Renewable Energy Systems

EE—325

Hydro—power plants

- **Hydroelectricity is one** of the oldest generators of electricity and does not include thermal energy in the conversion process.
- **Hydropower plants convert** potential energy into mechanical energy through water turbines, which then generate electricity.
- **Efficiencies of 90%** and higher are achieved through this clean and renewable route. However, its availability is limited to sites with certain geographical and environmental suitability.
- **Electricity production** from hydroelectric sources contributed to 15.9% of the total electricity generation in 2011 [6].

Hydro—power global capacity

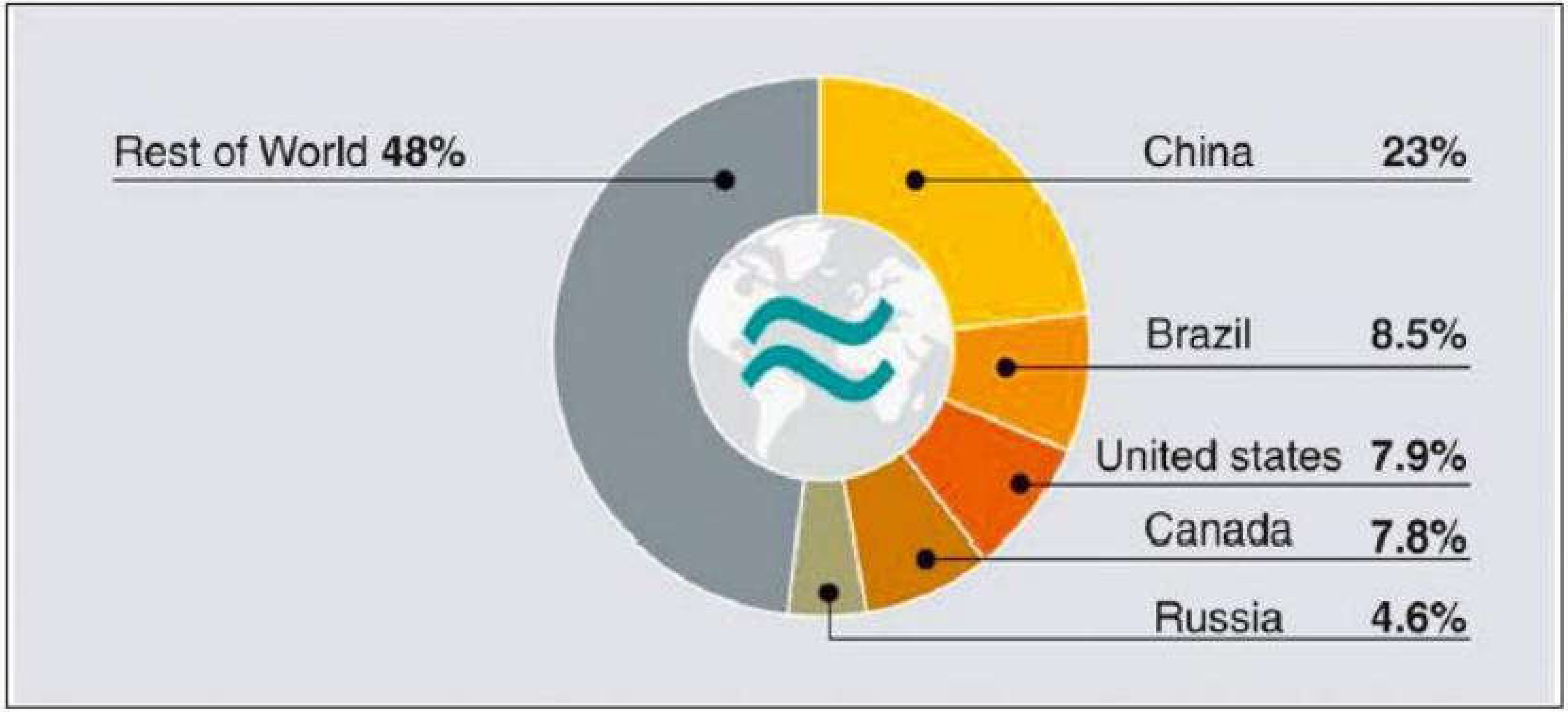


Figure 5.1 Hydropower global capacity – a typical distribution (2008).

Growth Of World Hydroelectricity Generation

- The world's earliest electricity distribution in 1881 was derived from hydroturbines of kW scale capacity.
- By 2008 hydropower capacity had reached about 874 GW, not including ~130 GW of pumped hydro-storage.
- The capacity of total worldwide installations continues to increase at about 2% per year, with hydroelectricity supplying about 16% of worldwide electricity (see Fig. 6.1). This proportion may itself increase.
- However, environmental and social concerns are often the largest challenges.

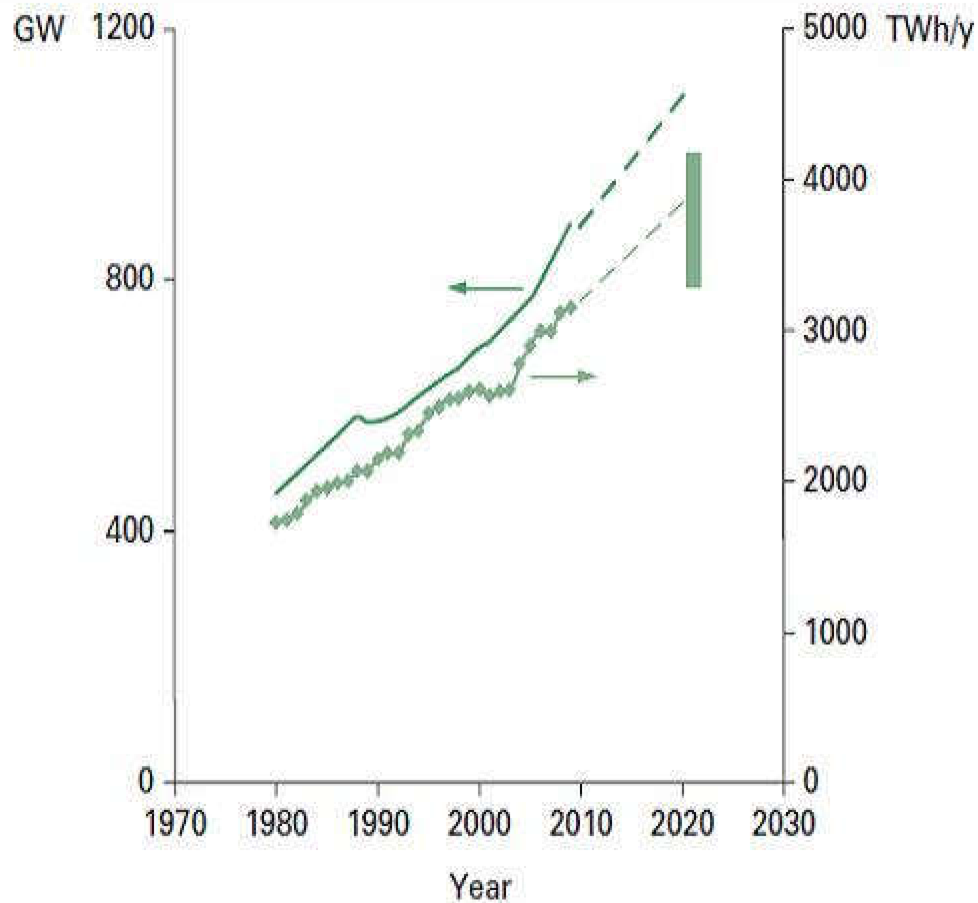


Fig. 6.1 Growth of world hydroelectricity generation (TWh/y) and capacity (GW). Actual data from US Energy Information Agency. (2011).

Early Irrigation Waterwheel

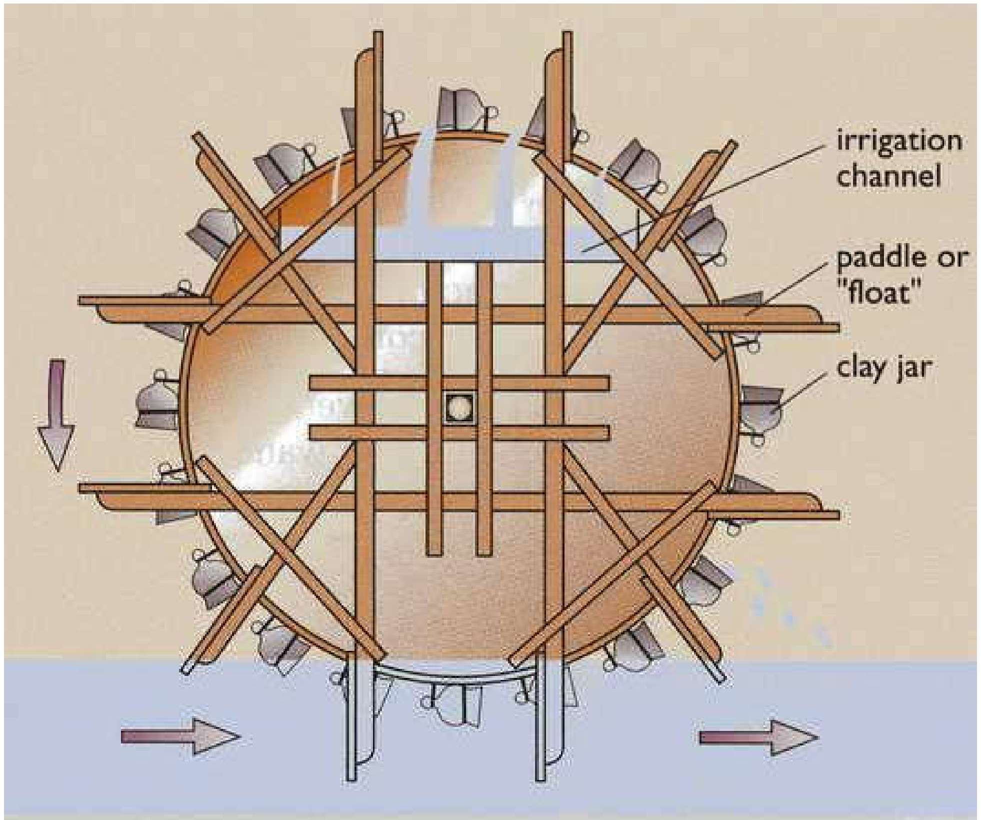


Figure 5.5 A noria. In this earliest water-wheel the paddles dip into the flowing stream and the rotating wheel lifts a series of jars, raising water for irrigation

Early Roman Water Mill

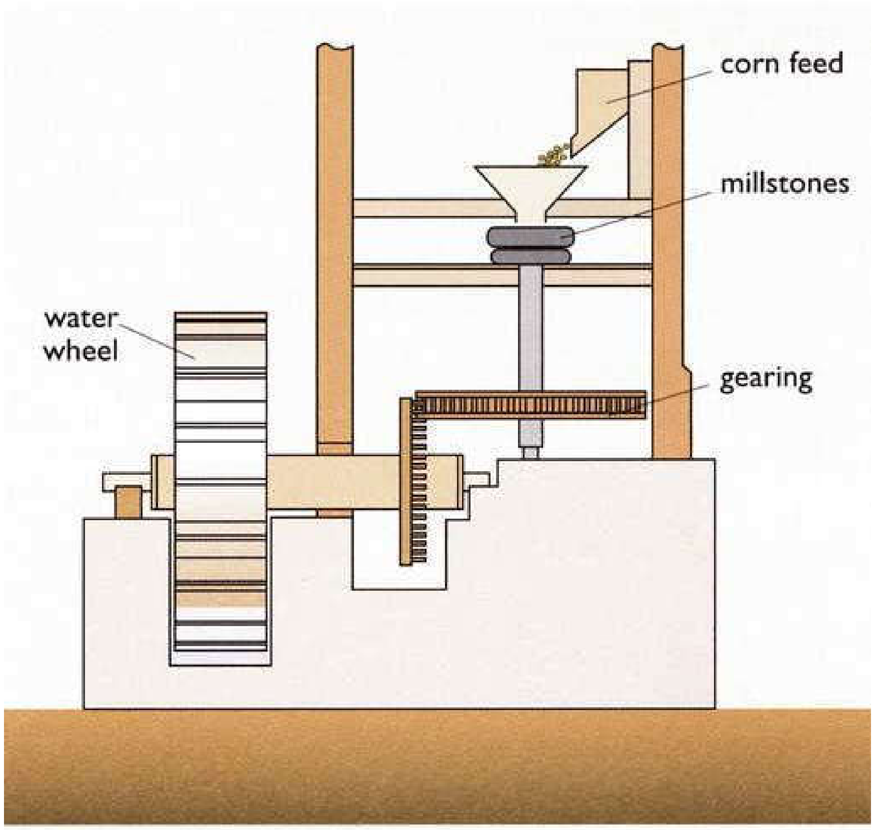


Figure 5.7 A Roman mill. This corn mill with its horizontal-axis wheel was described by Vitruvius in the first century BC. Note the use of gears

Hydropower potential, capacity and output by sample countries (2008).

A Region/e.g. country	B Gross potential TWh/y	C Technical potential TWh/y	D Actual generation TWh/y (2008)	E = D/C Proportion of technical utilized %	F Installed capacity (2008) GW	G Capacity factor D/(F × 8760 h/y) %

Notes

- **Gross potential** from rainfall runoff and mapping, **technical potential** from constructional experience, actual capacity installed and actual generation.

- **Actual generation** in one year

- Capacity and output figures exclude stations that are mainly or purely pumped hydro.

Source: Data from World Energy Council (2010), Survey of Energy Resources.

Hydropower potential, capacity and output by sample countries (2008).

A Region/e.g. country	B Gross potential TWh/y	C Technical potential TWh/y	D Actual generation TWh/y (2008)	E = D/C Proportion of technical utilized %	F Installed capacity (2008) GW	G Capacity factor D/(F × 8760 h/y) %
WORLD, total	39842	15955	3194.0	20	874.0	42
AMERICA North	5511	2416	694.0	29	168.0	47
Canada	2067	820	377.0	46	73.4	59
USA	2040	1339	255.0	19	77.5	38
ASIA	**16618**	**5590**	**985.0**	**18**	**306.8**	**37**
China	6083	2474	580.0	23	171.0	39
India	2638	660	114.8	17	37.8	35
Indonesia	2147	402	11.5	3	4.5	29
Japan	718	136	74.1	54	27.9	30
Pakistan	475	204	27.7	14	6.5	49
EUROPE	4919	2762	714.8	26	220.7	37
France	270	100	59.3	59	21.0	32
Italy	190	65	41.6	64	17.6	27
UK	35	14	5.1	36	1.6	36
MIDDLE EAST	690	277	27.7	10	11.5	27

Three gorges dam-18200MW

Three gorges dam-18200MW

Hydropower Design

Hydro—Power Principles

The fundamental equation (6.1) is sufficient for estimating hydropower potential at a particular location; the methods described in article 6.3 give a more accurate assessment.

Water of volume per second $\boldsymbol{Q}$ and density $\boldsymbol{\rho}$ falls down a slope. The mass falling per unit time *is* $\boldsymbol{\rho Q}$, and the rate of potential energy lost by the falling fluid is

$$P_0 = \rho Q g H \tag{6.1}$$

where $\boldsymbol{g}$ is the acceleration due to gravity and $\boldsymbol{H}$ is the vertical component of the water path.

The turbines convert this power to shaft power. There is no fundamental thermodynamic or dynamic reason why the output power of a hydro system should be less than the input power $\boldsymbol{P_0}$, apart from frictional losses that can be proportionately very small.

For a site with a water reservoir, $\boldsymbol{H}$ is fixed and $\boldsymbol{Q}$ is adjustable. Hence the power output is quickly controlled at, or less than, the design output, provided that there is sufficient water supply.

Terminology

- **Head**
  - Water must fall from a higher elevation to a lower one to release its stored energy.
  - The difference between these elevations (the water levels in the forebay and the tailbay) is called **head**
- **Dams: three categories**
  - **high-head**
  - **medium-head**
  - **low-head**
- Power is proportional to the product of *head x flow*

According to the head, schemes can be classified in three categories:

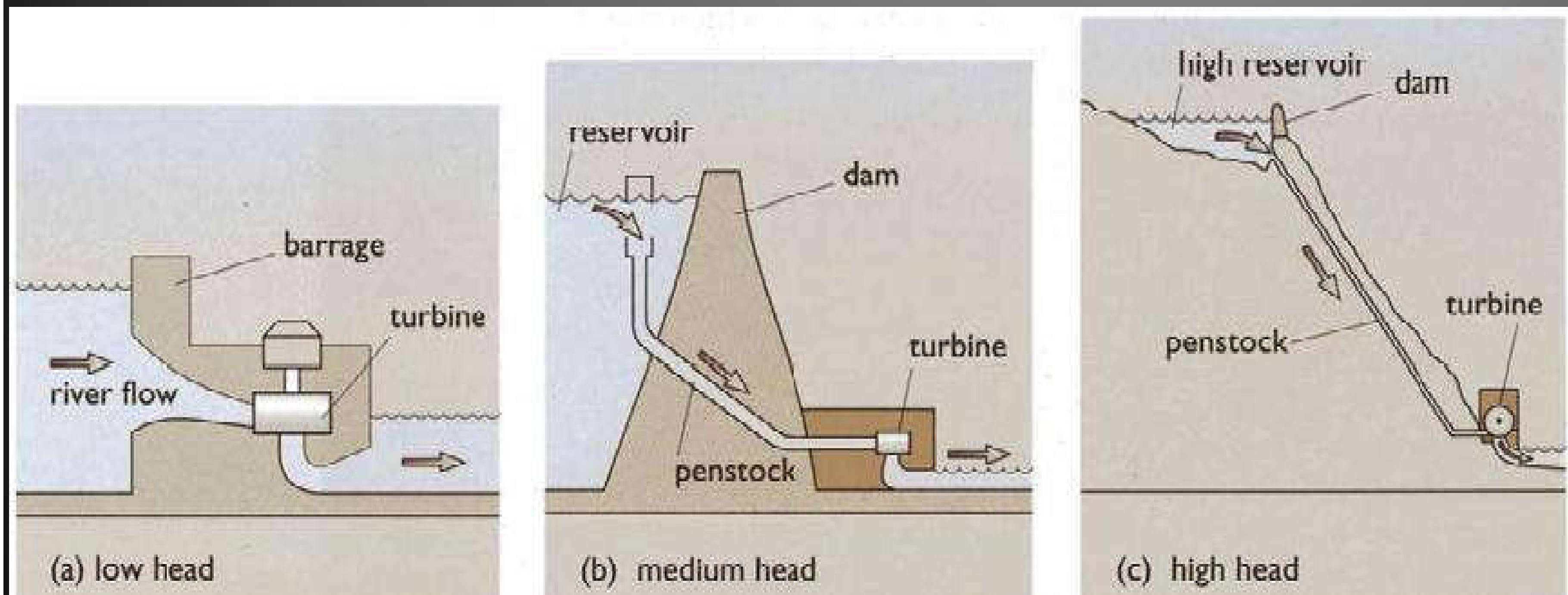
High head: 100 m and above

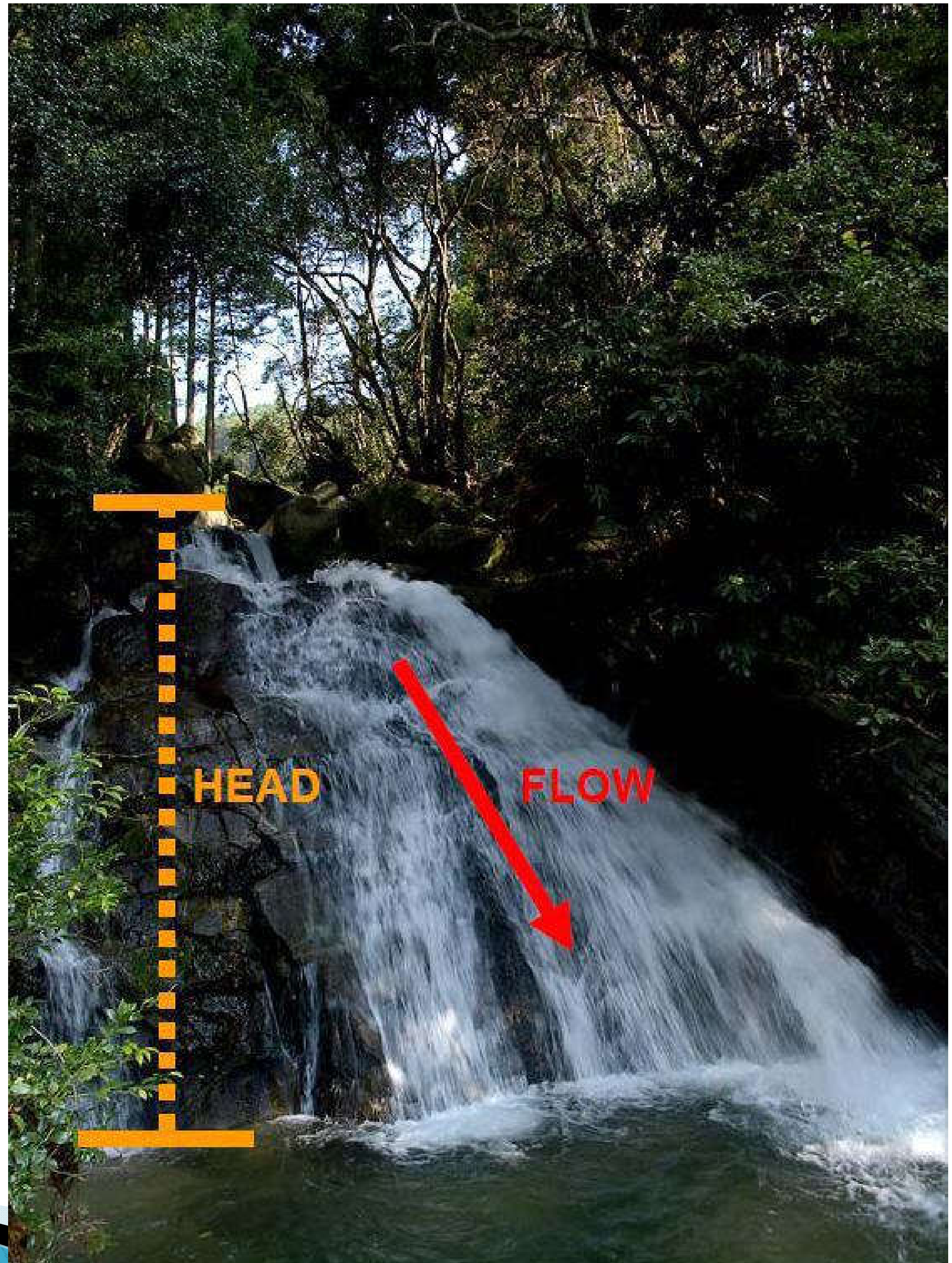
Medium head: 30 - 100 m

Low head: 2 - 30 m.

These ranges are not rigid but are merely means of categorizing sites.

Types of Hydroelectric Installation




HEAD
FLOW

The Gross Head (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head.

The Flow Rate (Q) in the river is the volume of water passing per second, measured in m^3/sec. For small schemes, the flow rate may also be expressed in liters/second where 1000 liters/sec is equal to 1 m^3/sec.

Hydro—Power: Assessing the Resources

Suppose we have a stream available which may be useful for hydropower. At first, only approximate data, with an accuracy of about ±50%, are needed to estimate the power potential of the site. If this survey proves promising, then a detailed investigation will be necessary involving data, for instance, rainfall taken over several years.

It is clear from (6.1) that to estimate the input power P_0 we have to measure the flow rate Q and the available vertical fall H (usually called the head).

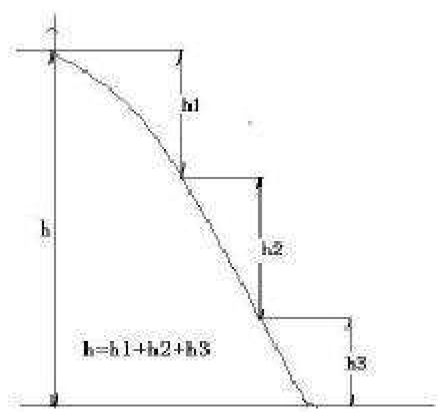
For example, with Q=**40liter/s** and H = **20 m**, the maximum power available at source is **8 kW**. This might be very suitable for a household supply.

Hydro—Power: Measurement of head H

For nearly vertical falls, trigonometric survey methods or level and pole surveying is used. Note that the power input to the turbine depends not on the geometric (or '*total*') head $\boldsymbol{H_t}$ as surveyed, but on the *available* head $\boldsymbol{H_a}$:

$$H_a = H_t - H_f \qquad (6.2)$$

where the ***head loss*** $\boldsymbol{H_f}$ allows for friction losses in the pipe and channels leading from the source to the turbine. With suitable pipework $\boldsymbol{H_f} =<\sim \boldsymbol{H_t}/3$; however, by $\boldsymbol{H_f}$ increases in proportion to the total length of pipe, so the best sites for hydropower have steep slopes.



Hydro—Power: Measurement of Flow Rate Q

The flow through the turbine produces the power, and this flow will usually be less than the flow in the stream. However, the flow in the stream varies with time, for example, between drought and flood periods.

For power generation, the *minimum* (dry season) flow is required, since a turbine matched to this will produce power all the year round without overcapacity of machinery.

Also, the *maximum* flow and flood levels is required to avoid damage to installations.

The measurement of Q is more difficult than the measurement of H.

For large installations, the 'sophisticated method' is always used.

WORKED EXAMPLE 6.1

Water from a moderately sized river flows at a rate of 100 m^3/s down a perfectly
into a turbine.

(a) How much power is available? (b) If in practice 10% of the power is lost by fr
distribution, how many houses having average electricity use of about 0.5 kW (i.e
power supply?

Solution

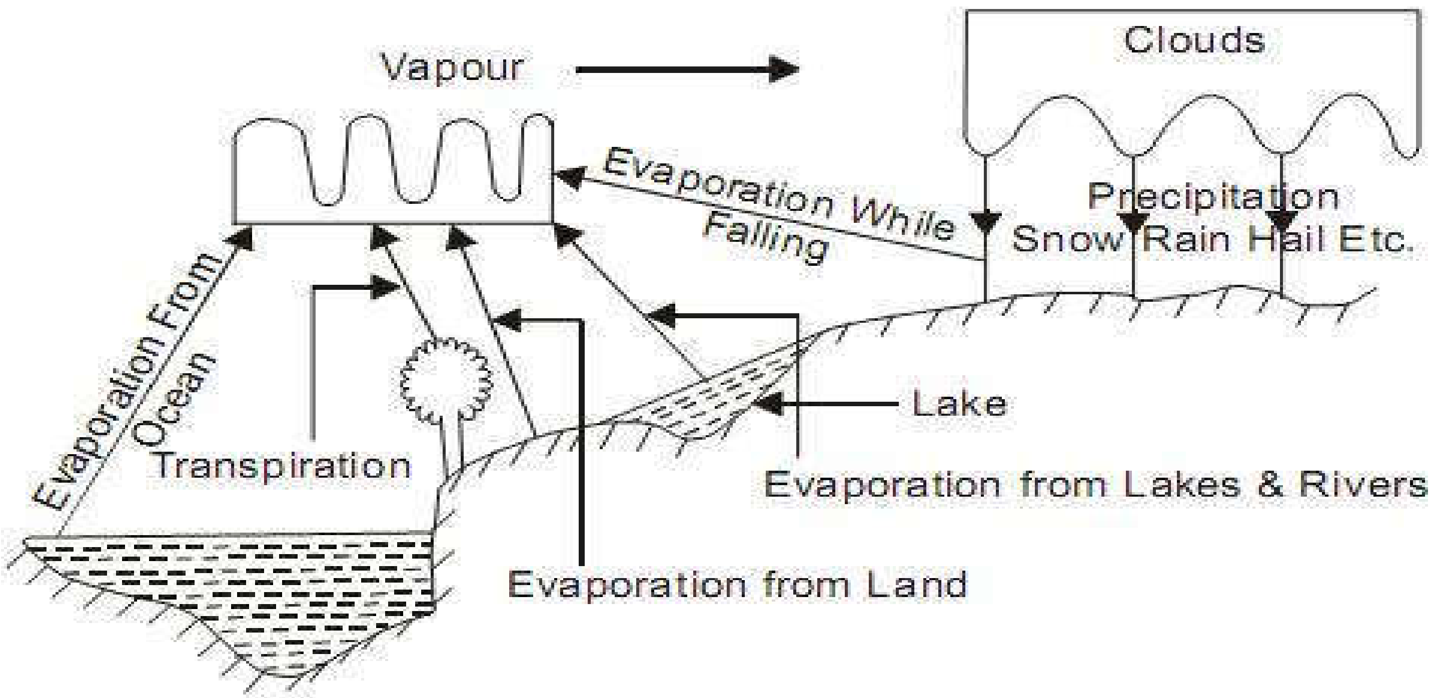
From (6.1),

$$P_0 = (1000\,kg/m^3) \times (100\,m^3/s) \times (9.81\,m/s^2) \times 50\,m$$

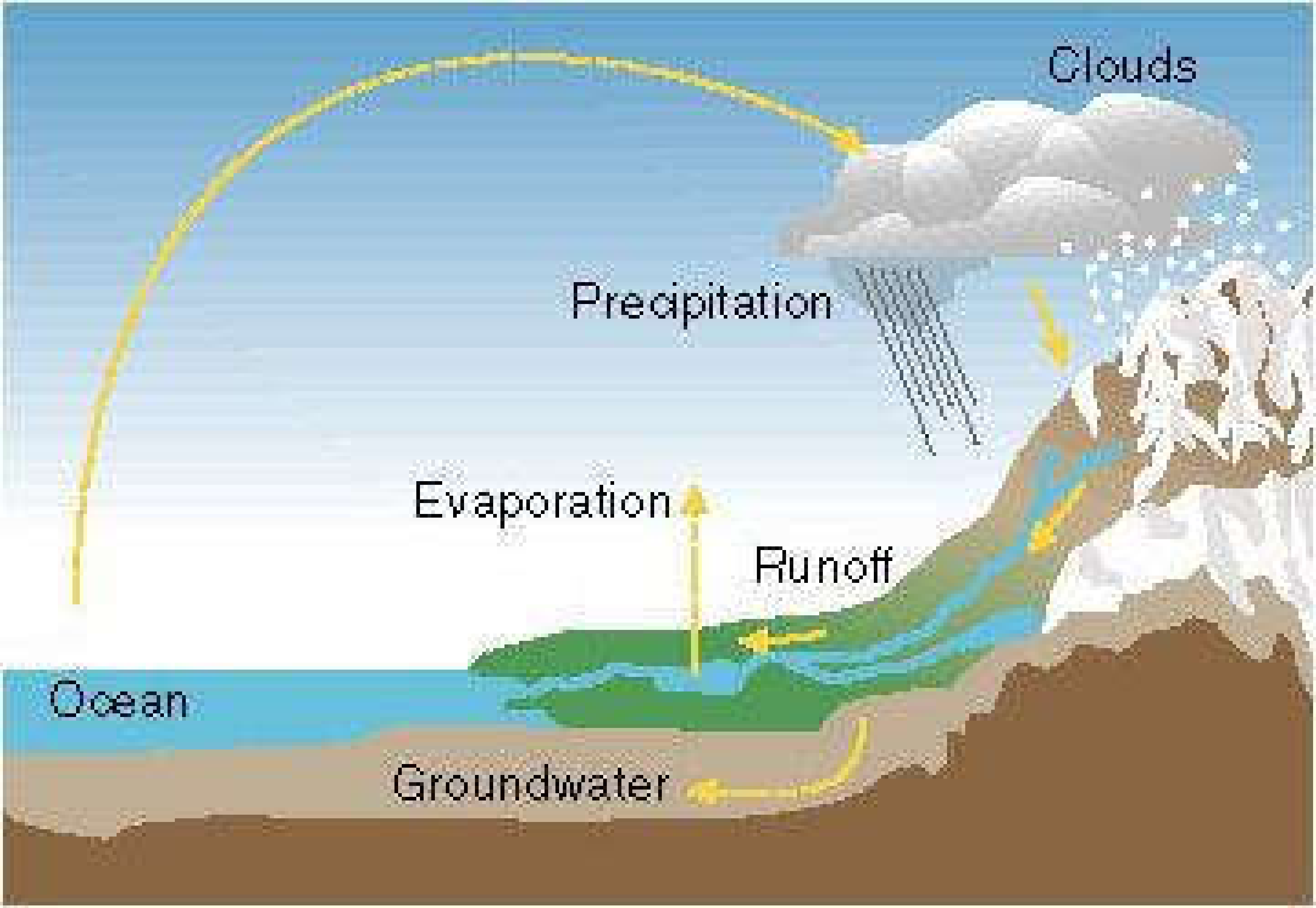
$$= 49 \times 10^6\,kg.m/s^3 = 49\,MJ/s = 49\,MW$$

- The generation of electric energy from falling water is only a small process
  -Hydrological cycle” or rain evaporation cycle”

This cycle is shown in figure.



Water cycle


Clouds
Precipitation
Evaporation
Runoff
Ocean
Groundwater

- The input to this cycle is the solar energy.
- Due to this, evaporation of water takes.
- On cooling, these water vapours form clouds. Further cooling makes the clouds to fall down in the form of rain, and snow etc; known as precipitation
- Before a water power site is considered for development, the following factors must be thoroughly analyzed
  - –1. The capital cost of the total plant.
  - –2. The capital cost of erecting and maintaining the transmission lines and the annual power loss

–3. The cost of electric generation compared with steam, oil or gas plants which can be conveniently set up near the load center.

- Inspite of the above factors, following advantages which make these suitable for large interconnected electric system:

–1. The plant is highly reliable and its maintenance and operation charges are very low.

–2. The plant can be run up and synchronized in a few minutes.

–3. The load can be varied quickly and the rapidly changing load demands can be met without any difficulty.

–4. The plant has no stand by losses.

–5. No fuel charges.

–6. The efficiency of the plant does not change with age.

–7. The cost of generation of electricity varies little with the passage of time.

- the hydro-electric power plants have the following disadvantages also:

–1. The capital cost of the plant is very high.

–2. The hydro-electric plant takes much longer in design and execution.

–3. These plants are usually located in hilly areas far away from the load center.

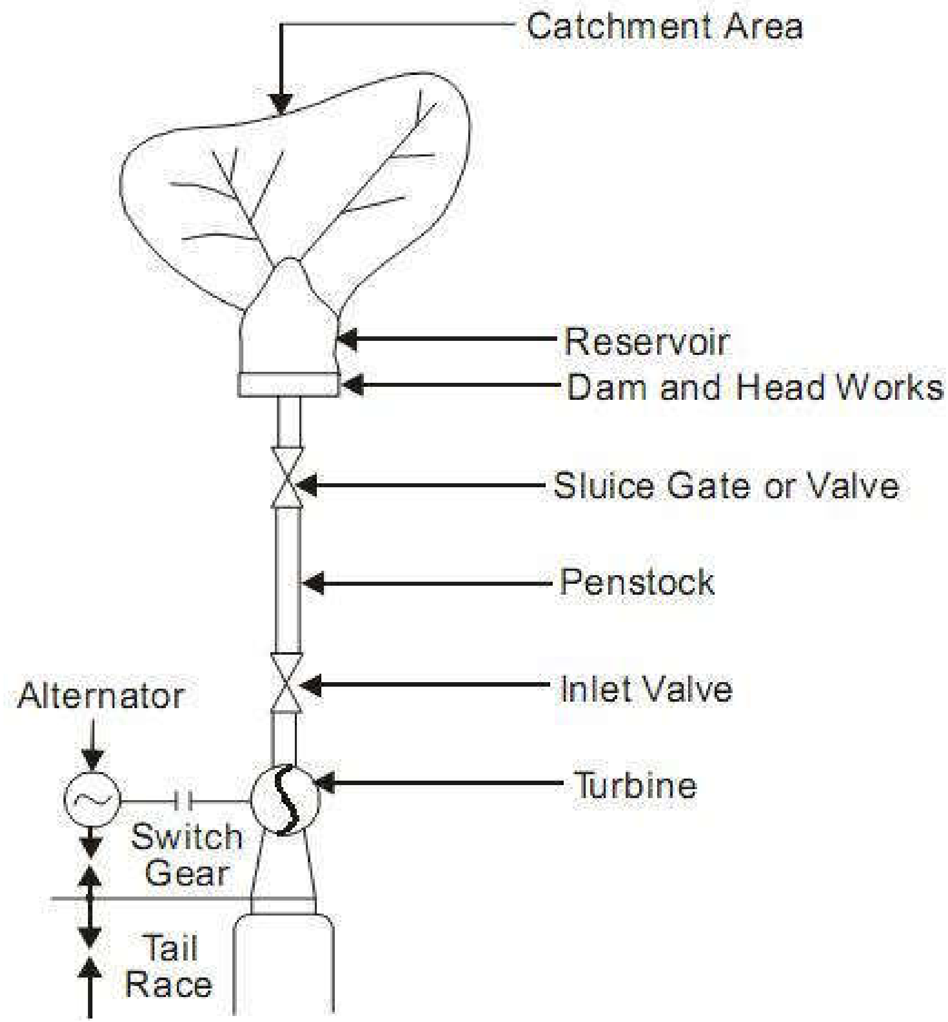
–4. Transformation and transmission costs are very high.

-5. The output of a hydro-electric plant is never constant due to An unpredictable change of

monsoons(A seasonal wind in southern Asia; blows from the southwest (bringing rain) in summer and from the northeast in winter) and their dependence on the rate of water flow in a river.

ESSENTIAL FEATURES OF A WATER-POWER PLANT

- 1. Catchment area.
- 2. Reservoir.
- 3. Dam and intake house.
- 4. Inlet water way.
- 5. Power house.
- 6. Tail race or outlet water way.



2. **Reservoir.**

-The purpose of the storing of water in the reservoir is to get a uniform power output throughout the year

3. Dam

-Are built to create head

- **Head**

-Water must fall from a higher elevation to a lower one to release its stored energy.

-The difference between these elevations (the water levels in the forebay and the tailbay) is called head

4. Inlet water way

-the passages, through which the water is conveyed to the turbines from the dam. tunnels, canals, forebays and penstocks and also surge tanks.

- A forebay is an enlarged passage for drawing the water from the reservoir

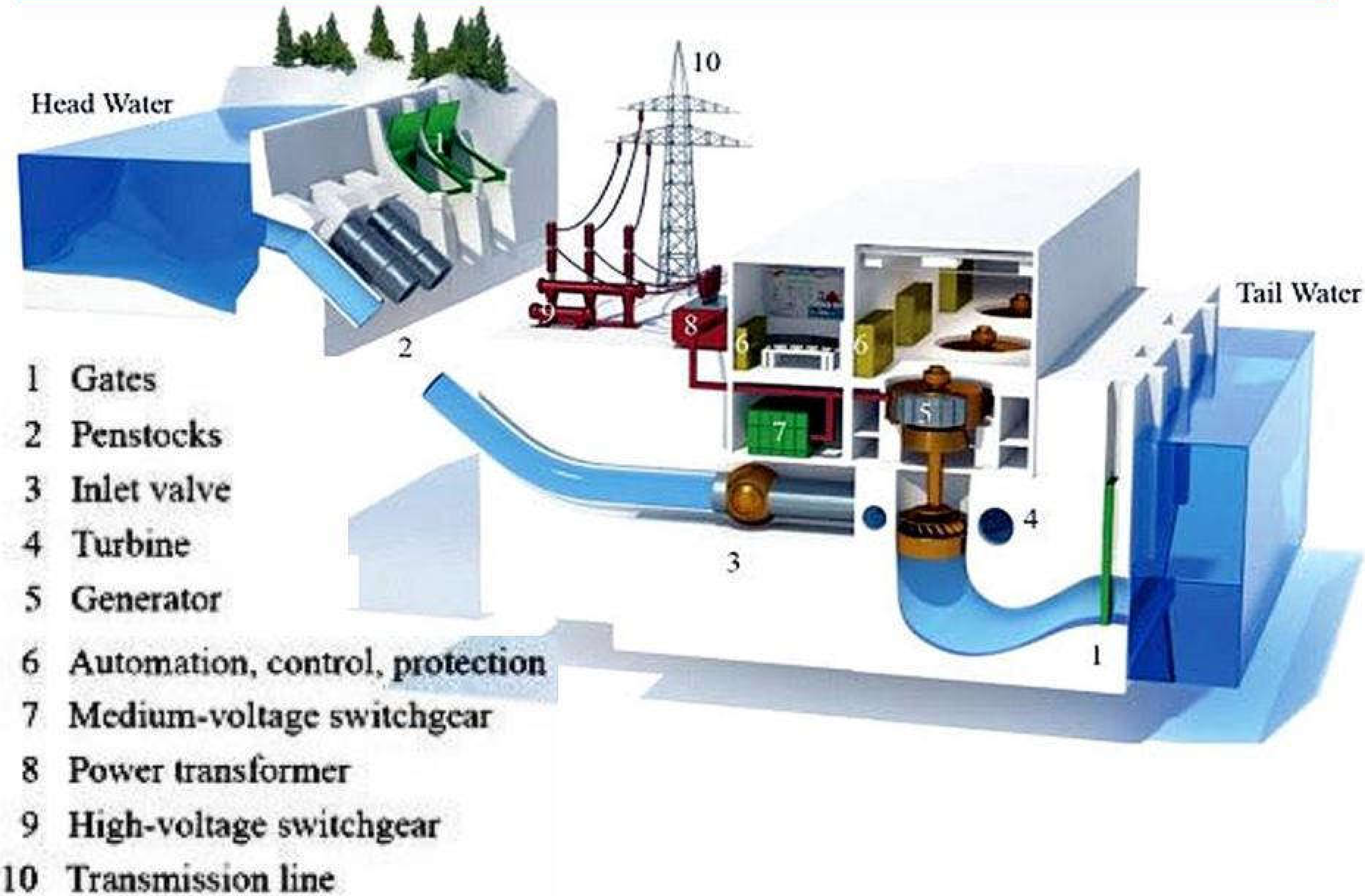
-Tunnels are of two types:

pressure type and non-pressure type.

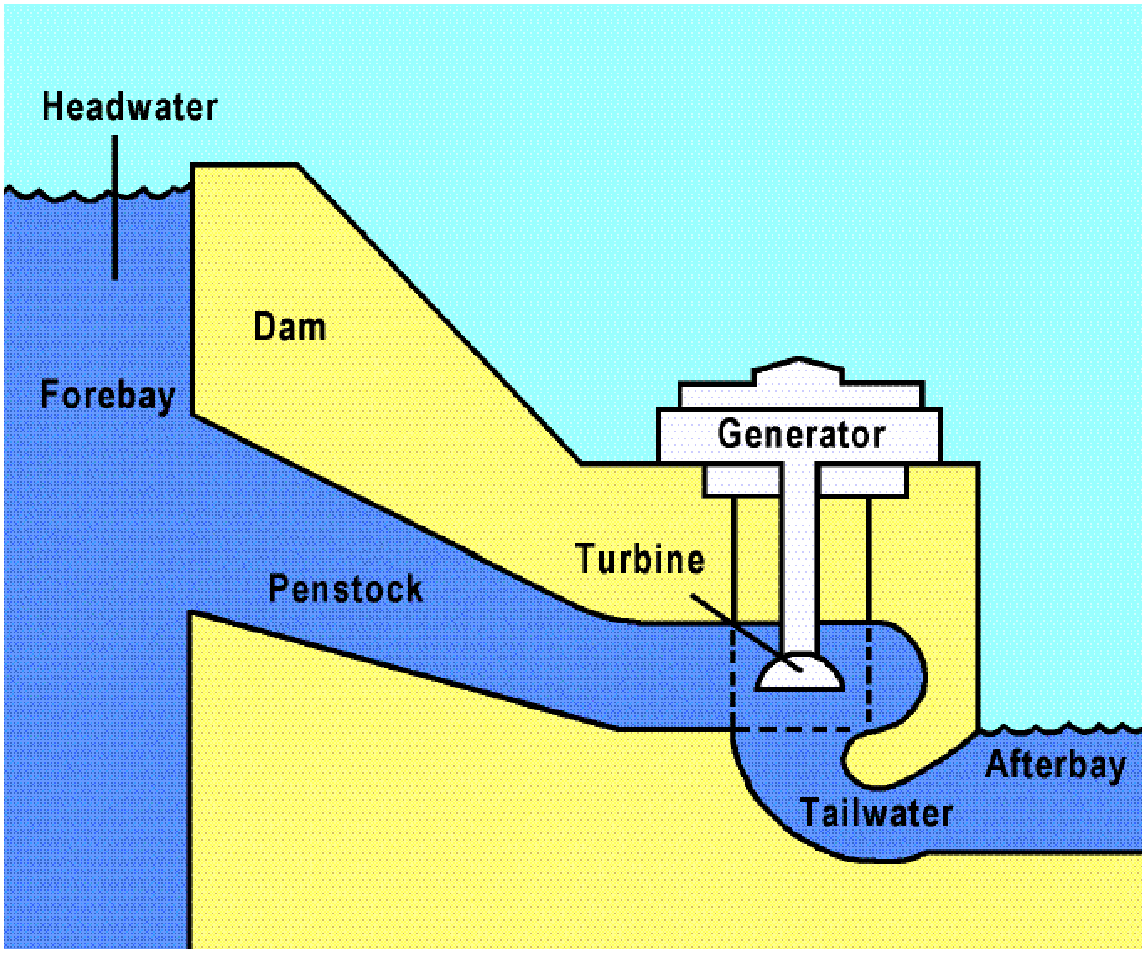
- 6. Tail Race or Outlet Water Way

-Tail race is a passage for discharging the water leaving the turbines

Hydro—Power Typical Installation



Lay out of hydro electric power plant



Constituents of hydro electric power plant

- Spillways

  -when river flow exceeds the storage limits
- Surge tanks

  -pipe to absorb sudden rises of pressure as well as to quickly provide extra water during a brief drop in pressure

  -at high or medium head

- Penstocke

  -A gate that controls water flow, or an enclosed pipe that delivers water to hydraulic turbines

  -concrete: less than 30m

  -steel : any head

  -thickness increases with head or working pressure

Scale of Hydropower Projects

Large-hydro

- More than 100 MW feeding into a large electricity grid

Medium-hydro

- 15 - 100 MW usually feeding a grid

Small-hydro

- 1 - 15 MW - usually feeding into a grid

Mini-hydro

- Above 100 kW, but below 1 MW
- Either stand alone schemes or more often feeding into the grid

Micro-hydro

- From 5kW up to 100 kW
- Usually provided power for a small community or rural industry in remote areas away from the grid.

Pico-hydro

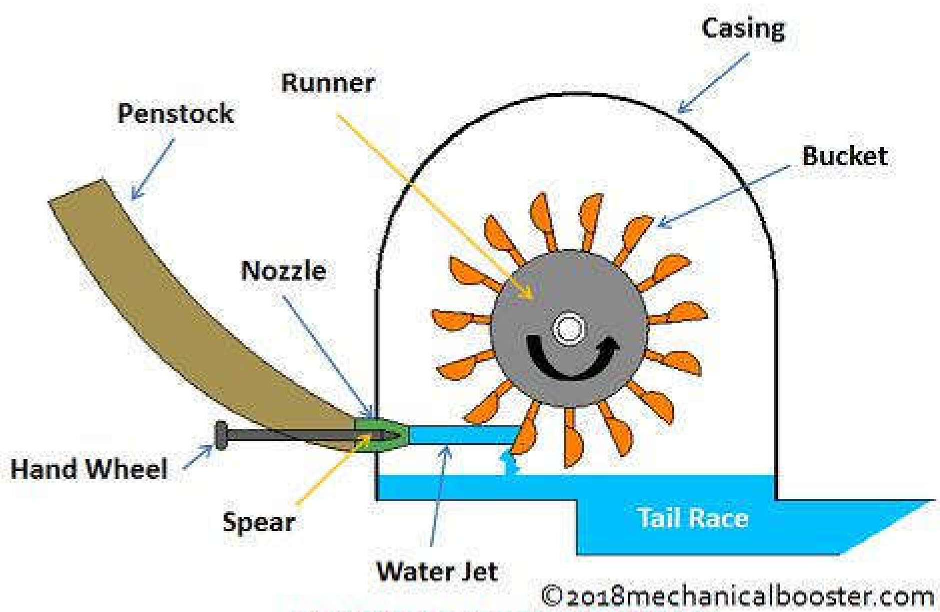
- From a few hundred watts up to 5kW
- Remote areas away from the grid.

Turbines

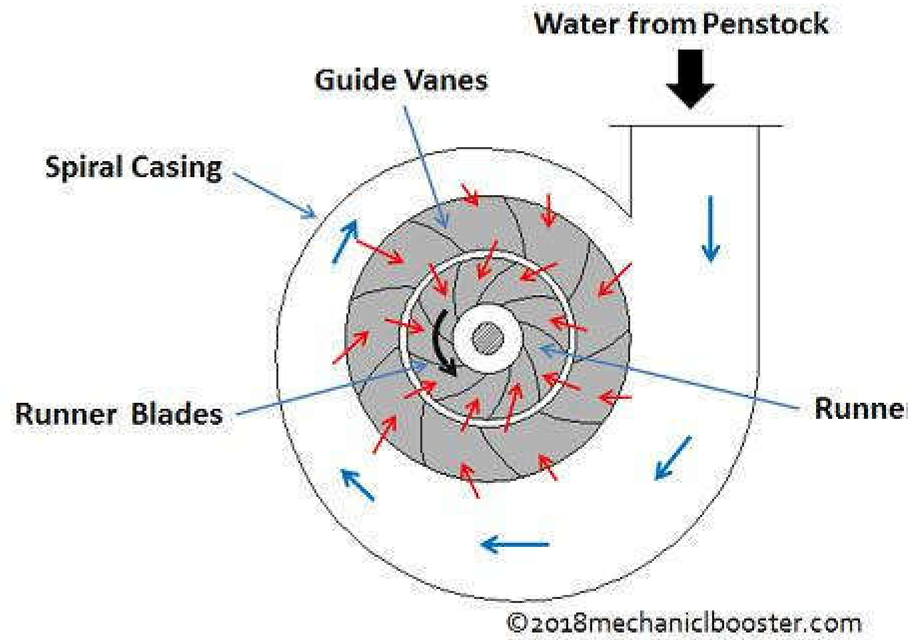
Turbines are of two types:

(a) **Impulse Turbines**, where the flow hits the turbine as a jet in an open environment, with the power deriving from the kinetic energy of the flow (see §6.4); and

(b) **Reaction Turbines**, where the turbine is totally embedded in the fluid and powered from the pressure drop across the device (see §6.5).



Main Parts of Impulse Turbine



Reaction Turbine

Turbines: Classifications

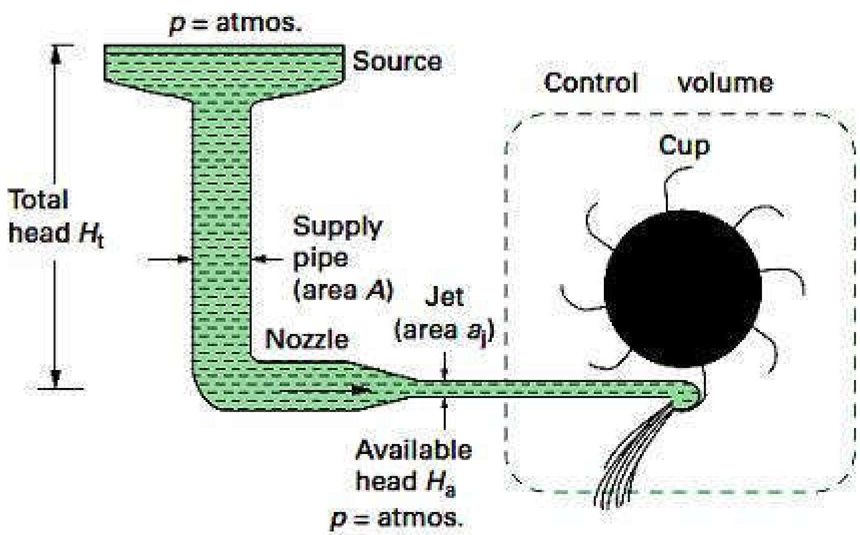
The main classification depends upon the type of action of the water on the turbine. These are:

1. Impulse turbine: The potential energy is converted to kinetic energy in the nozzles. The impulse provided by the jets is used to turn the turbine wheel. The pressure inside the turbine is atmospheric. This type is found suitable when the available potential energy is high and the flow (discharge) available is comparatively low.

2. Reaction turbine: The available potential energy is progressively converted in the turbine rotors (stages) and the reaction of the accelerating water causes the turning of the wheel. These machines are again divided into radial flow, mixed flow, and axial flow depending upon the head available. Radial flow machines are found suitable for moderate levels of head and medium quantities of flow. The axial machines are suitable for low levels of head and large flow rates.

Impulse Turbines

We first consider a particular impulse turbine: the *Pelton wheel turbine*. The potential energy of the water in the reservoir is changed into kinetic energy of one or more jets. Each jet then hits a series of buckets or 'cups' placed on the perimeter of a vertical wheel, as sketched in Fig. 6.4. This tangential force applied to the wheel causes it to rotate. Although the ideal turbine efficiency is 100%, in practice, values range from 50% for small units to 90% for accurately machined large commercial systems.

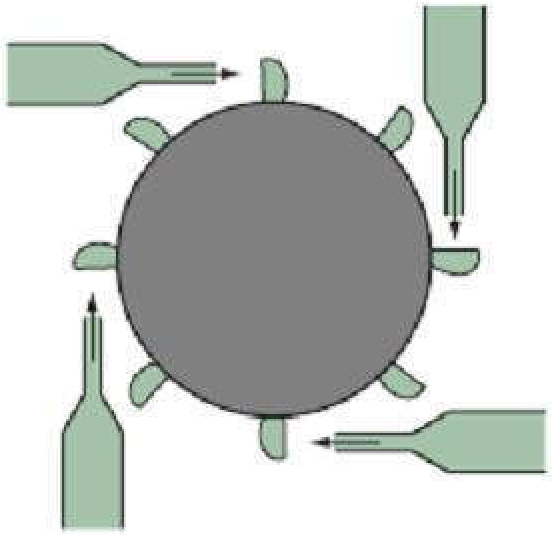


6.4
Schematic diagram of a Pelton wheel impulse turbine.

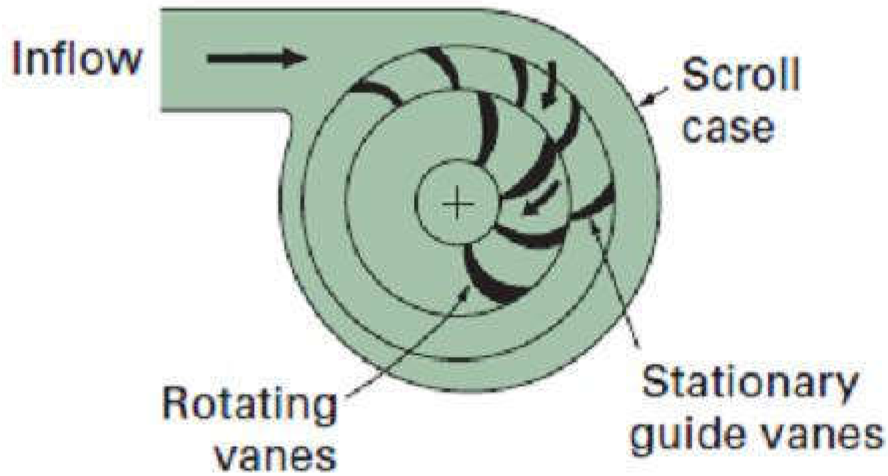
The nozzles are adjusted so that the water jets hit the moving cups perpendicularly at the optimum relative speed for maximum momentum transfer. The ideal cannot be achieved in practice, because an incoming jet would be disturbed both by the reflected jet and by the next cup revolving into place.

Impulse Turbines

(a) Pelton (impulse)



(b) Francis (impulse)

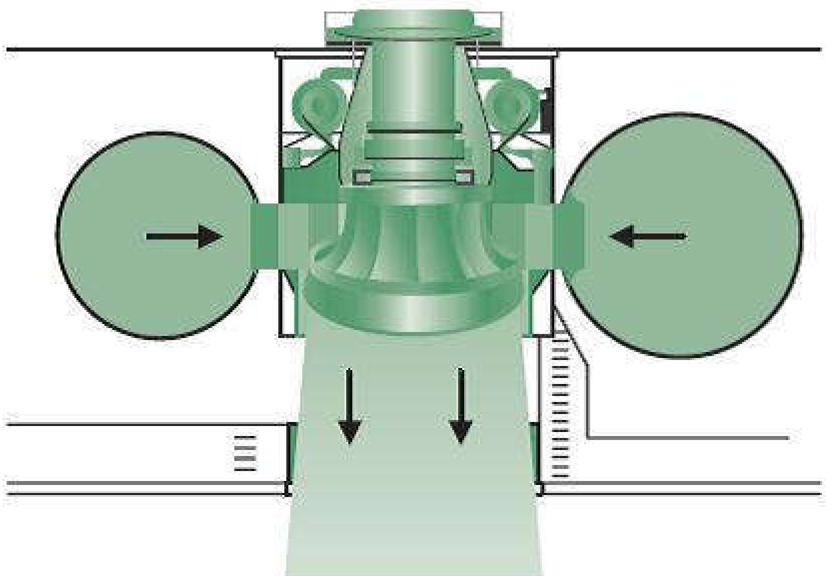


Reaction Turbines

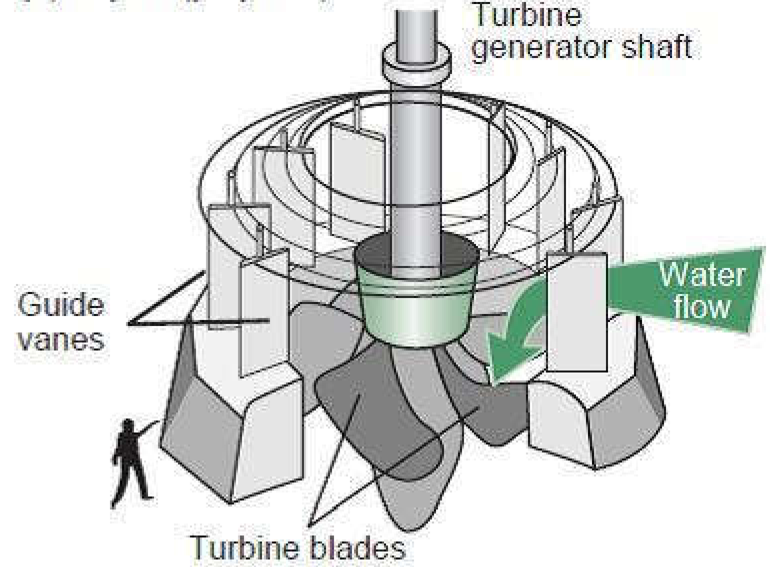
Low-head situations (6.1), require a greater flow Q through the turbine than for high-head. Likewise, considering the shape number S of (6.19), to maintain the same ω and P with lower H, we require a turbine with larger S. For instance, by increasing the number of nozzles on a Pelton wheel: see (6.18) and Fig. 6.7(a). However, the pipework becomes unduly complicated if $n > 4$, and the efficiency decreases because the many jets of water interfere with each other. To maintain a larger flow through a turbine, design changes are needed, as in the Francis reaction turbine of Figs 6.7(b) and 6.7(c). In effect, the entire periphery of the wheel is made into one large 'slot' jet for water to enter and then turn in a vortex to push against the rotor vanes. Such turbines are called *reaction* machines because the fluid

Reaction Turbines: Examples

(c) Francis (side view)



(d) Kaplan (propeller)



Turbines convert the energy of rushing water, steam or wind into mechanical energy to drive a generator.

Francis turbine : Water strikes the edge of the runner, pushes the blades and then flows toward the axis of the turbine. It escapes through the draft tube located under the turbine. It was named after James Bicheno Francis (1815-1892), the engineer who invented the apparatus in 1849.

Kaplan turbine : Engineer Viktor Kaplan (1876-1934) invented this turbine. It's similar to the propeller turbine, except that its blades are adjustable; their position can be set according to the available flow. This turbine is therefore suitable for certain run-of-river generating stations where the river flow varies considerably.

Propeller turbine : Since they can reach very high rotation speeds, propeller turbines are effective for low heads. Consequently, this type of turbine is suitable for run-of-river power stations.

Pelton turbine : Named after its inventor, Lester Pelton (1829-1908), this turbine uses spoon-shaped buckets to harness the energy of falling water.

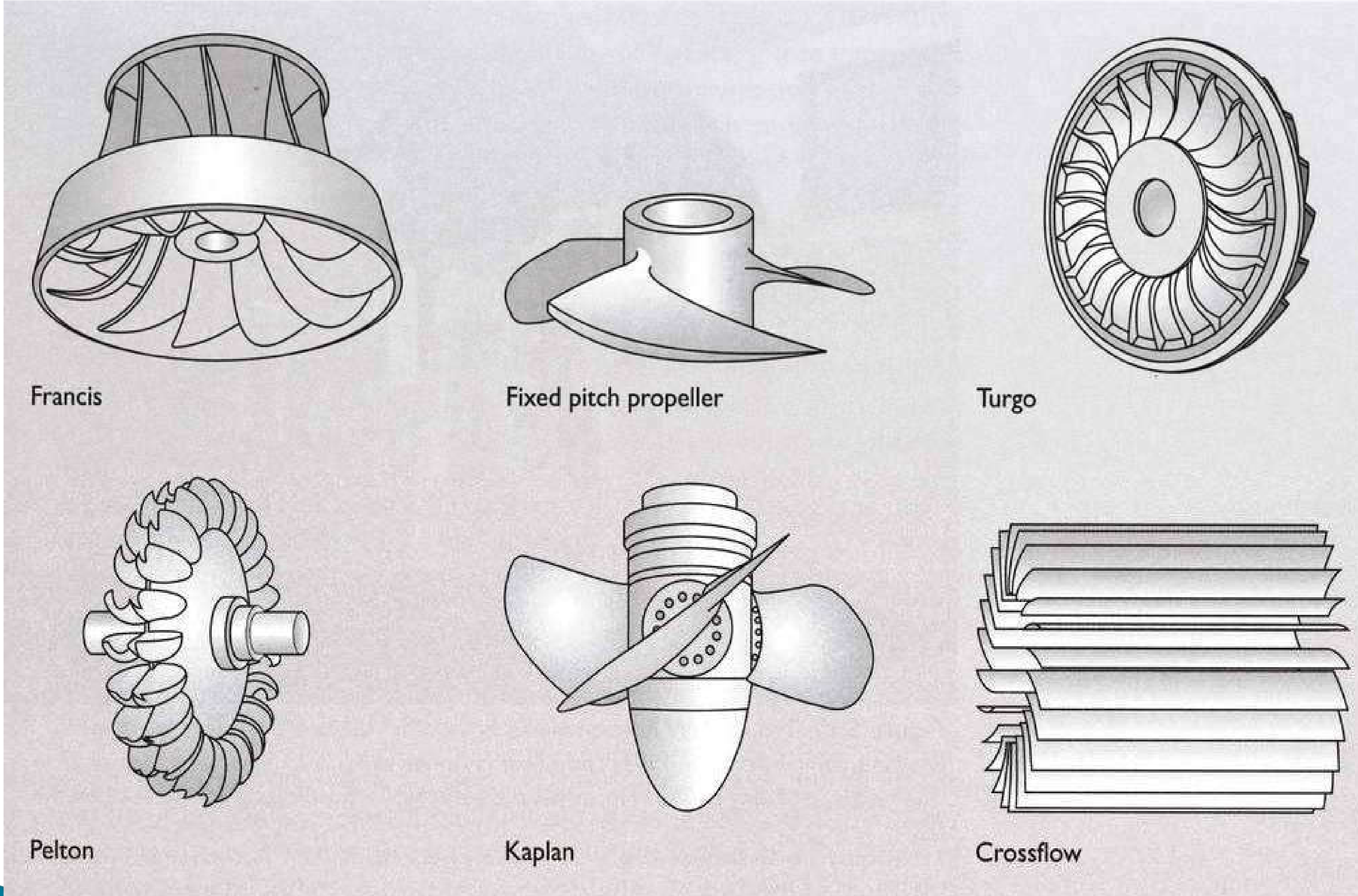


Figure 5.15 Types of turbine runner

Francis Turbine

Propeller Turbine

Kaplan turbine

Pelton wheel turbine

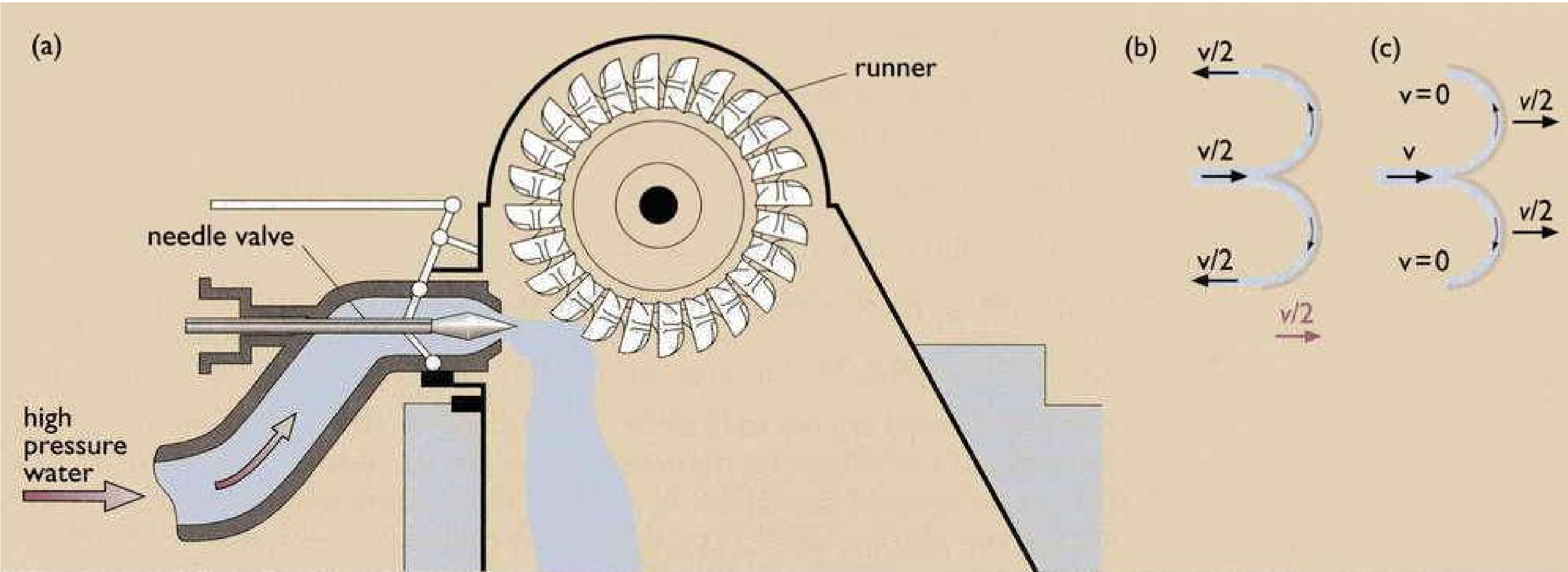


Figure 5.21 Pelton wheel turbine: (a) vertical section; (b) water flow as seen from moving cup; (c) actual motion of water and cup

Turgo turbine

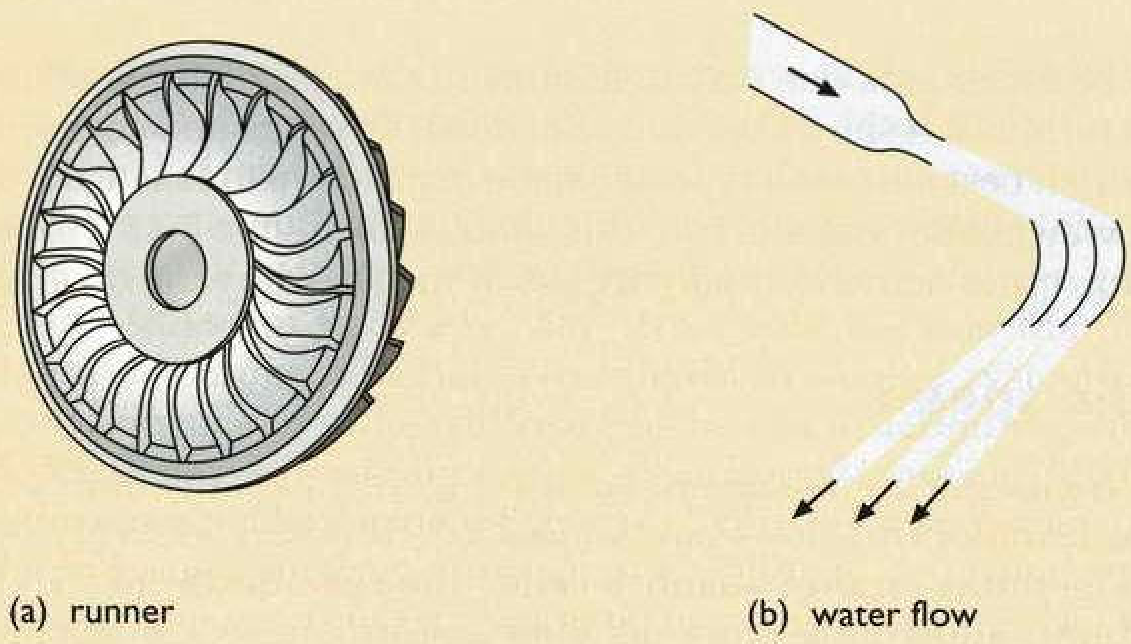


Figure 5.22 Turgo turbine: (a) runner; (b) water flow

Turbine Design Ranges

- Kaplan $2 < H < 40$
- Francis $10 < H < 350$
- Pelton $50 < H < 1300$
- Turgo $50 < H < 250$

(H = head in meters)

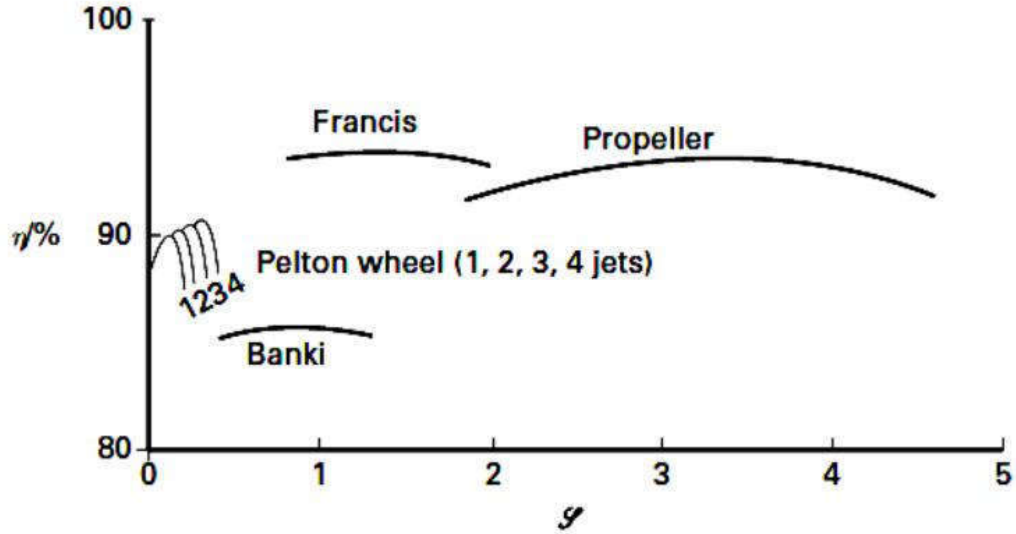


Fig. 6.8

Illustrative peak efficiencies, here ranging between 85% and 95%, of various turbine types in relation to shape number.

Source: Adapted from Çengel and Cimbala (2010).

Kaplan Turbine **(Propeller Hydro Turbine)**

Francis Turbine

Turbine Efficiency versus Specific speed

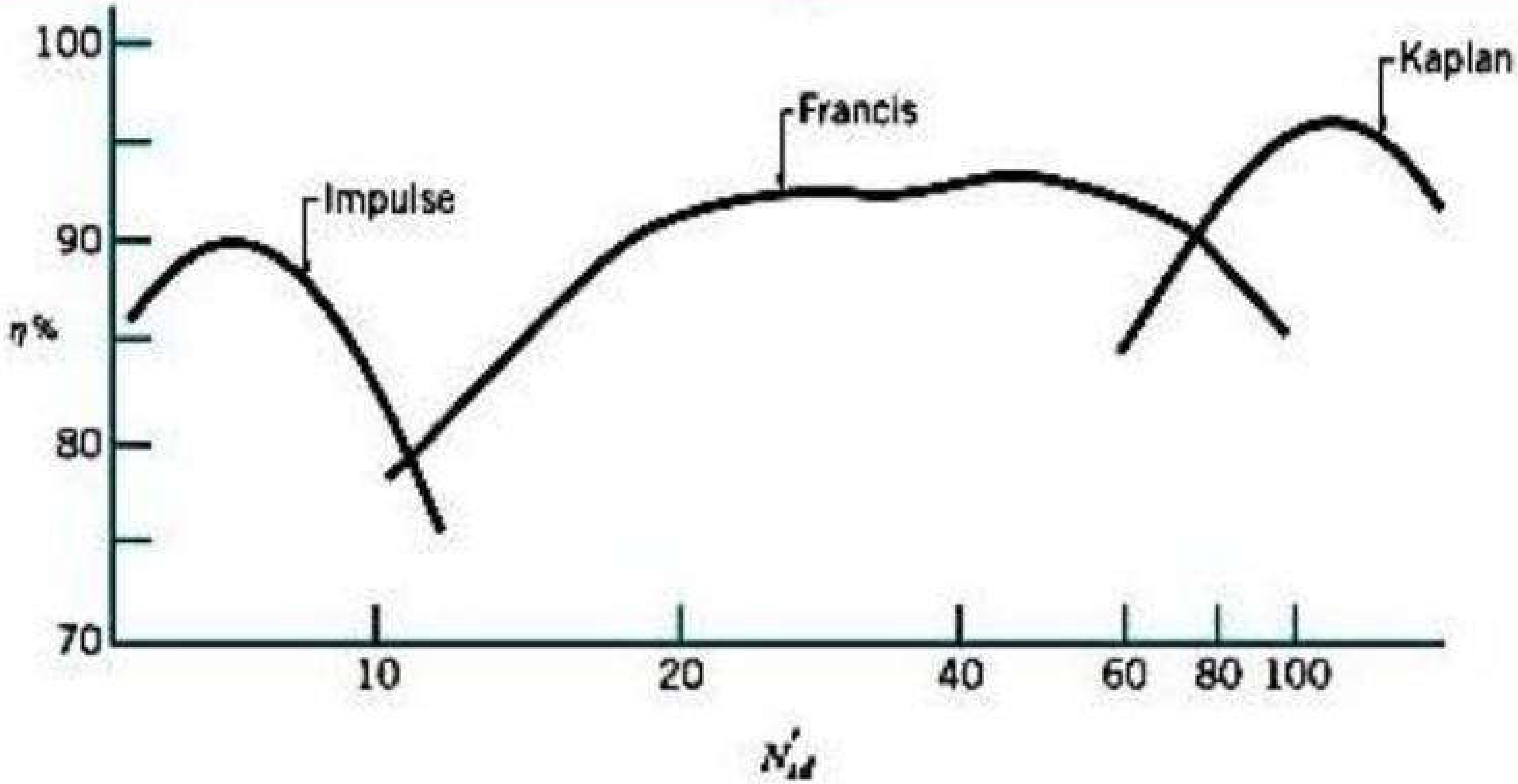


FIGURE 12.32
Typical turbine cross sections and maximum efficiencies as a function of specific speed.

Specific speed

The specific speed is used to select a particular type of pump. The performance curves of the pumps supplied by the manufacturers make use of this quantity for preparing such documents. The expression for the dimensionless specific speed is given by:

$$N_s = \frac{N\sqrt{Q}}{(gH)^{3/4}}, \text{ for pump} \tag{5.1}$$

$$N_s = \frac{N\sqrt{(P/Q)}}{(gH)^{5/4}}, \text{ for turbine} \tag{5.2}$$

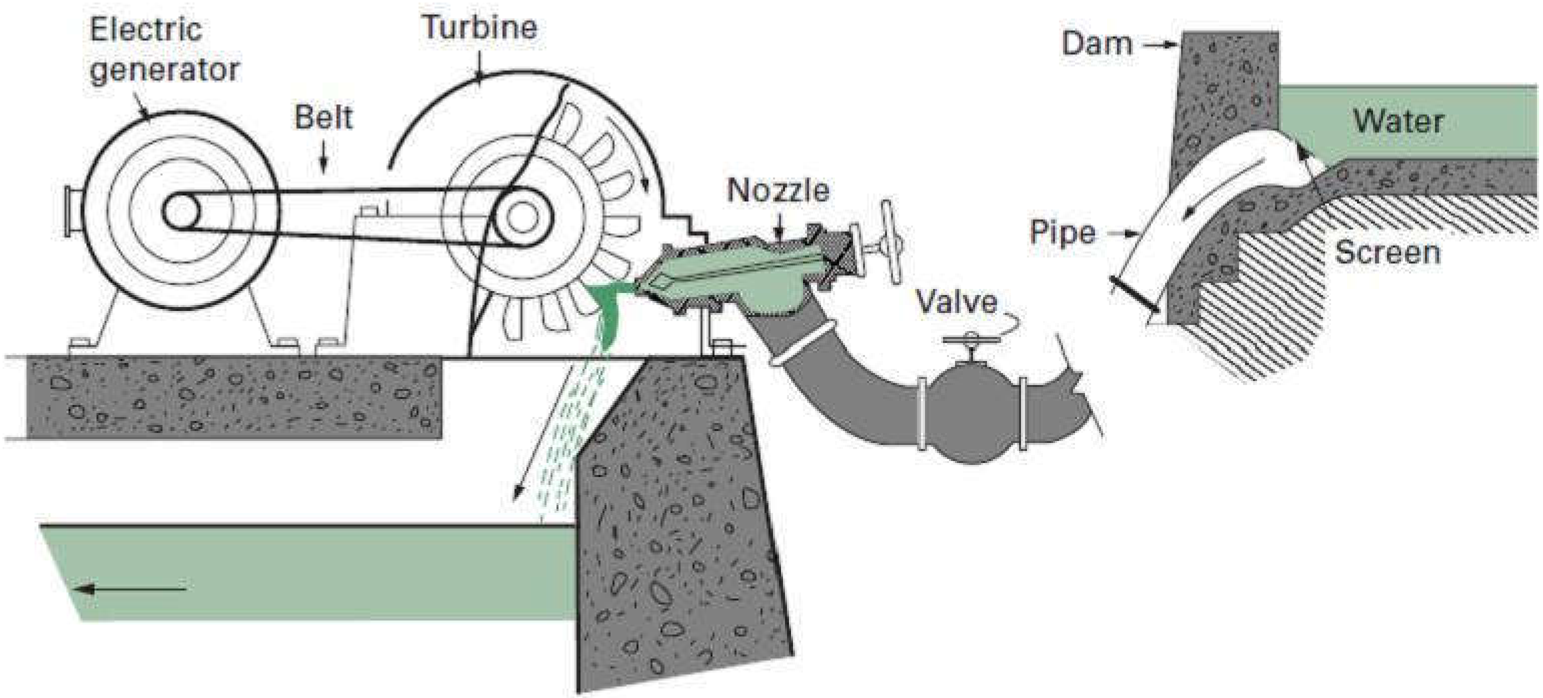
where N is rotational speed in rpm, Q is discharge in m^3/s, P is power in W, H is head in m, and g is gravitational acceleration in m/s^2.

Design considerations

	Head Pressure		
	High	Medium	Low
Impulse	Pelton Turgo Multi-jet Pelton	Crossflow Turgo Multi-jet Pelton	Crossflow
Reaction		Francis Pump-as-Turbine	Propeller Kaplan

Hydroelectric Systems

The *dam* insures a steady supply of water without fluctuations, and, most importantly, enables *energy storage* in the reservoir. It may also provide benefits other than generating electricity (e.g. flood control, water supply, a road crossing).



The supply pipe (penstock) is usually a relatively major construction cost. It is cheaper if thin walled, short and of small diameter; but these conditions are seldom possible. In particular the diameter $\boldsymbol{D}$ cannot be small due to excessive head loss $\boldsymbol{H_f \propto D^{-5}}$. The greater cost of a larger pipe has to be compared with the continued loss of power by using a small pipe. A common compromise is to make $\boldsymbol{H_f \leq 0.1\ H_t}$.

The material of the penstock needs to be both smooth (to reduce friction) and strong (to withstand the static pressures, and the considerably larger dynamic ‘water hammer’ pressures from sudden changes in flow).