Small Hydro Power Systems

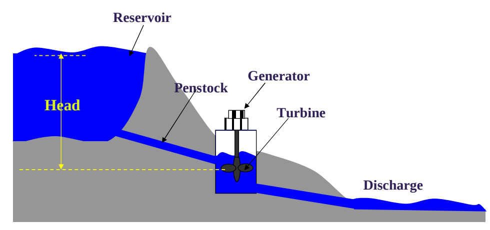
Lecture #3

- Hydroelectric power plants can be driven from a water stream or accumulation reservoir.
- Run-of-river hydroelectric plants (those without accumulation reservoirs) are built along a river or a water stream without lake formation for the intake of water. Like this, the river course is not altered, and its minimum flow will be the same or higher than that of the turbine output power. The excess of water should be diverted and, in this case, use of the water volume is not total.
- The costs are less as opposed to the ones with reservoirs with less environmental impact, there is no need for many hydrological studies but the plant is unable to store energy.

Hydro Power Systems

- **Hydroelectric power plants can be driven from a water stream or accumulation reservoir.**
  - **Reservoir-Type**, a dam creates a reservoir at high elevation behind the dam, suitable for water bodies with high heads.
  - **Diversion-Type** , built along a river or a water stream without lake formation for the intake of water. Suitable for strong current through turbines, at low heads.
  - **Pumped Storage**, operates on dual action, when power demand is low, the generated electricity is used to pump water from the lower level to the upper one.

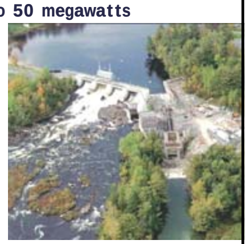
Reservoir or Impoundment Plant



- An impoundment plant project demands far more complex hydrological and topographical studies to determine the site elevation. The water use is total, and the civil works cause a tremendous social and environmental impact.
- Six components: dam, reservoir, penstock, turbine, generator, governor

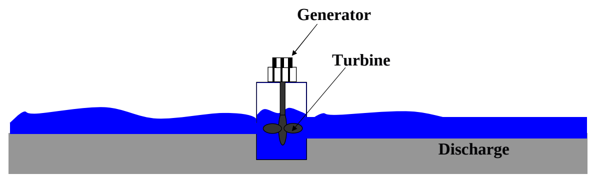
Small Reservoir Type Power Plant

- Depending on local definitions, small Hydro installations can range in size from a few Kilowatts to 50 megawatts or more of rated power output.
- Internationally "small" hydro power plant capacities typically range in size from 1 MW to 50 MW, with projects in the 100 kW to 1 MW range sometimes referred to as "mini" hydro system and projects under 100 kW referred to as "micro" hydro system.
- However, installed capacity is not always a good indicator of the size of a project.
- A 20 MW, low-head "small" hydro plant is anything but small as low-head projects generally use much larger volumes of water, and require larger turbines as compared with high-head projects.

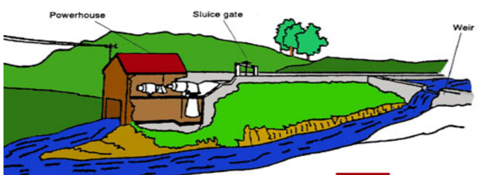


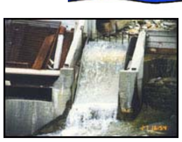
Diversion Type Plant

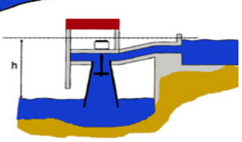
- Less environmental impact, there is no need for many hydrological studies but the plant is unable to store energy.



Run off the river

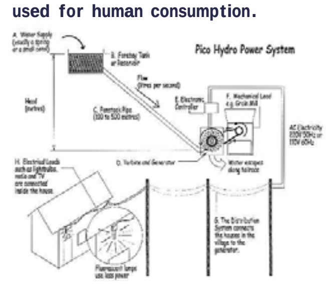






Pico Hydro Systems

- A pico system has a tank that is filled by a water diversion and sometimes integrated with pumping of surplus power of renewable energy, i.e. in addition to battery storage a wind turbine at night would be pumping other to be reconverted to electricity or to be used for human consumption.

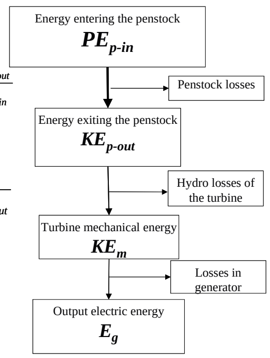


Power Flow

$$\eta_p = \frac{KE_{p-out}}{PE_{p-in}}$$

$$\eta_h = \frac{KE_m}{KE_{p-out}}$$

$$\eta_g = \frac{E_g}{KE_m}$$



Potential Energy in the Reservoir

$$PE_r = W * H$$

Weight of water in reservoir　　Water head

$$W = M * g$$

$$PE_r = M * g * H$$

Potential Energy of Water at the Penstock Intake

$$PE_{p-in} = m * g * H$$

mass of water entering penstock　　Water head

Water flow in penstock $f = \dfrac{m}{t}$

$$PE_{p-in} = f * g * H * t$$

Kinetic Energy of Water Exiting Penstock

$$KE_{p-out} = \frac{1}{2} m\, v^2 = \frac{1}{2} vol * \rho * v^2$$

Water velocity　　Water density, 1000kg/m^3

$$KE_{p-out} = 500\, vol * v^2$$

$$vol = A v t$$

Cross section of penstock

$$KE_{p-out} = 500\, A * v^3 * t$$

Example

- **A man owns a property with a small river. He wants to build a dam to create a reservoir for a small hydro system. The site can accommodate a penstock of 3m in diameter. In order for him to generate 2MW of electricity, compute the height of the dam. Assume that the penstock efficiency is 97%, the hydro efficiency is 50%, and the generator efficiency is 95%.**

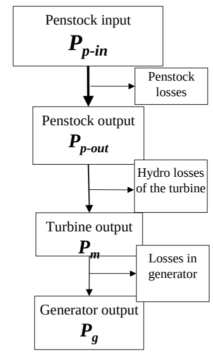
Solution

$$P_m = \frac{P_g}{\eta_g} = \frac{2}{0.95} = 2.105 \quad MW$$

$$P_{p-out} = \frac{P_m}{\eta_h} = \frac{2.105}{0.5} = 4.21\ MW$$

$$KE_{p-out} = 500\ A * v^3 * t$$

$$P_{p-out} = 500\ A * v^3$$



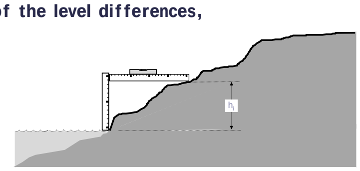
$$v = \sqrt[3]{\frac{P_{p-out}}{500\,A}} = \sqrt[3]{\frac{4.21*10^6}{500(\pi*1.5^2)}} = 10.6 \quad m/s$$

$$\eta_p = \frac{KE_{p-out}}{PE_{p-in}} = \frac{v^2}{2\,g\,H}$$

$$H = \frac{v^2}{2\,g\,\eta_p} = \frac{10.6^2}{2*9.8*0.97} = 5.91 \quad m$$

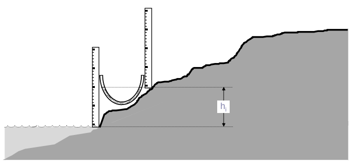
Simple Measurements of Elevation

- **Using a carpenter level and two very flat rulers - one of 3 to 4 meters long and the other 2 meters long – which are not flexible and are marked with the metric scale.**
- **The inferior tip of the smaller ruler is placed at the level of the water, in a vertical position. Then, the larger ruler is placed on the ground and the carpenter level controls its horizontal position.**
- **Re-starting from that position, the operation is repeated between several pairs of elevation points making sure they were verified in all level differences.The height of the total head is the straight summation of the level differences,**



Simple Measurements of Elevation – Cont.

- For the second method, it is necessary to use two rulers (of about 2 m long) and a plastic tube (flexible and transparent, with 1 cm of internal diameter and at least 6 m long). The rulers should be marked with the metric scale. The two rulers are placed on two points in the vertical position between which the elevation is measured. With the help of the plastic tube (full of water), points of equal level are determined on each ruler, creating a horizontal plan of reference. Summation of all differences between the ground heights of every two points gives the total difference of level.



Measurements of Stream Water Flow

- In measurements with a float, a straight passage of the watercourse whose bed is uniform and where the water calmly flows is chosen. It is measured, a length, if possible 10 m above the river course, marking then the beginning and the end. Demarcation of the points of interest can be made with two strings tied in stakes nailed on the margins and in perpendicular position to the ditch or stream axis.
- Such a float can be a closed bottle ballasted with water at about 1/3 of its volume to keep it in the vertical position. A chronometer measures the time, in seconds, the float takes to travel the chosen passage.
- Flow is calculated by the formula:

$$Q = 0.8L\overline{A} / t$$

where:

L = length of the passage to measure the flow in

A = average area of the cross sections

t = time of the float course in seconds

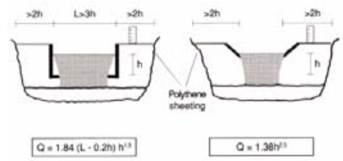
0.8= coefficient of the surface speed correction for an average speed across the measured section.

Using a SpillWay

- The watercourse is obstructed with a board panel with a rectangular central aperture of a known area, enough for the passage of all the water.
- The spillway width should be from one half to two thirds of the watercourse width. The aperture cuts should be chamfered in direction of the water flow.
- Once the drainage of water is normally made through the spillway, the height of the water level, is measured above the top of the stake

Using a SpillWay – Cont.

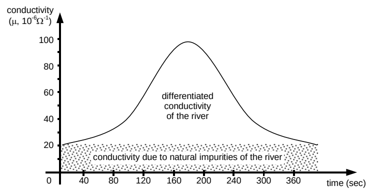
- There are formulas for rectangular and triangular spillways



- We can also measure the current stream with dilution of salt in the water and recording the conductivity variation with time.

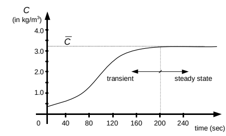
Dilution of Salt in the Water

- Determination of water flow can also be accomplished through methods using the resistivity alteration caused by salt dilution along the river course.
- In the first method, salt is poured in the water all at once, and the variation in the concentration of salt in the course is measured downstream during a certain period of time.



Dilution of Salt in the Water – Cont.

- In the second method, the solution of salt is poured in the water at a certain constant rate, and the concentration is measured downstream.



flow in m³/s is $Q = q(C_0 / \overline{C})$

where q is the rate of salt dilution, $\overline{C}$ is the final concentration of salt, and C_0 is the initial concentration of salt.

Reservoir Calculation

M: the water mass behind the dam in kg

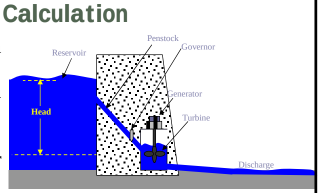
g: the acceleration of gravity in m/s²

H: the water head in m.

PE_r: Potential Energy of reservoir in Joules (Watt s)

Vol: the volume of water in m³

ρ: the water density in kg/m3. (At 20°C, ρ =1000 kg/m³)



$$PE_r = M * g * H$$

$$M = Vol * \rho$$

The volume of the reservoir behind a dam is 20 km³. The water head is 100 m. Compute the potential energy of the reservoir.

Reservoir Calculation – Cont.

$$PE_r = Vol * \rho * g * H = 20*10^9*1000*9.81*100$$
$$= 1.962*10^7 \ GJ$$

Penstock

$$P_w = \frac{KE}{t} = \frac{1}{2}\frac{m}{t} * v^2 = \frac{1}{2} f * v^2$$

m: mass of water entering the turbine.

v: velocity of water in m/s.

f: flow of water

Penstock Calculation

$$f \equiv \frac{m}{t} = \frac{vol \;\; \rho}{t}$$

$$vol = A v t$$

A: cross section of the penstock

$$P_w = \frac{1}{2}\frac{vol}{t} * \rho * v^2 = \frac{1}{2} A * \rho * v^3$$

A penstock of a hydroelectric dam allows 2000 m^3/s of water to flow into the turbine at a speed of 50 m/s. Compute the mechanical power of the penstock water.

Penstock Calculation – Cont.

$$P_w = \frac{1}{2}\frac{vol}{t} * \rho * v^2 = \frac{1}{2} 2000 * 1000 * 50^2 = 2.5\ GW$$

Useful Turbine Power

- In general terms, ordinary turbines and water wheels use the energy that can be evaluated as the summation of the three forms of energy given by the theorem of Bernoulli. This expression remains constant for a given cross section and position in a canalization, as:

$$\frac{v^2}{2g} + h + \frac{p}{\rho g} = \frac{P}{\rho g Q}$$

where

v = water flow speed in meters/second

g = gravity constant 9.81 meters/square second

h = height of the water in meters

p = pressure of the water in Newton/square meters

ρ = density of the water in kilograms per cubic meters (≅ 1,000.00 kg/m3).

P = power in kilogram-meter per second (1 hp = 75 kgm/s = 746 Watts)

Q = flow of the watercourse (in m3/s).

- Neglecting the terms for kinetic energy v and pressure energy p and assuming that all the converted energy is because of the height of water and assuming an efficiency, we have

$$P_t = \eta_t \rho g Q H_m$$

where
η_t = is the turbine efficiency
H_m= is the water head

Assuming that the efficiency = 0.6, density = 1000 kg/m^3 and g approximately 10 m/s^2, then

$$P = 6.0QH \quad \text{kW/m}^2$$

where $Q = Av$

Useful Hydro Power

- Useful power in the machine shaft should be the same as the maximum electric power that can be generated at that place.
- An approximate expression for power in terms of area. Given that $P_t = \eta_t \rho g Q H_m$

Let us assume : $\eta = 0.6$
$g = 9.81 m/s^2$
$\rho \cong 1000 kg/m^3$

- Then the electric power (in kW/m^2) can be determined by :

$$P = 6.0QH \quad (kW/m^2)$$

where $Q = Av$ so, we need to measure H, A and v

Regulation Systems

- Regulation systems maintain voltage and rotation at constant levels and, therefore, the frequency of the generating unit within the variation limits of the electric network demands. A centrifugal pendulum of the mechanical type - constituted by a servomechanism working under pressurized oil - commands the conventional automatic speed regulators used in small hydroelectric power plants. The simplest types are the inertial flywheels.
- In the acquisition of a regulator, its cost, the distance of the powerhouse to the load, and the load type should be taken into account. When considering cost, it is advisable to use a regulator for turbine powers above 20 kW. In smaller turbines, the regulation can be made either by load adjustment, by manual control of the water flow, or through a simplified control for small integrated generating units.

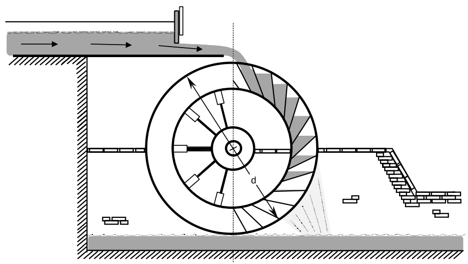
Water Wheels

- Water wheels are quite primitive and simple machines, usually built of wood or steel, with some regularly fixed shovels of steel blades around their circumference.
- The water pushes these shovels in a tangent movement around the wheel. The water does not exert any thrust action or shock on the shovels, as is the case with turbines. The water develops a torque on its shaft, and the wheel rotates.
- They work with low angular speeds and are of low efficiency due to losses by friction, turbidity and incomplete filling of the buckets



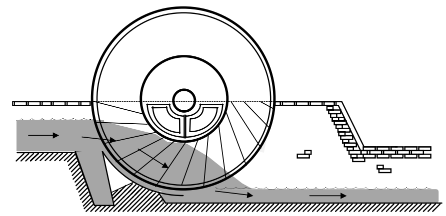
Water Wheel of Upper Buckets

- **The upper bucket wheel diameter is the minimum head of the necessary water to move it.**

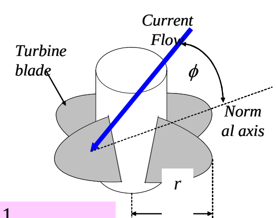


Water Wheel of Lower Buckets

- **The lower bucket wheel is adapted for smaller heights of the order of the wheel shovel length or less.**



Turbine Captured Mechanical Power



sweep area A_s $\quad A_s = \pi r^2$

$$A_s = \pi r^2 \cos\phi$$

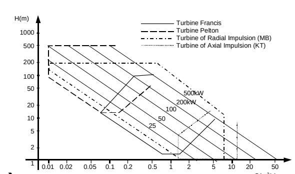
Mechanical power of water P_w $\quad P_w = \frac{1}{2} A_s * \rho * v^3$

Coefficient of performance Cp $\quad C_p = \frac{P_m}{P_w}$

Mechanical power of turbine P_m $\quad P_m = C_p \left(\frac{1}{2} A_s * \rho * v^3 \right)$

Commercial Turbines

- **The choice of the turbine type depends on:**
  - the application range (P);
  - height and of the water flow (Q and h);
  - cost of the turbine
  - sensitivity to materials in suspension
- **High head turbines:**
  - **Pelton**
- **Medium head turbines:**
  - **Francis**
- **Low head turbines:**
  - **Mitchell Banki (cross flow)**
  - **Kaplan (propeller)**



Pelton Turbine

- A **Pelton Turbine** is a turbine of free flow (action). The potential energy of the water becomes kinetic energy through injectors and control of the needles that direct and adjust the water jet on the shovels of the motive wheel. They work under atmospheric pressure, approximately. Thus, the net height is limited in its lower quota by the impact of the jet on the shovels of the motive wheel.

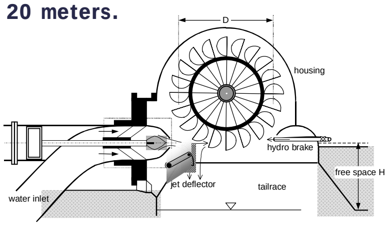


Pelton Turbine – Cont.

- **A Pelton turbine has one or more jets of water impinging on the buckets of a runner that looks like a water wheel. The Pelton turbines are used for high-head sites (50 feet to 6,000 feet) and can be as large as 200 megawatts**
- **Being an impulse turbine, the efficiency is high and stable over the majority of the flow range. Multiple jets provide two to four times the normal power output for a given diameter of wheel.**
  - Designs available up to 800 metres net head.
  - Simple governing by jet deflector and spear valve control.
  - Stable efficiency throughout majority of flow range.
  - Actuation of spear valves by electric or hydraulic means.
  - Bearing designs include rolling element or sleeve type.
  - Single and multi-jet versions available.
  - Design provides for easy maintenance.

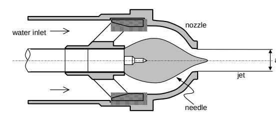
Cross Section of a Pelton Turbine

- **In small hydroelectric power plants, the operation of the PT can result in a reasonable economy when it operates with flows above 30 L/s and heads from 20 meters.**

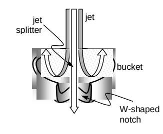


Details of the PT Jet Control Action

- **Injector Nozzle, Needle and Jet Diameter**



- **bucket and jet splitter**



Francis Turbine

- A **Francis Turbine** has a runner with fixed vanes, usually nine or more. The water enters the turbine in a radial direction with respect to the shaft, and is discharged in an axial direction. Francis turbines will operate from 10 feet to 2,000 feet of head and can be as large as 800 megawatts.

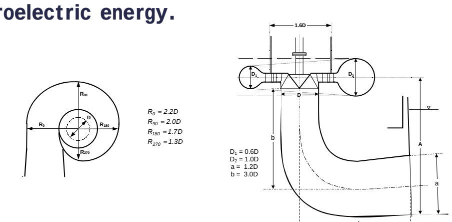
Francis Turbine – Cont.

- Designs available up to 280 m head.
- Horizontal or vertical shaft design.
- Spiral cased units or 'open' penstock units available.
- Special designs available for high head and also high temperature differential applications.
- Special materials for corrosive fluids or abrasive water.
- Complete factory assembly ensuring simple on-site installation.
- Bearing assemblies and designs to suit all applications.
- Hydraulic and eletronic guide vane regulation.

Francis Turbine Vertical Shaft

Francis vs. Pelton

- The advantage of a Francis Turbine over a Pelton Turbine is mainly because of the suction tube, which makes usable the totality of the elevation between up and downstream used for generation of hydroelectric energy.



Low Head Turbines

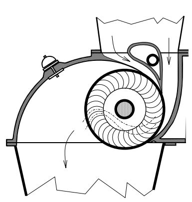
- **Low head machines can be installed in existing low head hydro sites giving greatly improved efficiencies. They are particularly useful where access is limited or where the minimum amount of new civil work is desirable.**
  - Designs available up to 18 meters net head.
  - Horizontal or vertical shaft design with fixed or variable pitch blades.
  - Complete factory assembly ensuring simple on-site installation.
  - Bearing assemblies and designs to suit all applications.
  - Design variations available to cover special situations.

Michel-Banki Turbine

- **Michell-Banki turbine is a crossflow turbine with drum-shaped runner consisting of two parallel discs connected together near their rims by a series of curved blades. A crossflow turbine always has its runner shaft horizontal.**
- **The Michel-Banki Turbines (also called *radial thrust*) currently manufactured can reach capacity of up to 800 . Their flows vary from 25 to 700 L/s (according to the machine dimensions), with heights of head in the range of 1 to 200 meters. The number of slats installed around the rotor varies from 26 to 30, according to the wheel circumference whose diameter is from 200 to 600 mm.**

MBT with Vertical Input

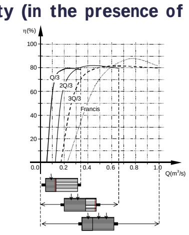
- **The MBT can be installed with an output free from the water or with a suction tube, in which the whole elevation of the water is used.**



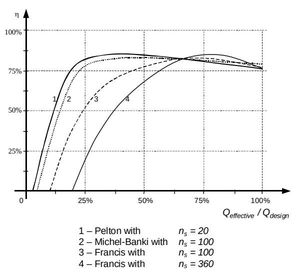
- **up to 800 kW; its flow varies from 25 to 700 liters/s; heads ranging from 1 to 200 meters; the number of slats installed in the rotor varies from 26 to 30, according to the circumference of the wheel whose diameter is of the order of 200 to 600 mm.**

MB Turbine

- **Compared with other types of turbines, the MBT - with a rotor division in cells (longitudinal segments of the rotor) in the proportion of 1:2 - presents a big advantage.**
- **This multi cell turbine can be operated with one or two thirds of its capacity (in the presence of low or average flows) or with its full capacity (in the presence of design flows - that is, three thirds).**

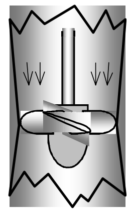


Efficiency Comparison for Pelton, Francis and MB



Kaplan Turbine

- The **Kaplan Turbine** type is used for low heads or to water stream, small powers, and optimum flow variations along the year and is recommended for heads from 0.8 to 5 meters, approximately.



Kaplan Turbine – Cont.

Kaplan Turbine – Cont.

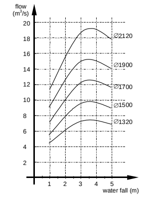
- To start the Kaplan Turbine, a vacuum pump fills the siphon with water and forms an elevation between up and downstream. To stop this turbine, it is enough to stop the water flow through the relief valve on the distributor's upper part.
- Very low cost, in addition the Kaplan Turbine has the advantage of maintaining the electromechanical parts out of the water. This feature eases routine inspection and maintenance, as well as safety in case of floods. As its installation does not demand water reservoirs or prominent civil works, the impact on the environment is negligible.

Kaplan Turbines – Cont.

- The water enters the turbine laterally, is deflected by the guide vanes, and flows axially through the propeller. For this reason, these machines are referred to as axial-flow turbines. They have the advantage over radial-flow turbines that it is technically simpler to vary the angle of the blades when the power demand changes what improves the efficiency of power production.
- The flow rate of the water through the turbine can be controlled by varying the distance between the guide vanes; the pitch of the propeller blades must then also be appropriately adjusted. Each setting of the guide vanes corresponds to one particular setting of the propeller blades in order to obtain high efficiency. Important feature is that the blade speed is greater than the water speed – as much as twice as fast. This allows a rapid rate of rotation even with relatively low water speeds
- Kaplan turbines come in a variety of designs. Their application is limited to heads from 1 m to about 30 m. Under such conditions, a relatively larger flow as compared to high head turbines is required for a given output. These turbines therefore are comparatively larger.

Curves Flow x Head of the Kaplan Turbine

- The selection of a Kaplan Turbine that better adapts to the flow and head of a watercourse can be based on a graph similar to the one below.
- The small power plant using the Kaplan turbine does not dispense some auxiliary services. These are the electric motor of the vacuum pump and the electric motor drivers of the wheel shovels, when applicable (approximately, from 0.5 to 3.0 kW). A rotation multiplier should also be installed for high-speed generators. All of this contributes to additional losses.



Head and Specific Speed Range for Various Types of Turbine Runners

Turbine runner	head range (m)	specific speed range
Pelton	400 a 2000	0 a 30
Francis	50 a 500	20 a 120
Mixed-flow	20 a 80	120 a 180
Kaplan (vertical)	8 a 50	180 a 260
Bulb Pit (horizontal)	0 a 10	260 a 360
Michel-Banki	1,50 a 150	30 a 210

Water Pumps Working as Turbines

- The inverse use of water pumps as turbines for small hydroelectric power plants has become quite popular for its appreciable reduction in facility costs. Those pumps, usually of small capacity, have been used for many years in industrial applications to recover energy that would otherwise be lost. Throughout the world, pump-turbines have been used in small power plants with energy storage. They present the following advantages:
  - they cost less because they are mass produced for other purposes, (i.e. in water pumping for buildings and residences);
  - their acquisition time is minimal because they already have a wide variety of commercial standards and they are available in hardware stores and related shops.

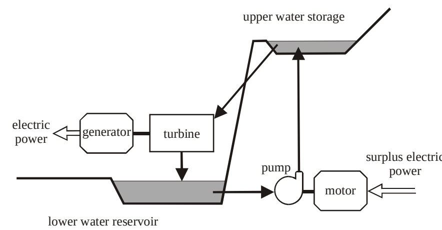
Pumped Hydro Energy Storage

- The initial potential energy associated with the head is transformed into kinetic energy. One part of this energy is associated with the mass moving with velocity. The other is the pressure part, with the enthalpy given by the pressure P over the density of water multiplied by the remaining mass :

$$E_{initial}^{potential} = mgh = m'\frac{1}{2}u^2 + (m - m')\frac{P}{\rho} = E^{kinectic} + enthalpy$$

Pumped Hydro Energy Storage – Cont.

- During peak demand, water is released from the upper reservoir. The turbines drivea power generators that create electricity.When production exceeds demand, water is pumped up and stored in the upper reservoir, usually with an early morning surplus.



Pumped Hydro Energy Storage – Cont.

- The overall efficiency of pumped hydro systems must consider the ratio of the energy supplied to the consumer and the energy consumed while pumping. The energy used for pumping a volume of water up to a height with pumping efficiency as well as the energy supplied to the grid while generating with efficiency is given by :

$$E_{pumping} = \frac{\rho g h V}{\eta_p}$$

$$E_{generator} = \rho g h V \eta_g$$

Specification of Hydro-Turbines

- To get a good purchase price for the turbine, several manufacturers should be consulted. Comparing of values demands good specifications, (as close as possible to what is desired), so that small differences in the product characteristics do not unduly influence the final price. Super dimensioning should be avoided; that dissuades the manufacturer from offering equipment better adapted to each case. The following items are suggested for the time of purchase:
  - buyer's identification (name, profession, address, telephone, etc.);
  - cost estimation or a detailed specification;
  - a sketch of the installation site for the small power plant (if possible, with pictures), available elements besides nature, and usable technical characteristics.

Specification of Hydro-Turbines – Cont.

- available average, minimum and maximum height;
- available flow for generation with its duration curve, site capacity of water storage, information about historical variations, etc.;
- quality of the water (materials in suspension, abrasiveness and other useful characteristics);
- present and future energy needs of the generator or turbine, according to the effective capacity of the place - otherwise, any specification becomes useless;
- need or not of an isolation valve for the turbine;
- specification of the required type of regulator;
- specification of the generator
- type (induction, synchronous or direct current)
- electric output (alternate or direct current, maximum power, voltage, number of phases, frequency)
- climate (winds, temperature and humidity)

Specification of Hydro-Turbines – Cont.

- operating mode (manual, automatic, semiautomatic or remote control, stand alone or for injection in the network - in this last case, is there a sale, purchase or exchange agreement with the electric power company?);
- other indispensable equipment (control panels, protection and drivers, single-phase or three-phase transmission and distribution lines)
- location of the powerhouse, if there is one, with upstream head, distance from the water intake, dimensions, drainage height (minimum, maximum and average);
- specification of the diameter, length, configuration and manufacturing material, if a feeder of water is used under pressure for the turbine;
- access means to the place (boat, bike, highway, rails, walk path or inhospitable access by land) for transport of equipment and maintenance planning;
- existence of animals, fishes or any other life likely to be preserved.