times 3600} = \mathbf{0.19\ kWh}$$